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Estratégias para o desenvolvimento de redes óticas de próxima geração

Strategy on the deployment of next generations optical networks

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Tese apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Doutor em Engenharia e Gestão Industrial, realizada sob a orientação científica do Doutor António Luís Jesus Teixeira, Professor Catedrático do Departamento de Eletrónica, Telecomunicações e Informática da Universidade de Aveiro e da Doutora Marlene Paula Castro Amorim, Professora Auxiliar do Departamento de Economia, Gestão, Engenharia Industrial e Turismo da Universidade de Aveiro.

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palavras-chave

Gestão Estratégica, Industria de Telecomunicações, Redes Óticas Passivas, Curvas de Crescimento, Curva de Gompertz, Curva Logística, Bi-Logística, Bi-Gompertz, Previsao de Mercado.

Resumo

O presente trabalho analisa as atuais redes de telecomunicações em vários contextos, nomeadamente, o tipo de redes implementadas, os requisitos e a competitividade. As atuais tecnologias PON, nomeadamente, GPON, XG(S)-PON e NG-PON2 são apresentadas e exploradas tecnicamente assim como os seus limites tecnológicos.
São também apresentadas e discutidas as mais recentes tecnologias de acesso, tais como o 25GS-PON e 50G-PON onde são analisadas as futuras tecnologias óticas.
As radicais mudanças do mercado das telecomunicações são normalmente marcadas por um complexo processo entre avanços científicos e procura de mercado. Este processo é estudado e analisado usando modelos económicos de difusão epidémica.
São também estudados e modelizados em curvas de crescimento o mercado Global, Europeu e Norte Americano das redes óticas passivas para a tecnologia GPON, assim como as incertezas que afetam o investimento e crescimento desta tecnologia. Modelos baseados em Gompertz, Logística, Bi-Logística, Bi-Gompertz, Multi-Logística e Multi-Gompertz são propostos como forma de modelização.
Os modelos baseados em Bi-Logística, Bi-Gompertz e Modelo de Substituição Logística são utilizados como forma de predição de mercado para as mais recentes tecnologias PON, tais como o XG(S)-PON, NG-PON2, 25GS-PON e 50G-PON.
Este trabalho estuda e analisa as implementações futuras de rede, quando, em que contexto, quais os seus benefícios e como pode ser influenciada a arquitetura do serviço de telecomunicações.

keywords

Strategic Management, Telecom Industry, Passive Optical Network, Growth Curves, Gompertz curve, Logistic Curve, Bi-Logistic, Bi-Gompertz, Market Forecast.

abstract

The present work analyzes the current telecommunications networks in several contexts, namely, the type of networks implemented, requirements, and competitiveness. Current PON technologies, namely, GPON, XG(S)-PON, and NG-PON2 are presented and technically explored as well as their technological limits.

The latest access technologies are also presented and discussed, such as the 25GS-PON and 50G-PON, where future optical technologies are analyzed.

The radical changes in the telecommunications market are usually marked by a complex process between scientific advances and market demand. This process is studied and analyzed using economic epidemic diffusion models.

The global, European, and North American markets for passive optical networks for GPON technology are also studied and modeled in growth curves, as well as the uncertainties affecting the investment and growth of this technology. Models based on Gompertz, Logistics, Bi-Logistics, Bi-Gompertz, Multi-Logistics, and Multi-Gompertz are proposed as a form of modeling.

The models based on Bi-Logistics, Bi-Gompertz, and Logistic Substitution are used as a way of market forecasting for the latest PON technologies, such as XG(S)-PON, NG-PON2, 25GS-PON, and 50G-PON.

This work, studies and analyzes future network implementations, when, in what context, what are their benefits, and how the architecture of the telecommunications services can be influenced.

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List of Acronyms

10GEPON - 10-Gigabit Ethernet Passive Optical Network

25GS-PON – 25-Gigabit Symmetric Passive Optical Network

50G-PON – 50-Gigabit Passive Optical Network

AP – Asia-Pacific

APD- Avalanche Photodiode

ARPU – Average Revenue per User

ASIC – Application-Specific Integrated Circuit

ATM - Asynchronous Transfer Mode

B2B – Business to Business

BM LA – Burst Mode Limiting Amplifier

BM TIA – Burst Mode Trans-Impedance Amplifier

BOSA - Bidirectional Optical Sub-Assembly

B-PON - Broadband PON

Cala – Caribbean & Latin America

CAPEX – Capital Expenditure

CBU - Cell-site Backhauling Unit

CDR – Clock and Data Recover

CEMx – Coexistence Element

CEx- Coexistence element

CMTS – Cable Modem Termination System

CO – Central Office

CoC - code of conduct

CoMP - Coordinated MultiPoint

CPRI - Common Public Radio Interface

C-RAN - Cloud-RAN

CT - Channel Termination

CTI - Cooperative Transport Interface

CU - Central Unit; Control Unit

DBA- Dynamic Bandwidth Assignment/Allocation

DML – Direct modulated Laser

DPU - Distribution Point Unit

DQPSK - Differential Quadrature Phase Shift Keying

DSL – Digital Subscriber Line

DSP - Digital Signal Processing

DU - Digital Unit or Distributed Unit

DWBA - Dynamic Wavelength and Bandwidth Assignment

DWDM – Dense Wavelength Division Multiplexing

EMEA – Europe, Middle East, and Africa

EML - External Modulated Laser

EPON – Ethernet PON

EU – Europe

FBA - Fixed Bandwidth Allocation

FOAN - Future Optical Access Network

F-PCB - Flex Printed Circuit Board

FPGA – Field Programmable Gate Array

FSAN - Full-Service Access Network

FTTB - Fiber to the Building

FTTC - Fiber to the Curb

FTTCab - Fiber to the Cabinet

FTTCell - Fiber to the Cell site

FTTdp - Fiber to the distribution point

FTTH - Fiber to the Home

FTTS – Fiber to the Mobile Cell Sites

G.fast – Fast Access to subscriber terminals

G-PON – Gigabit-Capable Passive Optical Network

HSPON - Higher Speed Passive Optical Network

IEEE – Institute of Electrical and Electronics Engineers

IIASA - International Institute for Applied Systems Analysis

IoT - Internet-of-things

IPTV – Internet Protocol Television

IT – information technology

ITU – International Telecommunication Union

ITU-T – International Telecommunication Union Telecommunication Standardization Sector

LAN - Local Area Network

Laser – Light Amplification by Stimulated Emission of Radiation

LC – Line Card

LD Driver – Laser Diode Driver

LSM – Logistic Substitution Model

M2M – Machine-to-Machine

MBH – Mobile Backhaul

MDU - Multi-Dwelling Unit

MEF - Metro Ethernet Forum

MENA - Middle East and North Africa

MPM - Multi-PON Module

MSA - Multi-Source Agreement

NA – North America

NGMN - Next Generation Mobile Networks

NG-PON - Next-Generation Passive Optical Network

NG-PON2 – Next-Generation Passive Optical Network 2

NLS – Non-Linear–Least Squares Regression

NRZ – Non-return-to-zero

OBSAI - Open Base Station Architecture Initiative

ODN – Optical Distribution Network

ODNA - Optical Distribution Network at Antenna

OFDM - Orthogonal Frequency-Division Multiplexing

OLT - Optical Line Termination

OMCI - Optical network unit Management and Control Interface

ONT - Optical Network Terminal

ONU - Optical Network Unit

OpEx - Operational Expenditures

ORI - Open Radio Interface

PDH - Plesiochronous Digital Hierarchy

PAM - Pulse Amplitude Modulation

PIC- Photonic Integrated Circuit

PMD - Physical medium dependent

PON - Passive Optical Network

PtMP - Point-to-Multipoint

PtP - Point-to-Point

PtP WDM PON – Point-to-Point Wavelength Division Multiplexing Passive Optical Network

QoS – Quality of Service

QOSA- Quad Optical Sub-Assembly

R&D – Research and Development

RAN - Radio Access Network

RF – Radio Frequency

RoAP – Rest of Asia-Pacific

RoF - Radio-over-Fiber

RU – Radio Unit / Remote Unit

SDH - Synchronous Digital Hierarchy

SE - Spectral Efficiency

SME – Small and Medium Size Enterprise

SOA- Semiconductor Optical Amplifier

SOHO – Small and Home Office

SONET - Synchronous Optical Networking

SP – Service Provider

TCL - Transmission Convergence layer

TDMA - Time Division Multiple Access

TDM-PON - Time Division Multiplexing Passive Optical Network

TEC - Thermoelectric Cooler

TIA – Trans-impedance Amplifier

TOSA- Transmitter Optical Sub-Assembly

TWDM - Time and Wavelength Division Multiplexing

UAE – United Arab Emirates

UDWDM - Ultra-Dense Wavelength Division Multiplexing

UHD - Ultra-High Definition

UK – United Kingdom

UNI - User Network Interface

USA – United States of America

VoD - Video on Demand

VoIP – Voice over Internet Protocol

vRAN - Virtual Radio Access Network

WDM- Wavelength Division Multiplexing

WDM1r – Wavelength Division Multiplexer 1r

Wi-Fi – Wireless Fidelity

WM – Wavelength Multiplexer

WM1 – Wavelength Multiplexer 1

WR - Wavelength-routed

WS - Wavelength-selected

xDSL – X Digital Subscriber Line

XFP - 10 Gigabit Small Form Factor Pluggable

XG-PON - 10-Gigabit Passive Optical Network

XGS-PON - 10-Gigabit-capable Symmetric Passive Optical Network

xHaul – Fronthaul, midhaul and Backhaul transport networks

Chapter 1: Introduction

1.1 Motivation and Objectives

"The tools of the economist and the technology manager are almost never as precise as those used by the physical scientist." [1]

Today it is ultra-high-speed broadband infrastructure a determining factor in ensuring the economic fortune of cities and regions, but are telecom operators able to cope with this responsibility and ensure the demand? Are they using the right network strategy? Are telecom operators assuring the need for bandwidth and the necessity for new types of services? Are equipment telecom manufactures using the right strategies for new equipment manufacturing?

The research work performed in this thesis will try to address the listed questions challenging different strategies for modeling the deployment of next-generation optical networks to improve business operations and gain an advantage in the very competitive telecommunication industry.

Thus, the thesis aims to analyze the actual telecommunication networks in several contexts, namely, type of implemented networks, requirements, and competitiveness.

Through the technological study and analysis of the future networks and exploring its limits and expectations, we intend to predict the future implementations, the timelines context, its benefits, and how it can influence the telecom service architecture.

Any service provider due to competition aims to shorten the development and the introduction time of services. A telecom operator needs to create a more flexible service environment for the development, deployment, execution, monitoring, and life-cycle management of user-centric applications [1]. At the same time, the cost for service delivery needs to be lowered to maintain customer satisfaction.

Telecom service providers need to re-engineer their information technology (IT) and telecommunications services environment to offer new value-added services faster and more cost-efficiently with the new passive optical network (PON) technologies. The organizations need to adopt a service-oriented architecture to rationalize the infrastructure, introduce self-service systems and manage 3rd party business-to-business interactions.

A Service-Oriented Architecture can affect the whole infrastructure (marketing and sales, operations, finance, and telecommunication services [1].

In fast-growing businesses such as PONs for the telecommunications industry, suppliers need to be able to adapt its offering to a wide variety of customers. Understanding the customer's needs together with the right demand chain structure results in good co-operation in improving the joint demand chain, which further leads to superior demand chain efficiency and customer satisfaction [2]–[4]. The essential question for a supplier is

[1] *Forecasting and Management of Technology, Second Edition*
Alan Thomas Roper, Scott W. Cunningham, Alan L. Porter, Thomas W. Mason, Frederick A. Rossini, Jerry Banks

how to draw the demand chain architecture according to the characteristics of distinct customer needs and situations. Demand chain architecture means understanding the nature of demand and developing a modular demand chain structure —including decisions of the order-penetration point, inventory buffer locations and sizes, and assembly capacity. The demand chain architecture must be robust—to apply different demand chains in different customer situations [3].

Most important in the environment for innovative products is reading market signals correctly and being able to react quickly during the product's short life cycle. The crucial flow of information occurs from the marketplace to the demand chain.

The first step in designing a responsive supply chain is to accept that uncertainty is inherent in innovative products. Uncertainty can be avoided by cutting lead times and increasing the supply chain's flexibility, so that, it can produce to order or at least assemble the product at a time closer to when demand materializes and can be accurately forecasted. The company can hedge against the remaining uncertainty with buffers of inventory or excess capacity [3].

The manufacturing process and supply chain structure need to be considered together to create a capability for mass customization. The optical networks equipment configuration and delivery belong to customize industry. In a customize industry, buyers have a wide variety of choices from which to select features of the final product. Customized standardization tends to be the preferred customization strategy in this type of industry. Transactions between the buyer and the supplier involve negotiations and reciprocal relationships between buyers and sellers. Once the configuration has been decided, the production function assembles prefabricated components into finished products [5].

Great benefits could be achieved by co-operation between the customer and the supplier and giving the supplier access to the customer's real demand data. Customer–supplier relationships in which close long-term co-operation simultaneously increase the value produced by the demand chain and decreases the overall cost of the chain. Suppliers and customers can form joint development teams to improve various aspects of the supply chain or suppliers can suggest changes that may lead to quality or cost improvements. Successful supplier alliances are associated with high levels of information sharing and information quality and participation [2].

1.2 Thesis Outline

The thesis is organized into eight chapters which cover the following topics:

Chapter 2 presents an overview of the state-of-the-art of current PON technologies. GPON, XGS-PON, and NG-PON2 are presented as well as a study on the energy efficiency of NG-PON2. Radio Access Networks and their requirements are discussed and analyzed. The technologies beyond 10 Gbit/s, namely 25GS-PON and 50G-PON are studied as well as future laser requirements and possible technologies to cope with the new PON requirements.

Chapter 3 analyzes the change in the telecom industry. Economic theories of technical change and innovation management are used to model the complex process marked by the interactions between scientific advances and market demands.

Chapter 4 focuses on the growth concepts discussed throughout the thesis. Several Epidemic diffusion models are studied, namely, the three-parameter Logistic curve and the Gompertz Curve. Several parametrizations and re-parametrizations of the Gompertz curve are investigated. The research methodology is presented.

Chapter 5 presents the PON and FTTH historical view as well as the current FTTH/B market. The Global, European, and North American markets are modeled to the different growth curves presented in chapter 4. A deep analysis of the current GPON market is made as well as the future growth.

Chapter 6 discusses the uncertainties that affect the PON market and the importance of the growth models in a business plan is analyzed. Different growth models are proposed to map the historical uncertainties of the GPON market. A Bi-Gompertz, a Bi-Logistic, a Multi-Gompertz, and Multi-Logistic are proposed and fitted.

Chapter 7 takes the findings from the research done in chapters 4, 5, and 6 as an input for forecasting the next-generation PON markets. A Logistic Substitution Model, as well as Multi-technological substitution models, are analyzed as forecast methods for the PON market. The NG-PON market opportunities are discussed.

Chapter 8 summarizes the work and presents the main conclusions. Proposals for future work are also presented.

1.3 Main Contributions

The most important results presented in this thesis are:

- The characteristics of technological breakthroughs for future PON, namely, the optical technologies for 25GS-PON and 50G-PON. The feasibility of PON to support the existing and future Radio access networks applications and the importance of PON technology in our daily life and the social necessity in having high technological OLT and ONUs on the different scenarios capable of supplying their needs.

- Investigation of Telecom Industry as a complex process marked by the interactions between scientific advances and market demands.

- Study of the dynamics of innovation and PON technologies by Identifying and studying different epidemic diffusion models and their dynamics on PON diffusion.

- Proposal model the GPON market to the identified epidemic diffusion models, namely: Logistics, Gompertz, Zwietering, Zweifel and Lasker, Gompertz-Laird and Norton´s.

- The exploitation of the uncertainties related to investment in PON technologies and model these uncertainties by using the Bi-Logistic curve and Bi-Gompertz curve.

- Forecasting of new PON technologies, namely XGS-PON, NG-PON2, 25GS-PON, and 50G-PON using technological multi-substitution models, bi-S curves, and different situations of technological competition.

1.4 Result of research work

The major achievements obtained from the work of this thesis were submitted for peer review by the international scientific community through the list of publications that are listed below as well as several oral communications in relevant industry forums and conferences.

This work also contributed to several research and development projects listed above.

1.4.1 Oral Communications

- Cláudio Rodrigues, Francisco Rodrigues, Marlene Amorim, António Teixeira, “ 25 and 50G Optical Access Network Deployment Forecasts using Bi-Logistic curves”, Workshop on “FutuRe Optical Networking Salon (FRONT): The EDGE”, Barcelona, July 7th – 9th 2021;
- Cláudio Rodrigues, António Luis Jesus Teixeira, Marlene Paula Castro Amorim, “ Strategies for Deployments of Next Generation Optical networks”, Research Summit, Universidade de Aveiro, Aveiro, June 7th -9th 2021;
- Cláudio Rodrigues, António Luis Jesus Teixeira, Marlene Paula Castro Amorim, “ Strategy on the Deployment of Next Generations Optical Networks”, Research Summit, Universidade de Aveiro, Aveiro, June 24th -26th 2020;
- C. Rodrigues, “How to boost 5G cell capillarity using current xPON deployments”, Workshop: Beyond 5G: What is role of optical network, ECOC 2019, Dublin, 22-26 September 2019;
- C. Rodrigues, Panel discussion, Next Generation Networks, Examining Innovations and Leading Technologies in the FTTx Space to Deliver Broadband Access Services Efficiently and Realistically, Broadband World Forum Berlin, 24 - 26 October 2017.
- C. Rodrigues, “Operator Energy Saving achievements by using NG-PON2 functionalities”, NG-PON2 Forum Workshop, FTTH Conference 2017, Marseille, 14-16 de February 2017.

- C. Rodrigues, “How to use WDM-PON to boost your Fibre Investments”, Industrial Session, 21st European Conference on Networks and Optical Communications, Lisboa, 1-3 June 2016.
- C. Rodrigues, “How to use WDM-PON to boost your Fibre Investments”, Session 7: FTTH Technology Update, FTTH Conference 2016, Luxemburg, 16-18 de February 2016.
- C. Rodrigues, “PON Product “ 83rd Tech Day dedicated to Future PON Strategy, Altice Labs, 2nd March 2016.

1.4.2 Papers

- Cláudio Rodrigues, Francisco Rodrigues, Cátia Pinho, Nuno Bento, Marlene Amorim, António Teixeira, “ 25G and 50G Optical Access Network Deployment Forecasts using Bi-Logistic curves”, Proceedings Optical Fiber Communication Conference (OFC) 2021, 6–11 June 2021, Washington, DC, United States
- Cátia Pinho, Francisco Rodrigues, Ana Maia Tavares, Carla Rodrigues, Cláudio Emanuel Rodrigues, António Teixeira,” Photonic Integrated Circuits for NG-PON2 ONU Transceivers (Invited)”. Appl. Sci. 2020, 10, 4024.
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- Ali Shahpari, Ricardo M. Ferreira, Fernando P. Guiomar, Sofia B. Amado, Somayeh Ziaie, Cláudio Rodrigues, Jacklyn D. Reis, Armando N. Pinto, António L. Teixeira, “Field-Trial of a Real-Time Bidirectional UDWDM-PON Coexisting with GPON, RF Video Overlay and NG-PON2 Systems”, ECOC 2015, Valencia, Spain, 27th Sep - 01 Oct. 2015.
- Ana Tavares; Ana Lopes; Cláudio Rodrigues; Paulo Mão-Cheia; Tiago Mendes; Simão Brandão; Francisco Rodrigues; Ricardo Ferreira; António Teixeira, “Photonic integrated transmitter and receiver for NG-PON2”, Proc. SPIE 9286, Second International Conference on Applications of Optics and Photonics, 928605 (22 August 2014);
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1.4.3 Projects

- GPON-IN-A-BOX, January 2010 to December 2011.
- Fully-Converged Quintuple-Play Integrated Optical-Wireless Access Architectures, FP7-ICT-2009-4- 249142, EU/FP7, January 2010 to December 2012.
- NG-PON2, Consortium: IT and Altice Labs, January 2013 to December 2014.
- Photonic Integrated Circuits for NG-PON2, Consortium: IT and Altice Labs, May 2013 to December 2014.
- Future Passive Optical Networks, Consortium: IT and Altice Labs, POCI-01-0247-FEDER-003145, Funding P2020, June 2015 to May 2017.
- Virtual Fiber Box, Consortium: IT and Altice Labs, POCI-01-0247-FEDER-033910, Funding P2020 June 2018 to February 2021.
- PlugPON, Consortium, PicAdvanced, Altice Labs and IT, POCI-01-0247-FEDER-047221, Funding P2020 March 2020 to February 2023.

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Chapter 2: Optical Access Networks

This chapter presents the optical access networks and discusses the current technologies employed in the PONs as well as their evolution. The GPON, XGS-PON, and NG-PON2 technical characteristics are analyzed in detail. A review of the operator energy savings by using NG-PON2 technology is also presented, as well as its importance to fulfill the ecologic values.

The feasibility of PON to support the existing and future Radio access networks applications is analyzed in detail.

We examine the characteristics of technological breakthroughs for future PON, namely, the optical technologies for 25GS-PON and 50G-PON.

The major idea that emerges from this chapter is the importance of PON technology in our daily life and the social necessity in having high technological OLT and ONUs in the different scenarios capable of supplying their needs.

2.1 The Society impact of access networks

Fixed-access networks have had an enormous impact on society over the last few decades allowing residential broadband services and being a driver for the digitalization of society. With increasing broadband speeds, optical access technologies are playing an increasingly important role in fixed access.

Fiber to the home/building (FTTH/B) is being chosen due to its intrinsic ability as a vehicle to maximize bandwidth. This network provides enhanced network reliability, increased customer satisfaction, expanded service capability, and improved network Operational Expenditures (OpEx) [1]–[3]. FTTH enables the delivery of savings due to reductions in cost for network, central office (CO), and outside plant operations as well as customer service [4]–[6]. Network reliability dramatically increases as well as FTTH ensures a steady stream of revenue and enhanced customer satisfaction [6]–[8].

Broadband is not just a consequence of economic development, it is also recognized as a cause. In an increasingly information-based world economy, broadband networks are vital arteries of economic activity through which the supply and consumption of information content, services, and applications flow [9].

As an infrastructure, broadband networks can be seen in a similar way to the development of roads, railways, electricity, and the way that these networks have transformed economic activities for individuals, companies, and governments. The broadband networks being built today have been compared to “the roads and bridges and railways that were built in previous times”. These new infrastructures have made economies more efficient, enabled new economic activities which did not exist beforehand, and brought additional new economic growth [9].

Broadband networks have also profoundly changed the social environment in which we live, work and interact, allowing families to stay in touch with each other, governments to deliver services more effectively, and businesses to operate more globally [9].

The relationship between broadband expansion and economic growth could also vary across places. Broadband might offer greater benefit for places that are smaller or more isolated, helping local businesses or households to connect with larger markets: This line of thinking lies behind predictions that rural areas might benefit more from Internet technology [10].

Internet connectedness serves as a key element in stimulating growth, job creation, and investments in rural areas. Internet access often serves as a prerequisite for development opportunities, for example supporting short supply chains, accessing new markets, provision of services, education, and training, and better quality of life.[11][12]

According to [13], the presence of fiber networks is positively correlated with several socio-economic factors, which indicates that when controlling for the relevant variables, a 10% higher fiber penetration is correlated with reduced car use and 1.1% higher employment.

FTTH can contribute to equality of opportunity for all citizens, promoting info-inclusion and the development of human capital and contributing to the creation of externalities in a development policy at the level of employment, growth, competitiveness, and sustainability of the industries located in these areas.

While it can be argued that governments have more pressing priorities than FTTH, it can also be said that FTTH is a key to solving them:

- the economic downturn and global competition;
- education and unemployment;
- Sustainability and environment.

Specific services, such as high-definition video conference calls, require the high bandwidth that FTTH can provide. But even more important where home care is concerned; the services require the intrinsic reliability of fiber access networks.

Businesses themselves benefit directly from a multipurpose communications infrastructure. European businesses are relying more and more on cloud services to link multiple offices together, across the world. Companies save money by needing less office and meeting space, and by being able to distribute their activities away from large office towers in central cities. Decision-making happens faster. With real-time access to data, everyone is more productive.

There is evidence that FTTH impact is most pronounced in rural areas. In many sparsely populated regions, the existing broadband networks are substandard, and citizens are farther away from entertainment, education, and health services than urban dwellers.

Many rural areas are struggling to maintain their communities alive. FTTH allows local governments to:

- increase the economic attractiveness of their local region, retain citizens and businesses, and attract new businesses;
- reduce the urban-rural divide by enabling e-health, e-education, e-government, thus widening access to services typically located in cities;
- enable people from more isolated regions to have more direct communication with family, friends, and colleagues;
- preserve local culture and maintain a sense of local identity by encouraging consumption of local crafts, foods, and performing arts.

Residential content, triple-play services, was originally the primary focus however mobile, business, and machine-to-machine (M2M) services are demanding more and more content capacity with 5G coming and the Internet of Things having its market diluted throughout the world. Cloud-based business service is also a very important driver to evolve to NG-PON because: Software packages tend to be downloaded from data-center; Personal data is nowadays made and more stored in data-center what require very high upload and download speeds as well as symmetry and low latencies.

The access network of the future has to be prepared, which includes serving several segments and different backhaul features. We can conclude that future access networks will be a truly multi-service solution. The Communication on Connectivity for a European Gigabit Society (Sept 2016) sets a vision of Europe, where availability and take-up of very high-capacity networks enable the widespread use of products, services, and applications in the Digital Single Market. This vision relies on the three main strategic objectives for 2025: Gigabit connectivity, 5G coverage for all urban areas and all major terrestrial transport paths, and access for all European households to connectivity offering at least 100 Mbit/s [14], [15].

Bandwidth requirements for residential broadband connectivity have continued to grow to today´s technology capabilities of more than 100 Mbit/s. The emerging services, such as U-high definition (UHD) TV, augmented reality and virtual reality will continue to drive bandwidth requirements beyond 100 Mbit/s. In parallel to the development of high-speed residential access, broadband connectivity has evolved from interconnecting homes with fixed broadband to connecting people with mobile broadband and is now extending further to interconnecting devices, referred to as Internet-of-things (IoT).

IoT exploits the digitization of everything that humans interact with, processing and correlating information that people cannot see [13]. The result is a better understanding of the picture of the scenario, taking more profitable decisions on the local economy, motivating the return and inclusion of people that want to assure adequate services.

IoT goes beyond what we can imagine, it helps to improve efficient energy management, by the implementation of smart grids and smart consumer concept, making closer the demand and offer, by adopting new grid architecture and adapting at each time the offer to the demand needs.

Internet marketing, especially the World Wide Web is an optimal tool for people who want to be connected and informed, suggested by the use of social networks. People's lives are constantly connected despite being in various corners of the world. Besides, people communicate greatly when the Internet brings opportunities to access a range of knowledge, information, and entertainment.

It is irrefutable that Internet marketing is one of the vital tools for services nowadays thanks to its endless ability to deliver information. In addition to common webpage marketing, direct email marketing, etc. the consumer-generated media or social media, as Facebook, Twitter, YouTube, blogs, etc. are taking over the scene in internet marketing [16].

Nowadays, once the quantity of smartphone users is growing considerably, the development of mobile applications is inevitable. The bond between smartphones and mobile apps has led to a brand-new method of life, specifically a brand new method of communication.

As for services available by government administration, mobile apps have eased the life of citizens all around the world.

This means that superfast broadband is currently a staple demand across local services, businesses, and entertainment. Even the smallest local business needs a website, a presence on social media platforms wherever their customers share recommendations and criticisms. In the back office, a progressively more sophisticated variety of cloud-based applications and services is giving inhabitants of rural areas the chance to break down traditional barriers getting closer to the supplied services in the cities. It is an important tool to improve the performance and competitive edge of their business [17].

Without adequate broadband capacity, smart sensor networks that generate a huge amount of data, government services, people's activities in their homes and businesses, cannot be supported, as a consequence local economy cannot grow [15].

Wi-Fi connectivity for the local economy is a requirement rather than a luxury. With smartphones and tablets now everywhere, people expect to be able to access personal and business applications easily, wherever they are [18].

In addition, tourism complements rural businesses as a vital component in local economic development methods because of the potential relationships between totally different industrial sectors thereby not solely providing for extended circulation of money within local economies but also the development of new value-added products.

There is a global trend – in rural as well as urban areas – for increasing demand for communication capacity. As increased capacity has a significant effect in all sectors, it is essential to prepare and develop broadband strategies and plans.

2.2 Passive Optical Networks

Passive optical networks systems are designed to meet the requirements of access networks, supporting cost-effective deployment and high-end user peaks. PON poses several advantages, such as the simplification of infrastructure management, as it is based on a fully passive optical distribution network (ODN) [18]. A completely passive ODN made of buried glass with cabinets to ensure connections and splitting anticipates long-term expectation of 20 years or even more. Its architecture derives from the technical approach to be deployed at the PON ends.

Several generations of PONs have been specified both in ITU and IEEE and the deployed systems have predominantly been based on time-division multiplexing (TDM)-PON.

A TDM-PON is an optical system in which an optical line terminal (OLT) communicates with several optical network units or terminals (ONUs/ONTs) through an ODN compromising optical fibers and optical splitters. TDM-PON has been widely deployed worldwide because of its cost-effectiveness. It shares not only the optical fiber but also the OLT optical port and electronics among several ONT/ONUs connected to the OLT port.

TDM-PON relies on a scheme called time division multiple access (TDMA). The TDMA is controlled by the OLT, and the ONUs send their upstream signals as bursts using different time slots. In the downstream direction is used a time-division multiplexing (TDM) scheme. The data and other information that are sent to the ONUs are multiplexed using a specific time domain frame. All ONUs that are under an OLT port receives the downstream signal and each one extracts the data and information directed to it.

The physical network, ODN, is a multiple-stage optical splitting, where an OLT port can be connected typically from 16 to 128 ONUs. The point-to-multipoint optical connection is composed of optical fibers, splitters, connectors, and fusion splices.

In the 1990s the full-service access network (FSAN) group promoted the development of a common specification for TDM-PON, and the work resulted in an ITU-T standard, the broadband PON (B-PON). B-PON works at 155,52 Mbit/s in upstream and 155,52 Mbit/s or 622,08 Mbit/s in downstream direction. In the early 2000s the IEEE group and based on the transport of Ethernet frames over PON, led to the development of the EPON, which handles 1,25 Gbit/s in both directions. At the same time, FSAN and ITU-T developed the Gigabit PON (G-PON) capable of transporting several protocols and based on a generic frame with a downstream bit rate of 2,48832 Gbit/s and an upstream bit rate of 1,24416 Gbit/s. In the late 2000s, both FSAN/ITU-T and IEEE developed the standards for the 10 Gigabit PONs, XG-PON, and 10GEPON. XG-PON based on an asymmetric bit rate, 9,95328 Gbit/s in downstream and 2,48832 Gbit/s in upstream while 10GEPON with a symmetric bit rate of 10.3125 Gbit/s, but also supporting the legacy EPON in upstream. Later on, the FSAN/ITU-T also standardized the symmetric 9,95328 Gbit/s PON, the XGS-PON.

All previous PON systems mentioned are based on TDM in downstream and TDMA in upstream. In between the standardization of XG-PON and XGS-PON a new PON technology was standardized based on a time and wavelength division multiplexing (TWDM), where the advantages of a wavelength division multiplexing (WDM)-PON were put together with the advantage of the TDM-PON.

The most successful technology from its standardization till nowadays is GPON because of its cost-effectiveness and data capacity.

Figure 2-1 presents several generations of PON technology to date [1].

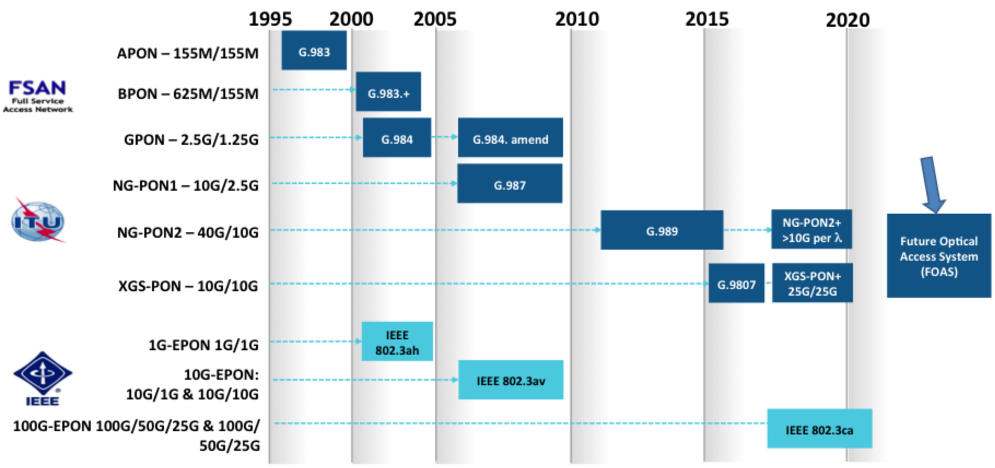

Figure 2-1 – PON standards evolution [1].

The optical section of an access network can be either active or passive and its architecture can be either point-to-point (PtP) or point-to-multipoint (PtMP). Several architectures, Figure 2-2, can be considered, which include, fiber to the home (FTTH), fiber to the cell site (FTTCell), fiber to the building/curb (FTTB/C), fiber to the cabinet (FTTCab), fiber to the distribution point (FTTdp), etc. The optical distribution network (ODN) is common to all the architectures, hence, the commonality of this system has the potential to generate large worldwide volumes. The differences among these FTTx options are mainly due to the different services supported and the different locations of the ONUs rather than the ODN itself. It must be noted that a single OLT optical interface might accommodate a combination of several scenarios described hereafter.

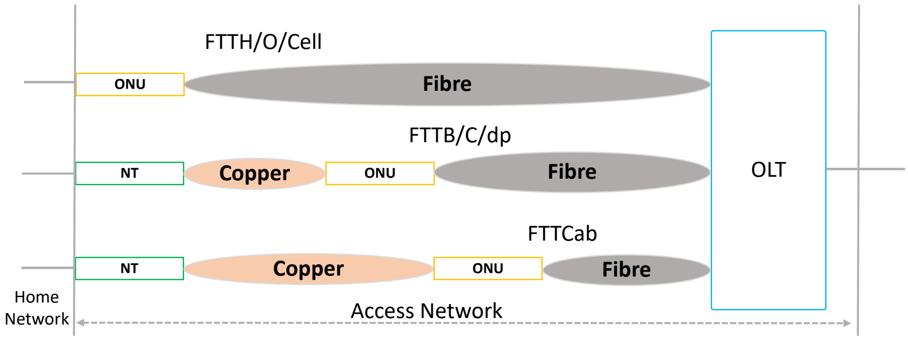

Figure 2-2 – Network Architecture.

The different FTTx scenarios are presented in Table 2-1.

Service	**Asymmetric broadband services**	**Symmetric broadband services**	**POTS**	**Private line**	**xDSL backhaul**
Scenario	IPTV, digital broadcast services, video on demand (VoD), file download, etc.	Content broadcast, e-mail, file exchange, distance learning, telemedicine, online games, etc.	Narrow-band telephone services using either emulation or simulation	Private-line services at several rates.	
FTTB for multi-dwelling units (MDU)-served residential users	x	x	x		
FTTB for multi-tenant units (MTU)-served business users		x	x	x	
FTTC and FTTCab	x	x	x		x
FTTH	x	x	x		
FTTO	x		x	x	
FTTCell wireless	The ONU will be called a cell-site backhauling unit (CBU) and will have to offer connectivity to wireless base stations: • symmetric TDM services (e.g., 2G cell site backhaul); • symmetric/asymmetric packet-based broadband services (e.g., 3G/4G cell-site backhaul); • hot spots.				
FTTdp	The ONU will be called a Distribution Point Unit (DPU) that in addition to the FTTB service categories and capabilities may support: reverse powering capability with power supplied through the copper drop from the end-user installation • xDSL or G.fast copper drop UNI				

Table 2-1 – FTTx scenarios.

2.2.1 GPON, XG-PON and XGS-PON

GPON provides a 2,5 Gbit/s of bandwidth in downstream and 1,25 Gbit/s in upstream. The operating wavelength range is 1480 to 1500 nm in the downstream direction and 1260 to 1360 nm for the upstream direction (ONUs based on Fabry-Perot lasers), the most common ONU/ONTs are based on wavelength selected lasers and work between 1300 and 1320 nm. The 1550 to 1560 nm wavelength range can be used for the distribution of video distribution.

XG-PON, defined by the ITU-T G.987 series of standards [19] can coexist with GPON and provide 10 Gbit/s in downstream and 2,5 Gbit/s in upstream (Figure 2-3).

Figure 2-3 - Wavelength plan GPON, XG-PON, and video overlay.

Coexistence between XG-PON1 and GPON is achieved by implementing a wavelength coupler located at the CO, WDM1r.

Driven by the 10G optical transceivers market, FSAN selected the downstream wavelength of 1575–1580 nm to promote the technology's maturity. The upstream wavelength was defined at around 1270 nm.

For configuration, operation, and maintenance, GPON, and XG-PON use the same, generic Optical network unit Management and Control Interface (OMCI), specified in ITU-T G.988.

A potential barrier to the deployment of GPON and XG-PON1 on the same outside plant is the existence (or non-existence) of wavelength blocking filters at the ONT/ONUs. Most modern GPON ONTs have an integrated filter to eliminate interference from XG-PON1 wavelengths. However, older installed ONTs will not have such a filter. Service providers with older GPON ONTs deployed have to install filters at the terminal locations to enable GPON and XG-PON1 co-existence.

XG-PON1 presents some power-saving mechanisms, as deactivating the transmitter for routine transmissions (dozing) and sleep mode, in which the ONT deactivates both its transmitter and receiver when the user has no activity (sleeping).

ITU-T G.9807.1 standardizes the 10 Gigabit-capable symmetric passive optical network (XGS-PON), a system that operates at a nominal data rate of 10Gbit/s both downstream and upstream direction [20].

The XGS-PON systems are capable of working in the same wavelengths as an existing XG-PON system or operating at the GPON wavelengths supporting the coexistence with GPON and NG-PON2.

One of the great advantages of the XGS-PON system is its coexistence options with GPON and XG-PON using wavelength overlay and/or TDMA methods, this is, the same XGS-PON OLT receiver can work on dual-mode and receive XG-PON (2.5 Gbit/s) and XGS-PON (10Gbit/s), and as the downstream wavelength and bit rate is the same as XG-PON, an XGS-PON OLT can control and manage the XG-PON ONTs.

Given the major investments spent on time and money on deploying Gigabit PON mainly in the fiber infrastructure, NG-PON must be able to protect the investment of the legacy Gigabit PONs by ensuring seamless and smooth migration capability for subscribers from Gigabit PON to NG-PON.

The most common PON scenario is the brown field scenario where a PON system has already been deployed and network operators decide to leverage this existing fiber infrastructure to offer higher bandwidth carrier services, using XGS-PON. Subscribers on an existing GPON or XG-PON system might require an upgrade to such higher speed tier service and the network operator may therefore choose to move over these subscribers to the XGS-PON system, while other subscribers remain on the Gigabit PONs or XG-PON [20]. At a certain point, some network operators may eventually perform a 'forced migration' from Gigabit PON to XGS-PON when the number of Gigabit PON subscribers becomes low. Both Gigabit PONs and XGS-PONs will likely continue to coexist for a relatively long time in this scenario. In a similar, but slightly different migration scenario, a network operator might want to replace an existing Gigabit PON with an XGS-PON completely. In this case, it would still make sense to run both Gigabit PON and XGS-PON at the same time and update customers one at a time. But the upgrade window is rather much shorter.

General requirements for this scenario are as follows:

- coexistence between Gigabit PON and XGS-PON on the same fiber must be supported for the case that the fiber resource is not necessarily abundant;
- service interruption for the non-upgrade subscribers should be minimized;
- XGS-PON must support/emulate all GPON and XG-PON legacy services in the case of a full migration.

When a PON system is migrated from a legacy PON to a next-generation PON (NG PON), coexistence and smooth migration are important requirements. External wavelength division multiplexers (WDM1 and WDM1r) and coexistence elements (CEx and CEMx) devices provide a good way to support coexistence and smooth migration. However, these external WDM approaches introduce extra insertion loss in the ODN. For example, loss without connectors for GPON bands is less than 0.8 dB but is applied and counted in the ODN design. This is a challenge in ODN cases with a tight optical margin. Furthermore, it is advantageous for some operators to have an upgrade approach that replaces existing line cards in the OLT chassis with new line cards to upgrade to multiple PON technologies integrated into the line card. The new line card can simplify the upgrade engineering and reduce the probability of manual operational error during migration [21]. To meet the requirements mentioned above, an OLT line card with an integrated WDM function is introduced. This line card is called an OLT multi-PON module (MPM).

When upgrading using an OLT MPM, no external coexistence element is necessary at the OLT side, since its function has been integrated inside the OLT optical module for each PON port. Hence no extra space or associated engineering operations are required to achieve coexistence [21].

To revise the OLT MPM with an integrated WDM in an upgrade scenario, a chipset supporting both legacy PON and NG PON may be required in the OLT configuration, including specific MSA with dual interfaces to legacy PON and NG PON [21].

The reference diagram of GPON/XG-PON/XGS-PON OLT MPM with WDM is shown in Figure 2-4. The WDM is used to support all three types of ONU on the same ODN. The GPON transmitter and receiver, XGS-PON transmitter, and dual-rate receiver (also supporting XG-PON ONUs) are connected to the internal WDM. Figure 2-4 terms:

- CDR – Clock and Data Recover;
- LD Driver – Laser Diode Driver;
- BM LA – Burst mode Limiting Amplifier;
- BM TIA – Burst mode trans-impedance Amplifier;
- APD- Avalanche Photodiode;
- QOSA- Quad Optical Sub-Assembly.

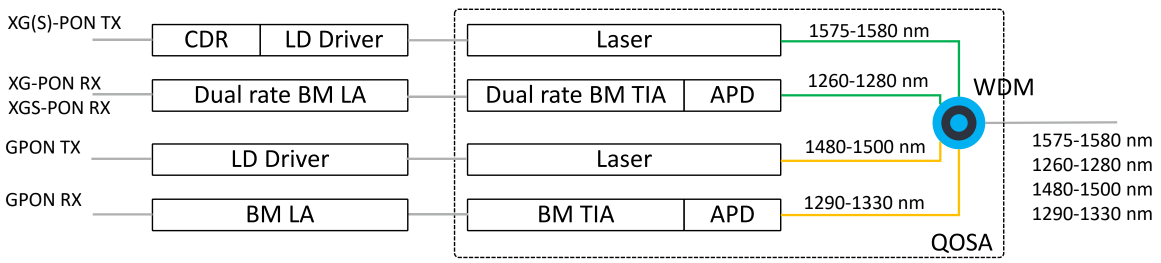

Figure 2-4 – GPON/XG-PON/XGS-PON OLT MPM with WDM.

The PMD requirements for the optical interface should ensure that the legacy GPON, XG-PON, and XGS-PON ONUs can work on the legacy ODN.

2.2.2 NG-PON2[2]

NG-PON2 is a 40 Gbit/s Capable Multi-Wavelength PON system that can grow up to 80 Gbit/s. It has 3 types of channel rates: basic rate 10/2.5 Gbit/s and as an option 10/10 Gbit/s and 2.5/2.5 Gbit/s. ONUs are colorless and can tune to any assigned Channel [22]–[25].

NG-PON2 is based on the ITU-T G.989 series:

- ITU-T G.989.1- 40-Gigabit-capable passive optical networks that contain the general requirements for the NG-PON2 [24].
- ITU-T G.989.2 - 40-Gigabit-capable passive optical networks (NG-PON2): Physical media dependent (PMD) layer specification, that specifies parameters for the physical layer as wavelength plans, optical loss budgets, line rates, modulation format, wavelength channel parameters, and ONU tuning time classes [25].
- ITU-T G.989.3 - 40-Gigabit-capable passive optical networks (NG-PON2): Transmission Convergence Layer Specification [26].
- ITU-T G.989 (no dot) that contains the common definitions, acronyms, abbreviations, and conventions of the G.989 series of Recommendations.

Figure 2-5 depicts the functional optical access network architecture that applies to NG-PON2 systems with legacy systems coexistence. The ODN consists of the splitter and the coexistence element (WDM) and, optionally, reach extenders may also be used in the ODN. The optical technologies specified for NG-PON2 systems are compatible with legacy

[2] This section of the thesis is based on the following magazine articles " C. Rodrigues, T. Mendes, F. Ruivo, P. M. Cheia, and J. Salgado, "NG-PON2," InnovAction #1 - Altice labs, pp. 18–31, 2016 " [67]; and an oral communication "C. Rodrigues, "How to use WDM-PON to boost your Fibre Investments", Session 7: FTTH Technology Update, FTTH Conference 2016, Luxemburg, 16-18 de February 2016." [68]

power splitting ODNs (that is an ODN that may contain power splitters and a coexistence element). NG-PON2 systems also support new (Greenfield) ODNs that may consist of wavelength filters only or a combination of both wavelength and power splitters.

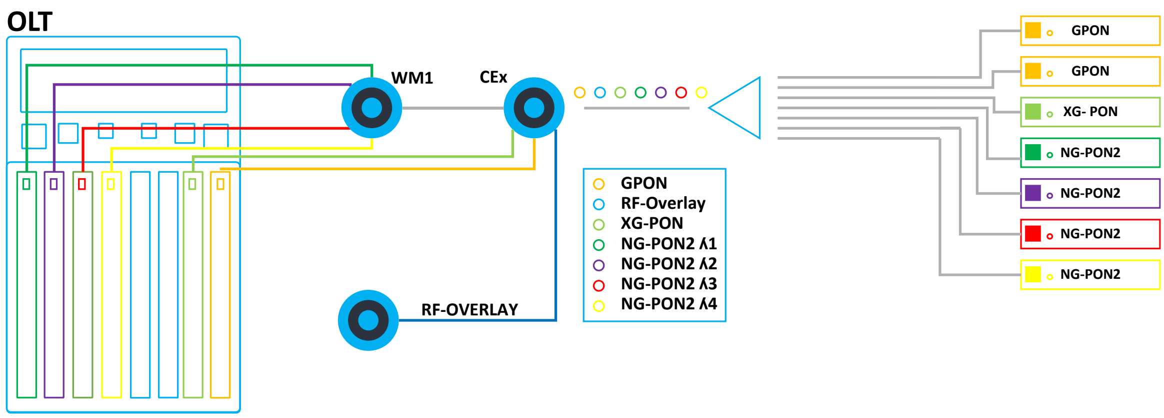

Figure 2-5 – Functional reference architecture for NG-PON2 system coexistence with legacy systems.

By wavelength agility TWDM-PON allows enhanced network functionalities unavailable in previous generations of pure TDM PONs, namely:

- Incremental bandwidth upgrade (Pay-as-you-Grow);
- Selective OLT port sleep for power saving during low traffic periods, this is, during times of low traffic load all ONUs can retune to a common wavelength and allow OLT ports to be powered down;
- Resilience against OLT transceiver failures through ONU retuning, this is, all ONUs can retune to a common standby or working wavelength under a fault condition to maintain a basic service until the fault is cleared;
- Fast, dynamic wavelength and timeslot assignment using dynamic wavelength and bandwidth assignment (DWBA) (extra degree of freedom c.f. dynamic bandwidth assignment (DBA) today) to improve bandwidth utilization efficiency.

The TWDM-PON has as major advantages, FTTH for everything, legacy investment saving, and pay-as-you-grow as described above.

FTTH for everything:

A major advantage of TWDM-PON is its ability to support different types of subscribers or applications by using different wavelengths and different bit rates on those wavelengths. It can assign a single wavelength to a particular customer, such as a business, or a particular application, such as mobile backhaul.

Legacy investment saving:

TWDM PON coexists with GPON, XG-PON, and XGS-PON. No changes are required to the ODN, including fibers, splitters, and cabinets, as so, GPON, XG-PON, or XGS-PON network investment is preserved. TWDM PON can be added on top of an existing GPON or XG(S)-PON network: an existing GPON network can be upgraded piecemeal and over time (pay as you grow). An operator could deploy TWDM PON where it has identified new market opportunities, such as enterprise subscribers or the leasing of MBH services. It could use TWDM PON for internal support of x-haul needs. The service provider could also opt to upgrade existing high-end residential customers to TWDM PON where it faces significant competition from other service providers promoting 1G and beyond.

Pay-as-you-grow:

Wavelengths can be added one by one as needed to support customer growth and high-bandwidth applications.

In the case of an existing GPON network, the most likely upgrade approach is to insert a TWDM card into the OLT platform. The TWDM PON line card can have the same wavelength on each port or different wavelengths on the various ports of the line card depending on the subscriber, application, and bandwidth projections. Several implementations of WM1 devices are possible, and they can be external to the TWDM card or integrated on it.

Three different options are possible:

- Option 1, one TWDM card per fiber with 4 wavelengths per PON card with WM1 integrated into a single output PON port (Figure 2-6, left);
- Option 2, one TWDM card per fiber with 4 wavelengths with external WM1 module;
- Option 3, based on the pay as you grow approach, where the wavelengths are across TWDM cards with external WM1 (Figure 2-6, right).

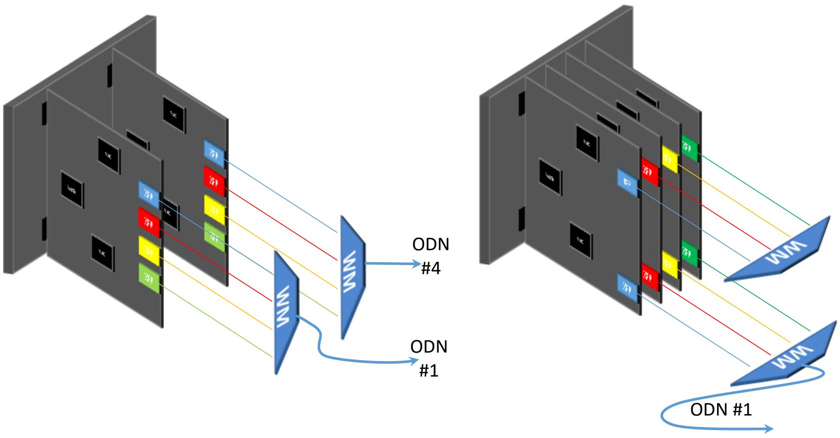

Figure 2-6 – Line Card OLT arrangement. Left – option 1, Right – option 3.

Table 2-2 provides a comparison from a service availability perspective of the different scenarios.

Scenario	Wavelengths on a single Card	Wavelengths across cards
Wavelength Failure	Affected ONUs moved to other wavelength ports of the same card; All ONUs are down while the card is rebooting.	Affected ONUs moved to other line cards; Other ONUs on the card are tuned to another wavelength before the card reboot.
Complete Line card Failure	Affected ONUs are down while the card is not replaced.	Affected ONUs are moved to other line cards.
Software Upgrade	Affected ONUs are down during reboot and reactivation	Affected ONUs are tuned in advance of upgrade.

Table 2-2 – Service availability TWDM-PON

The nonintegrated, modular approach provides several operational and economic advantages, such as:

- straightforward support for pay-as-you-grow wavelength adds
- easy bit rate configuration for each wavelength
- simple facilitation of wavelength unbundling per operator, which supports governmental requirements for fiber sharing or co-investment partnership business models

From an operational perspective, to upgrade a network from the legacy GPON to NG-PON2, existing GPON subscribers that will remain on GPON must be briefly out of service during installation of the coexisting element (CEX), after which, the service is restored. Residential subscribers that will be remaining on GPON and not upgraded to TWDM PON will experience a brief service outage (which can be planned during low-usage hours), but only when the CEx is introduced. Thereafter, wavelength additions or changes will not impact existing subscribers except those being upgraded or migrated to new wavelengths.

It should be noted that the same scenario described here would also apply in the case of XG-PON upgrades since a CEx would also have to be introduced to enable the combination of GPON and XG-PON.

Figure 2-7 (first phase) and Figure 2-5 (last phase) present a coexistence and pay as you grow scenario.

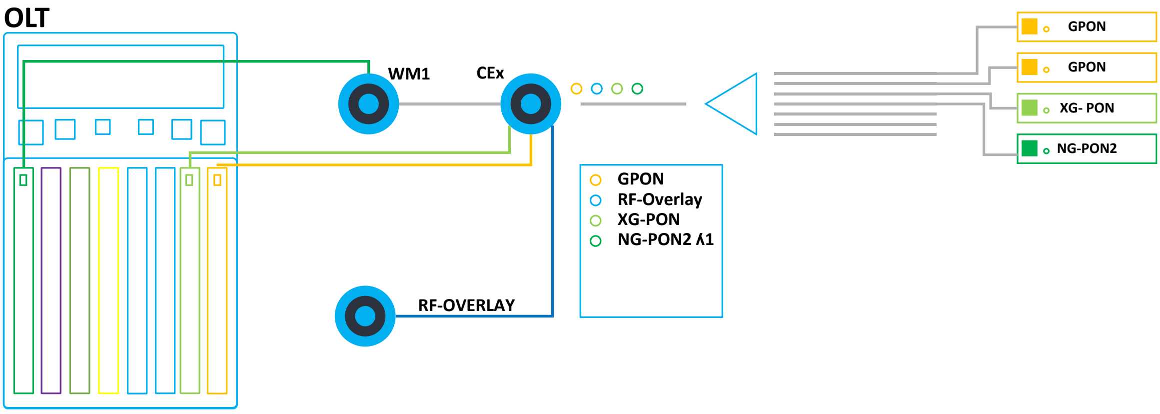

Figure 2-7 – Pay-as-you-grow. 1st phase.

TWDM PON is still the access technology that supports the widest range of subscribers and applications. The table below provides a summary of the advantages and disadvantages of TWDM PON versus GPON.

	GPON	TWDM-PON
Flexible growth – pay as you grow	+	+++
Ability to support MBH	+	+++
Ability to support mobile fronthaul	-	+++
Ability to support enterprise services	-	+++
Overall fixed-mobile convergence support	-	+++
Ecosystem – status	+++	++
Commodity priced equipment	+++	++

Table 2-3- GPON vs TWDM-PON.

TWDM PON's architecture enables the assignment of wavelengths to specific customers or applications. The wavelength design also enables a pay-as-you-grow platform. While GPON and XG-PON1 can support MBH, TWDM PON can provide more bandwidth, thereby supporting more x-haul traffic. The assignment of wavelengths enables the support of enterprise services. In addition, TWDM PON was designed to allow point-to-point overlays for the support of fronthaul.

2.2.2.1 Operator energy-saving achievements by using NG-PON2 functionalities[3]

The actual economic scene benefits ecologic and low power consumption solutions, due to resource exhaustion, global warming, and protecting the planet. Expectations about the increasing levels of energy consumption, associated with the growing demands for broadband services, are raising concerns and calls for the implementation of energy-efficient equipment and strategies. The latter is gaining growing attention, driven both by ecologic and economic values. The need to achieve significant breakthroughs in network energy efficiency requires hardware enhancements to be integrated with adequate energy-saving mechanisms that explicitly manage network delivery performance and resource consumption.

Power saving in telecommunication network systems has become an increasingly important concern due mainly to three crucial factors:

- reducing operators' OpEx;
- reducing the network contribution to greenhouse emission gases;
- legislation.

Next-generation equipment should be as efficient as possible for allowing minimal energy cost per bit. Equipment is the one that effectively consumes the power in passive ODNs.

A code of conduct (CoC) (European Commission Joint Research Centre 2008) [27], sets out the basic principles to be followed by all parties involved in broadband equipment, operating in the European Community, in respect of energy-efficient equipment. In the United States, the Energy Star program identifies and promotes energy efficiency for Small Network Equipment's.

Taking into account the NG-PON2 functionalities and to perform electricity power savings is necessary to perform load balancing, increase the power efficiency by reducing the number of PON cards in use and consolidate ONTs onto fewer wavelength channels, this is, concentrate the ONTs on the PON cards with operating interfaces The number of active (provisioned) subscribers on a particular wavelength channel on a PON may change over time and when bandwidth utilization levels are very low across comparable TDWM channels with residential customers during off-hours (e.g., during night), customers on these multiple channels are consolidated on a single TDWM channel, enabling the shutdown of some card interfaces

[3] This section of the thesis is based on an oral communication "C. Rodrigues, "Operator Energy Saving achievements by using NG-PON2 functionalities", NG-PON2 Forum Workshop, FTTH Conference 2017, Marseille, 14-16 de February 2017."[69]

As previously presented, NG-PON technologies aim to deliver more content. Even not knowing exact user profiles, is possible to extract and extrapolate a certain number of users' profiles:

- light user – voice, VOIP, gaming, data, and IPTV small part of the time;
- heavy user – voice, video conference, gaming, data, cloud computing, video on demand, live VOD, pear-to-pear, IPTV a great part of the time;
- business - high data during working hours;
- mobile back hauling (LTE) - heavy traffic during zone activity hours;
- data-center – serving at all times optimized by other machines to be as optimum as possible.

Table 2-4 is presented the users' bandwidth profiles, this is, the service average data rates for each type of end-users:

Profile	Light user	Heavy user	Business	Mobile BackHaul	Data Center
PON Network bandwidth use Symmetric (Gbit/s)	0.2	0.5	1	2.5	10

Table 2-4 – Users bandwidth profiles.

Because bandwidth utilization levels change during the day, five different types of bandwidth utilization were assumed:

Profile	1	2	3	4	5
Bandwidth usage	100%	70%	50%	30%	10%
PON Network use	10H	6H	5H	2H	1H

Table 2-5 – Usage pattern.

Four different OLT scenarios were studied depending on the type and number of OLT line cards (LCs). The first scenario, Figure 2-8, is an OLT system equipped with four LCs with four NG-PON2 channel terminations (CTs) each one. In a second scenario, an OLT system is equipped with eight LCs with four NG-PON2 CTs each. The third and four scenarios were based on an OLT system equipped with four LCs and eight LCs, Figure 2-9, each one with eight NG-PON2 CTs.

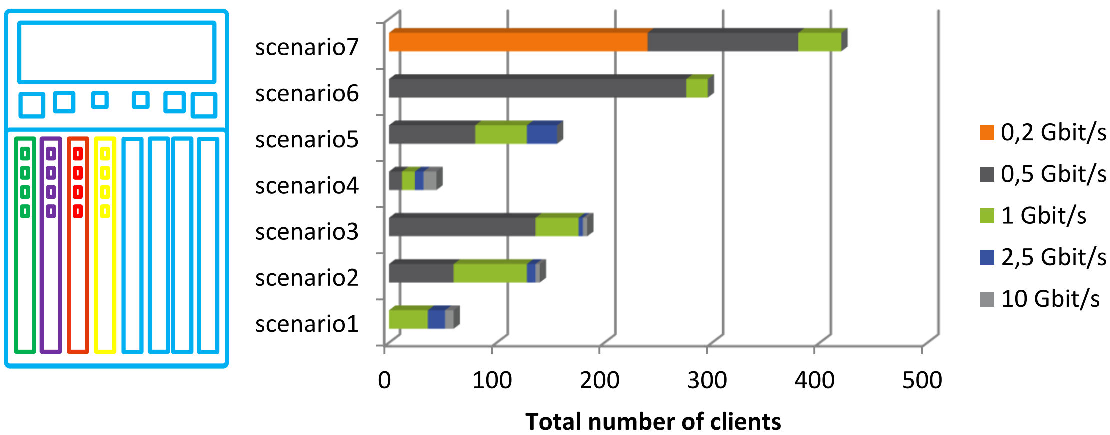

Figure 2-8 – Total number of clients on the scenario with four LCs with four CTs each.

Considering the different types of users and the different OLT scenarios, the various traffic environments were analysed. Each of the figures presents the traffic environment scenarios with the total number of clients over the OLT for the different users' bandwidth profiles. It has to be taken into account, that the total bandwidth per CT was rounded to 10 Gbit/s.

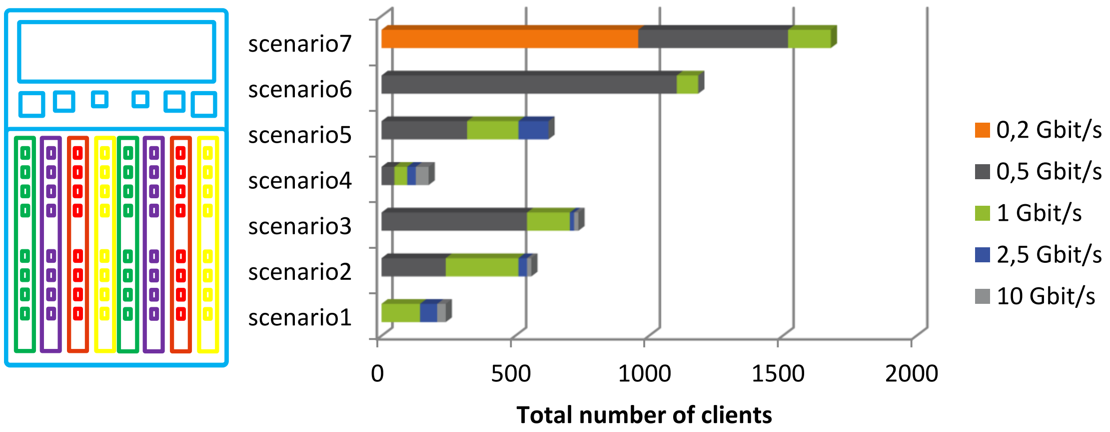

Figure 2-9 – Total number of clients on the scenario with eight LCs with eight CTs each.

Table 2-6 is presented an analysis example, in this case for the OLT equipped with four LCs with four CTs. The total fixed bandwidth and total bandwidth consumed for scenario 1 of Figure 2-8 are analyzed taking into account the different PON usage patterns and the different user's bandwidth profiles.

It is considered that the ONT bandwidth consumed for control and overhead is 4.736 Mbit/s (Overhead 128 kbit/s, guard time + preamble + delimiter 4.096 kbit/s, 512 kbit/s ONU management and control interface (OMCI) control) and a fixed traffic profile of 100 Mbit/s,

	Bandwidth usage		**100%**	**70%**	**50%**	**30%**	**10%**
	PON Network use		**10h**	**6h**	**5h**	**2h**	**1H**
Clients in System	**1**	**Gbit/s**	9	7	5	3	1
	2,5		4	3	2	2	1
	10		2	2	1	1	1
Total Assured Bandwidth		**Gbit/s**	39,0705	34,5564	20,0376	18,0282	13,5141
Total Fixed Bandwidth		**Gbit/s**	0	0,3141	0,7329	0,9423	1,2564
Total Bandwidth consumed		**Gbit/s**	39,0705	34,8705	20,7705	18,9705	14,7705

Table 2-6 – Users scenario 1 for four LCs with four CTs.

As it is possible to see, when the bandwidth usage drops to 30% it allows the turn off of two CTs. Figure 2-10 presents the representation of this user's scenario.

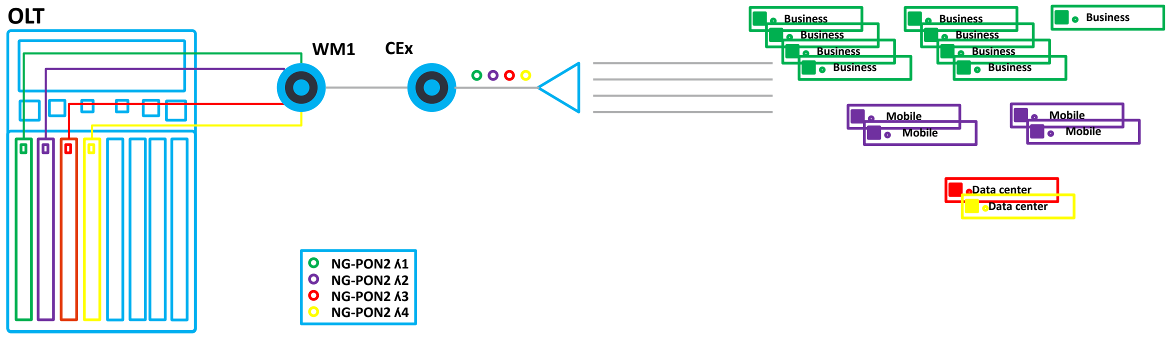

Figure 2-10 – Users scenario 1, for four LCs with four CTs.

The power consumption for the studied traffic environments scenarios with NG-PON2 was calculated as a comparison with the XGS-PON scenario (where no mobility is possible).

In this study was considered the power consumption of each line card and each of the optical modules, based on an XFP form factor. The presented higher power consumption of line cards was due to be based on FPGAs and not yet application-specific integrated circuits (ASICs) overdue to the early-stage developments of electronics. It is considered the maximum power consumption for the optics.

	4 CTs LC	8 CTs LC	XFP NG-PON2	XFP XGS-PON
Power consumption (W)	92	275	4	3

Table 2-7 – Power consumption

We have considered in our study that the LCs are placed in idle mode, as well as the optical modules when they are not required for service. The NG-PON2 analyzed scenarios are based on a pay as you grow approach, where the wavelengths are across TWDM cards with external WM1 (Figure 2-6, right).

The Energy consumption per day is calculated by:

$$E_{\left(\frac{kWh}{day}\right)} = \frac{P_W \times t_{h/day}}{1000_{W/kW}} \quad (2\text{-}1)$$

Figure 2-11 is presented the energy consumption per day for the scenario with eight LCs with eight CTs. It is possible to observe that NG-PON2 technology with wavelength mobility presents always less power consumption when compared to XGS-PON technology (without mobility). A minimal difference of about 10 kWh/day was noted for the scenario without mobility versus the NG-PON2.

The rest of the analyzed scenarios are presented in Appendix A- Operator energy-saving achievements by using NG-PON2 functionalities.

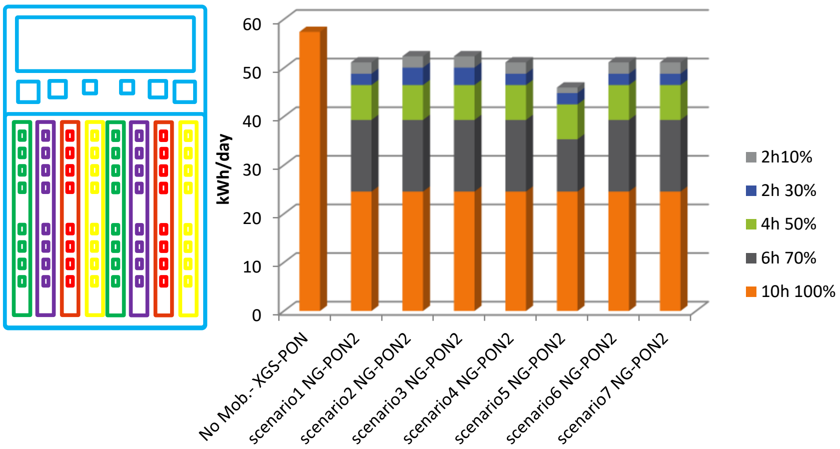

Figure 2-11- Energy consumption for eight LCs with eight CTs for the different traffic environments.

Assuming 500 OLTs and the average cost of electricity for the industry in EU28 of 0,1497€ (2015), significant energy savings can be achieved by using TWDM-PON functionalities, Figure 2-12. Cost savings of 350000 euros can be observed for the scenario with eight LCs with eight CTs versus the XGS-PON fixed wavelength scenario.

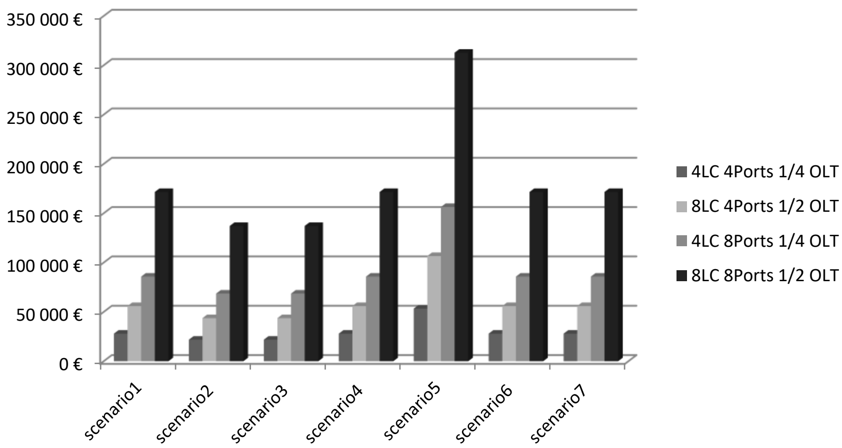

Figure 2-12- Savings per year considering 0,1497€/kW.

2.2.2.2 Energy efficiency in the tunable optical head for NG-PON2 Optical Network Unit

ONUs are the ones that effectively consume the power in passive Optical Distribution Networks (ODNs). Although the customer premises power does not account for the operators' costs of OpEx, it could be misleading not to consider this factor into the network design trade-off, and thus, not considering it the ONUs power consumption when deciding to implement a certain technology [28].

As presented in the previous section, a technique to save power on the OLT is to use power saving on the ONUs by consolidating their operation into fewer wavelengths. By having the ONU subject to any NG-PON2 channel assignments that are considered permanent the OLT can monitor the number of subscribers assigned by wavelength and if the traffic is reduced below a certain threshold, the OLT migrates the correspondent subscribers ONUs to other wavelengths that the OLT knows that have reduced power consumption. The ONTs potentially could also be spread among multiple eligible wavelengths. These OLT achievements can be only achieved if there are tunable ONUs.

In our scenario, the tunable optical head for NG-PON2 head incorporates a Bidirectional Optical Sub-Assembly (BOSA), from PICadvanced, and control electronics, developed by Altice Labs.

The developed tunable optical head for NG-PON2 is fully compliant with N1 type A and type B NG-PON2 standards in a class III Transmitter (TX)/Receiver (RX) Wavelength Channel Tuning Times [29]. The tunability was implemented following the pluggable optic module Multi-Source Agreement (MSA) for 10 Gigabit Small Form-Factor Pluggable, namely the MSA_INF-8077i Rev 4.5.

The power consumption of the tunable optical head was investigated under different conditions, namely, environment temperature and working channel. As the investigated BOSA is based on a tunable diode laser, changing the working channel means changing the temperature of the device. Two different temperature dependency lasers were investigated to analyze the power consumption and the effect of the environment temperature on the laser under similar working conditions fulfilling the NG-PON2 requirements.

The optical head power consumption was measured at environment temperatures of 25, 30, 40, and 45 degrees Celsius with 9.8 Gbit/s traffic in both directions. The optical head was installed in an NG-PON2 ONU. The working channels are presented in the table below:

Channel number	Upstream Frequency (THz)	Downstream Frequency (THz)
1	195.6	187.8
2	195.5	187.7
3	195.4	187.6
4	195.3	187.5

Table 2-8 – NG-PON2 channel plans.

Figure 2-13 and Figure 2-14, show the power consumption and laser setting temperatures for different environmental temperatures for optical head 1 and optical head 2, respectively. From the figures analysis, the higher the environmental temperature, the higher the power consumption of the optical head. The higher the ambient temperature, the higher effort is made by the Thermoelectric Cooler (TEC) to keep the BOSA cooled. This increase in effort is translated into more current from the driving circuit to be able to maintain the same laser temperature leading to higher power consumption.

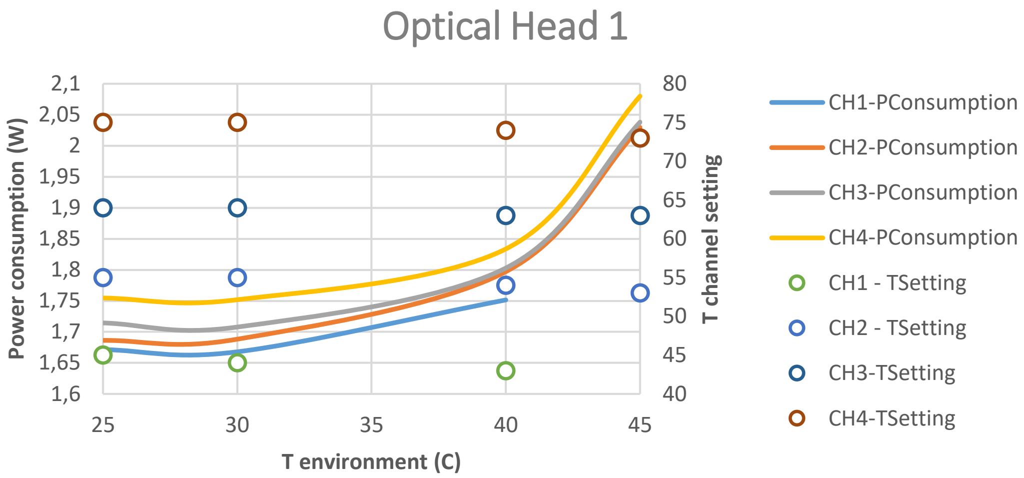

Figure 2-13 – Optical head 1 power considerations.

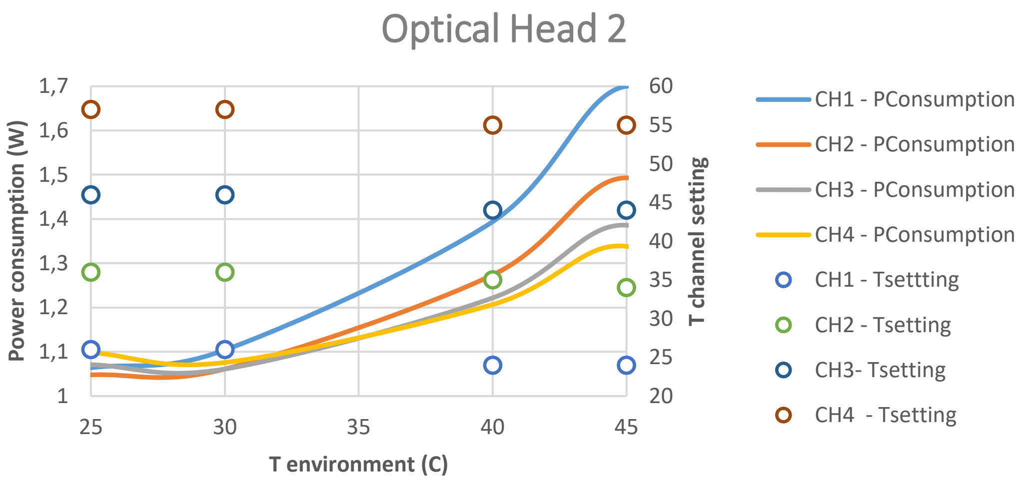

Figure 2-14 – Optical head 2 power considerations.

By comparing Figure 2-13 and Figure 2-14, we can note that optical head 1 has higher power consumption than optical head 2. This effect is due to the intrinsic temperature of the chips inside the optical heads. A higher temperature set point requires more effort in the TEC and its electronic circuitry.

NG-PON2 tunable optical head power savings will be presented considering the FTTH scenario of Figure 2-10, with the ONTs bandwidth consumption of Table 2-6.

As presented in Figure 2-13 and Figure 2-14, the power consumption of the optical NG-PON2 optical head changes with ambient temperature and between channels. In Figure 2-15 and Figure 2-16, it is possible to see the ONT channel distribution in the OLT scenario for an optimized and non-optimized scenario, respectively. In both scenarios, the bandwidth utilization and ONU NG-PON2 optical head power consumption were taken into account for different environmental temperatures.

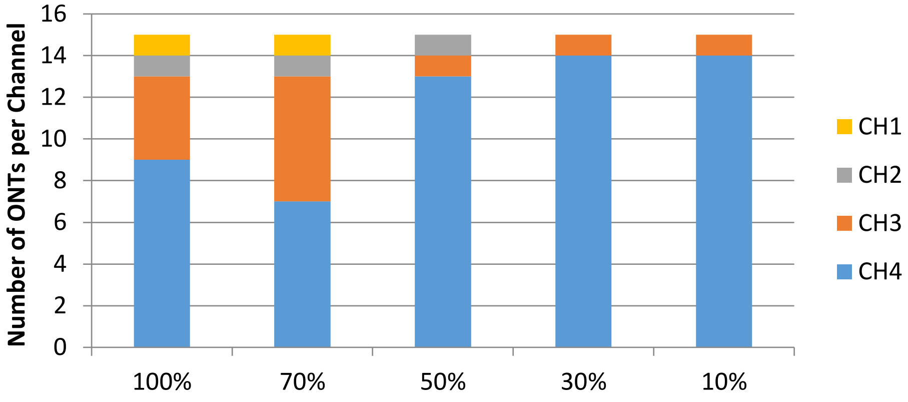

Figure 2-15 – ONT PON optimized channel distribution.

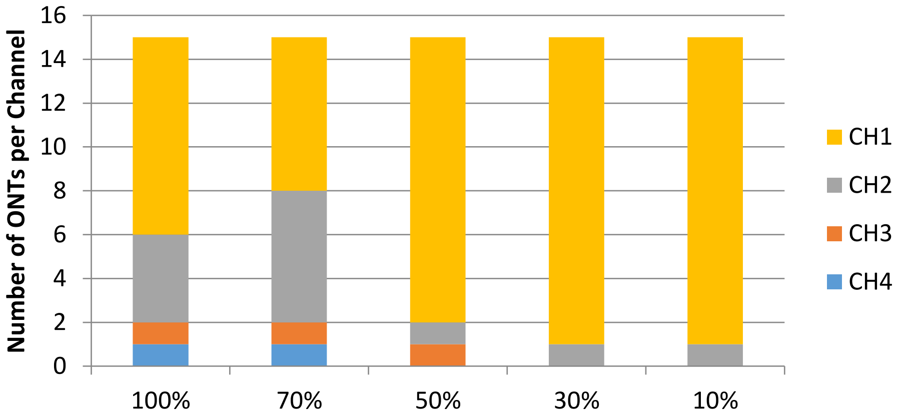

Figure 2-16 – ONT PON non-optimized channel distribution.

The optimization parameters considered were the threshold to change the users, taking into account the available bandwidth in the different channels, and to allocate as many as possible clients on channels with lower setting temperatures and thus lower power consumption.

Figure 2-17 presents the optical head power consumption (kWh/day) for the optimized ONT PON channel distribution for an ambient temperature of 25 ºC and Figure 2-18 for the non-optimized ONT PON organization.

The same analysis for an ambient temperature of 45ºC is presented in Appendix A-Energy efficiency in the tunable optical head for NG-PON2 Optical Network Unit

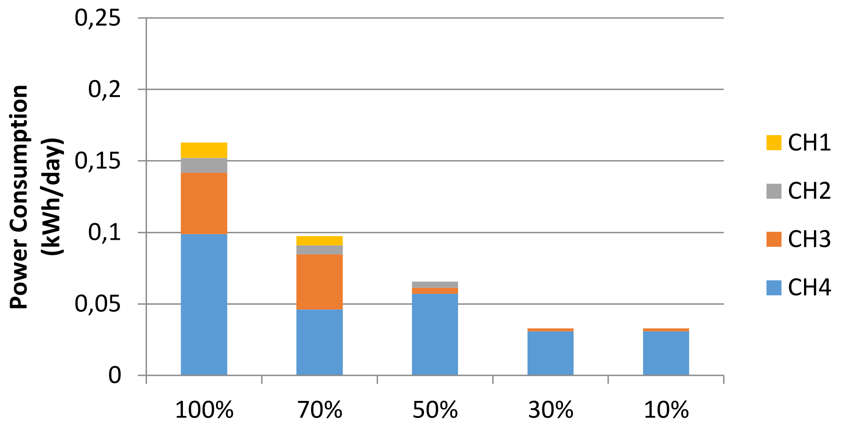

Figure 2-17 – Optical head power consumption (kWh/day) for a 25ºC ambient temperature – optimized channel distribution.

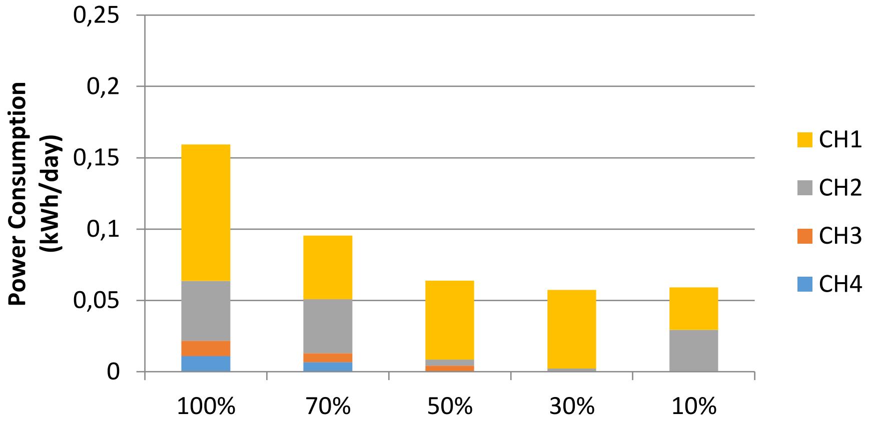

Figure 2-18 – Optical head power consumption (kWh/day) for a 25ºC ambient temperature.

It is noticeable the potential impact of wavelength mobility, on the OLT, by minimizing the number of active ports when bandwidth utilization levels change over a day.

The awareness of having energy-friendly equipment in telecommunication networks is increasing. There are pushes from the regulatory entities to move forward with codes of conduct, which are more restrictive and require taking into consideration power consumption and footprint when designing the new generation of optical communications.

NG-PON2, allows the operators to deploy a service of high bandwidth that simultaneously admits optimization of the power consumption of the equipment. Two optical heads for NG-PON2 were characterized in terms of power consumption in different operation conditions.

The presented model covers equipment, topology, and user profiles, which are among the most relevant parameters regarding the objective of energy savings. It demonstrates the power-saving achievements that can be obtained from a service provider perspective by employing several techniques available on the NG-PON2 technology.

The results demonstrate that by using the several functionalities of the NG-PON2 technology is possible to achieve significant energy savings for the end customer.

2.3 X-Haul over PON[4]

Traditional Radio Access Network (RAN) architectures are evolving to support centralized interference management required by complex heterogeneous wireless networks. In addition, antenna densification raises new challenges in terms of network coordination and energy efficiency. Cloud-RAN (C-RAN) and virtual RAN (vRAN) are attractive architectures to cope with these issues and offer potential benefits for site installation. Optical access operators have expressed a clear view of the potential interfaces and transmission systems that C-RAN and vRAN must offer to connect Digital Unit (DU) processing to Radio Unit (RU) blocks.

The feasibility of a Passive Optical Network (PON) to support the existing and future RAN applications will be discussed in this section.

2.3.1.1 Transport RAN definitions: backhaul, midhaul, fronthaul

The transport RAN includes three types of architectures: Backhaul, Midhaul, and Fronthaul.

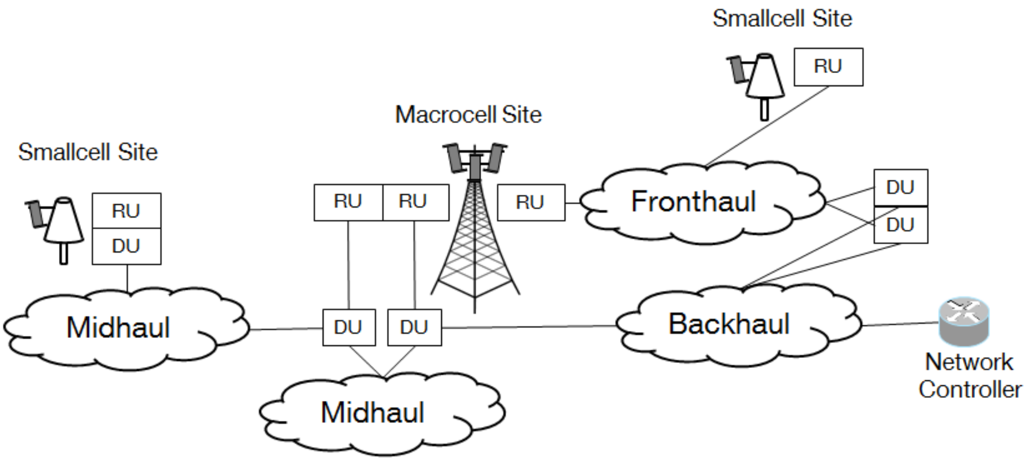

Figure 2-19 – Mobile Backhaul, Midhaul and Fronthaul from MEF [30].

- Backhaul:

The term Mobile Backhaul [30] refers to the network between the radio Base Station sites and the Network Controller/Gateway sites for all generations of mobile technologies. Plesiochronous digital hierarchy (PDH), synchronous digital hierarchy (SDH), synchronous optical networking (SONET), and asynchronous transfer mode (ATM) technologies were traditionally used to achieve this transport. Ethernet protocol and interfaces are becoming

[4] This section of the thesis is based on the following Journal article: "Philippe Chanclou, Hiroo Suzuki, Jin Wang, Yiran Ma, Mauro Renato Boldi, Kazuki Tanaka, Seungjoo Hong, Cláudio Rodrigues, Luiz Anet Neto," How does Passive Optical Network tackle Radio Access Network evolution?" IEEE/OSA Journal of Optical Communications and Networking Vol. 9, Issue 11, Nov. 2017" [70] ; and on an oral communication: "C. Rodrigues, "How to boost 5G cell capillarity using current xPON deployments", Workshop: Beyond 5G: What is role of optical network, ECOC 2019, Dublin, 22-26 September 2019;"[71]

increasingly used based on Metro Ethernet Forum (MEF) specifications [30] defining the Ethernet service layer function [31] which allows supporting Carrier Ethernet Services [32]. The Next Generation Mobile Networks (NGMN) Alliance also defines [33] backhaul requirements and produces recommendations on how to optimize the transport network. The NGMN Alliance underlying assumption is that the backhaul network utilizes an all-packet (Ethernet/IP) architecture. According to the NGMN Alliance requirements, the future networks will enable end-to-end packet transport using harmonized and shared transport networks allowing significant network cost reduction. Therefore, the NGMN future transport network nodes are required to become access and service agnostic.

- Midhaul:

The term midhaul has been defined by MEF [30] as the carrier Ethernet network between DU sites (especially when one site is a small cell site). The MEF reference scenario in Figure 2-19 shows that midhaul is considered as a backhaul extension between a small cell DU and its master macrocell DU. Two other scenarios are also considered: i) the midhaul between two DU pools (illustrated in Figure 2-19) and ii) the midhaul between two DU pools through a network controller (not illustrated in Figure 2-19). All midhaul scenarios are Ethernet-based networks.

The midhaul term is sometimes used to define a new functional split between DU and remote RU. The term midhaul adopts the MEF definition and not the term used to reflect redefined fronthaul.

- Legacy Fronthaul based on low layer RAN split:

MEF [30] also defines fronthaul as a connection from the radio digital unit to a remote RU. Supplement 55 to ITU-T G series Recommendations [34] provides also general information on radio-over-fiber (RoF) technologies and their applications in optical access networks. We focus our interest only on digital fronthaul. In this case, the fronthaul network segment carries the very high bit rate digitized baseband time-domain signals between the DU and remote RU over one of the following standardizing initiatives: Common Public Radio Interface (CPRI), Open Base Station Architecture Initiative (OBSAI), and Open Radio Interface (ORI). IEEE launched a standard specification action to draft a standard for Radio over Ethernet to achieve encapsulations and mappings of Inphase/Quadrature (I/Q) radio samples coming from a variety of fronthaul interfaces. This IEEE document P1914.3 is still under construction.

- New RAN functional split fronthaul:

Several initiatives exist presently, to define new functional splits between DU and RU. The application driver of this topic is 5G and RAN virtualization, but they could be applied to existing RAN generation. The technical drivers are to decrease in the line rate, allow interoperable interfaces with the potential ability to re-use the existing Ethernet backhaul network, get compatibility with statistical multiplexing and bandwidth adaptation as a function of antenna sites arrangements (number of antennas, carriers) and traffic supported. All these points are still under discussion and should be defined as soon as 5G requirements themselves are more clearly defined.

Their main objective is to migrate, at a higher or lower proportion, some signal processing blocks from the DU to the RU to allow a bit-rate reduction in the fronthaul while ensuring proper Coordinated MultiPoint (CoMP) and latency requirements. The standardization [35] of these new RAN functional split interfaces is not yet consolidated.

Figure 2-20 shows these coming RAN interfaces by splitting RAN equipment into three parts: Central Unit (CU), Distributed Unit (DU), and Radio Unit (RU). The abbreviation of DU identifies either Digital (for traditional RAN equipment) or Distributed Unit (for RAN equipment with virtualization).

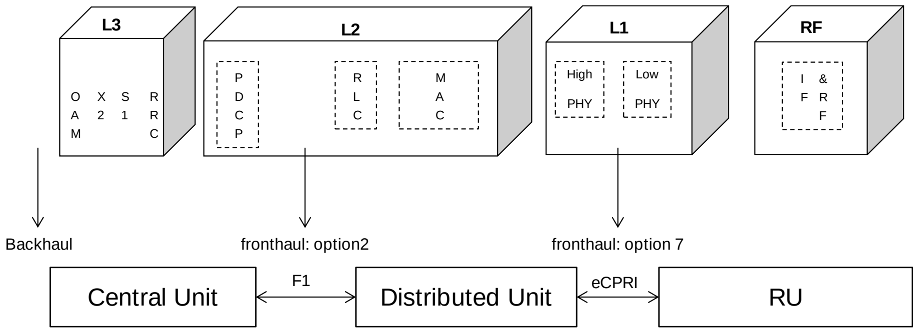

Figure 2-20 – Mobile architecture with CU and DU.

- Principle of an optical access network supporting RAN interface:

Backhaul, midhaul, and fronthaul based on high layer split are Ethernet-based, which would allow them to be transported using existing and coming to TDM PON (G-PON, XG-PON, XGS-PON) and Time and Wavelength Division Multiplexing (TWDM) (NG-PON2) [19], [29], [36]. We also consider in this work lower layer splits (CPRI/OBSAI) by T(W)DM PON. Point to Point Wavelength Division Multiplexing (PtP WDM PON) side of the NG-PON2 technology is also considered for either low or high layer splits. The generic WDM approach allows sharing the fiber to address a cell site by supporting any combination of backhaul, midhaul, and high and low level split fronthaul.

2.3.1.2 Cell site and optical access network description

This section discusses network descriptions for cell sites and fiber networks in the context of C-RAN and vRAN. C-RAN means Centralized RAN when we consider localization of DUs in one physical location (DU pool) and Cloud RAN when many identical DUs provide the capacity to process several radio technologies on the same hardware, aggregate the digital processing power of units together and dynamically allocate the necessary processing power to perform the real-time tasks of the digital unit, according to the network load. When this digital processing of the DU functions is processed on generic hardware, is the definition of a vRAN as defined by the NGMN Alliance. It has been proposed in a 2013 document with some suggestions on potential solutions for C-RAN [37].

- Cell site description:

In RAN, macro cells are generally deployed to provide seamless coverage for outdoor and partial indoor. Micro cells are deployed for street, hotspot, and deep indoor coverage with a distributed antenna system. Small cells are deployed for dead spots or hotspots and local deployment.

These three radio configuration descriptions (macro, micro, small) allow the understanding that several fronthaul interfaces and a large variety of combinations could be implemented. It is important to detail the three parameters that will have an impact on the total number of fronthaul interfaces: number of radio technologies, number of radio frequency bands, and number of radio sectors.

These descriptive ways of RANs (cell coverage and the number of RoF signals) are used to understand the applicability of proposed optical distribution networks (ODNs), network interface, and transmission mechanisms for fronthaul interfaces.

- Optical access network for mobile:

The optical access network for mobile applications is composed of the physical fiber plant (optical distribution network) and transport equipment for backhaul, or fronthaul for either low layer split between DU and RU or high layer split between DU and CU. More details referring to the different optical access network solutions suggested taking fiber availability into account are discussed in Appendix A- Cell site and optical access network description.

- Optical fronthaul distribution network:

The general structure of a fronthaul network is shown in Figure 2-21. We consider two optical network segments: i) the traditional ODN connected to the Optical Line Terminal (OLT), ii) the Optical Distribution Network at Antenna (ODNA) site which achieves the fiber links between RU or DU and the antenna cabinet. We consider RUs at the end faces of these ODN or ODNA. CU is connected to the OLT with either a potential co-localization for the master access node or through an aggregation network with localization of CU in the data center and OLT in CO. For DU, its localization is either near the OLT for low layer RAN split transport through ODN and/or ODNA to reach ONU, or at the end face of ODN or ODNA for high layer RAN split (or backhaul) transport between ONU and OLT.

The optical fronthaul networks may have common properties with legacy PONs: i) the absence of active components between OLT and Optical Networks Unit (ONUs), ii) the potential use or re-use of the same ducts, or fiber cable, or ODN, iii) potentially one same location at OLTs used for PON and optical fronthaul network, iv) ONU capable of operating under outdoor weather conditions.

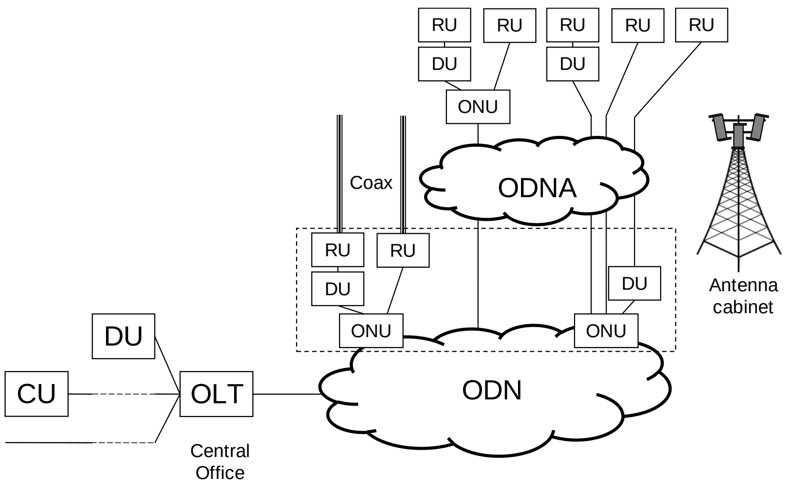

Figure 2-21 – General structure of an optical distribution network and optical distribution network at the antenna site.

It is important to highlight, however, that fiber to the antenna for fronthaul applications and fiber to the home networks have different requirements, namely: i) the presence at the macrocell antenna location of several and plurality of RUs with high and potentially symmetrical traffic requirements which could require several ONUs (unlike the FTTH (FTTHome) scenario where only one ONU is assigned to one access delivering location and unlike FTTB (FTTBuilding), FTTCab (FTTCabinet) or FTTC (FTTCurb) scenarios where several delivering locations share the capacity of one Multi-Dwelling Unit (MDU)), ii) the potential integration of ONU inside each RU or DU: typically, based on a small form factor pluggable module. This integration is strongly recommended for DU with a high-level split natively based on the Ethernet interface.

As shown in Figure 2-21, the optical fronthaul network can be deployed in three scenarios:

- the first one (left-hand side of the figure) represents the case where the ONU is located inside the antenna cabinet with the RU or DU. A coaxial feeder allows connecting the RU to the antenna. The ONU is directly connected to the ODN. This scenario is typically used for legacy RANs macro-cell sites with existing radio engineering.

- in the second one (center of the figure) both ONU and RU or DU is located at one extremity of the ODNA. ODN and ODNA are considered passive. The antenna cabinet hosts a passive optical patch cord panel with optionally passive optical devices: optical power splitter, Wavelength Multiplexer (WM), and de-multiplexer.

- in the last one (right-hand side in Figure 2-21), the ONU is located at the antenna cabinet, and the ODNA seen as a User-Network Interface (UNI), allows to connect ONU and RU or DU. This approach is similar to FTTB or FTTC or FTTCab scenarios for standard PON when it is considered that the last network segment to the subscriber's premises is deployed reusing legacy copper network. In this scenario, we consider that the last network segment could be fiber-based (ODNA) or could be transported through other media to support fronthaul applications.

The ODN description must also consider the fact that coexistence with other optical access systems is possible, this is, a brownfield scenario (buildings are already in place, but the existing infrastructure is of low standard [38]). Greenfield scenario (new build where the network will be installed at the same time as the buildings [38]) may help service providers achieve higher benefits and satisfy performance while carrying services such as fronthaul. Some operators are likely to establish the fronthaul networks in Greenfield scenarios on dedicated fibers. Either optical power splitter or WM can be used. In this case, the requirement of coexistence with legacy PONs is not necessary. For operators willing to take advantage of existing access infrastructure, however, fronthaul services will be carried either on PtP WDM overlay or TWDM channels of NG-PON2. The coexistence methods can be found in ITU-T G.989.1 and G.989.2 [29].

2.3.1.3 TDM PON technologies suitability for fronthaul

TDM-PON is a promising cost-effective solution for constructing mobile fronthaul because an optical fiber can be shared by multiple DUs and RUs as shown in Figure 2-22. To accommodate a variety of high-speed mobile use cases, not only high capacity but also lower latency is required.

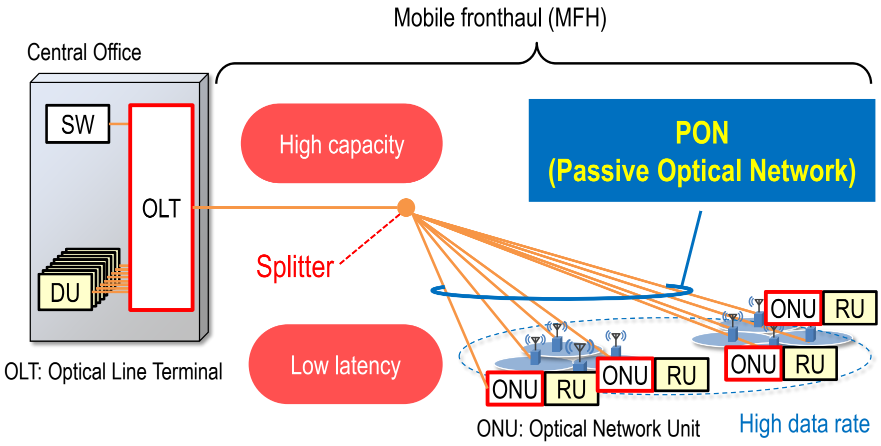

Figure 2-22- Mobile fronthaul architecture using TDM-PON.

- Low latency fixed bandwidth allocation (FBA) for low layer split:

When conventional CPRI (low-level functional split) is used, DBA for TDM-PON is not suitable. Instead, fixed bandwidth allocation (FBA) for upstream with low latency is required from PON because the CPRI signal has a constant bit rate and can be mapped over T-CONT1. The constant bandwidth is periodically allocated for each ONU and there is no Request message from ONU compared to conventional DBA. Latency can be reduced in FBA by a smaller Grant message from OLT.

- Low latency dynamic bandwidth allocation for high layer split:

When a high layer split is adopted, the actual optical transmission bandwidth in the mobile fronthaul is expected to be smaller and change in the time domain according to the variation of the wireless traffic. This means statistical multiplexing effects can be expected when TDM-PON is used. The 5G considers also low latency services. In this case, low latency DBA becomes a key factor for the applicability of TDM-PON to mobile fronthaul for also high layer split. In the low latency DBA, wireless scheduling information in the DU triggers PON scheduling in the OLT, no request messages are expected. Since the DU knows at what time user equipment transmits wireless signals, the OLT can start PON scheduling upon receiving the wireless scheduling information beforehand. Thus, the coordination of DU and OLT drastically reduces the latency due to DBA to less than several tens of microseconds. Related information can be seen in Appendix IX “Cooperative DBA by client systems for low-latency services” of ITU-T G.989.3 Amendment1. In the future, this coordination interface could be co-defined by fix and mobile standard development organization.

- TWDM-PON approach:

Figure 2-23 shows the application of TWDM-PON using four wavelength channels for mobile fronthaul. TWDM-PON handles multiple wavelengths for upstream and downstream, which can increase the transmission capacity of mobile fronthaul to 40-Gbps-class or more over a single power-splitter-based infrastructure. A “virtual PON” is formed between a channel termination (CT) and ONUs in each wavelength. TWDM-PON can dynamically and flexibly change the set of ONUs and each CT has a dedicated wavelength pair according to the change of the mobile terminal number and the communication bandwidth. For the application of the TWDM-PON to mobile fronthaul, low latency DBA should be extended to the wavelength domain. Also, TWDM-PON can simultaneously accommodate both mobile services and IP triple-play services on the same power-splitter-based infrastructure that is shared in a residential area with mobile fronthaul. Thus, it is expected that TWDM-PON has a great potential to flexibly and efficiently accommodate multi-services.

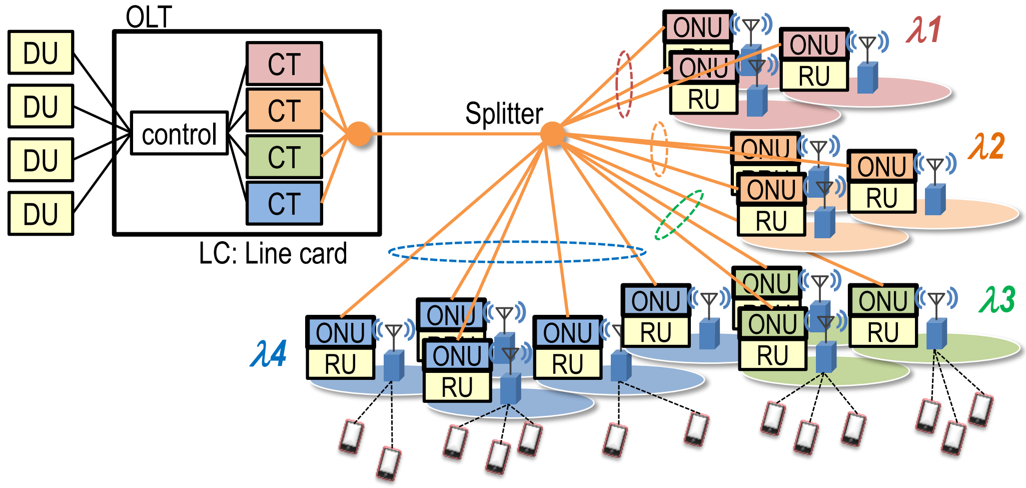

Figure 2-23 – Application of TWDM-PON for mobile fronthaul.

- PtP WDM PON technologies suitability for fronthaul

Each optical network unit occupies an individual wavelength channel pair working in both ways. The transmission layer structure will be simpler than TDM/TDMA, but still requires additional capacity for wavelength control and OAM.

The key technology of WDM PON is the colorless optical module at the ONU. The ONU has to be wavelength agnostic to be installed in any RAN equipment at the antenna site. Therefore, the optical module has to be colorless. There are many ways to achieve colorless optics, such as self-seeded, tunable wavelength, wavelength reuse, etc. No matter which one is applied, it has to solve the problem of cost and performance. WDM PON has been proposed by G989.1 with some restrictions under the name PtP WDM PON to among other applications carry wireless services such as low or high layer RAN splits.

The WDM PON system architecture is shown in Figure 2-24, following the G.989 description. A WDM PON system consists of OLT, passive branching node, passive optical multiplexer(s), and ONU(s), with point-to-multi-point physical connectivity and a point-to-point logical one.

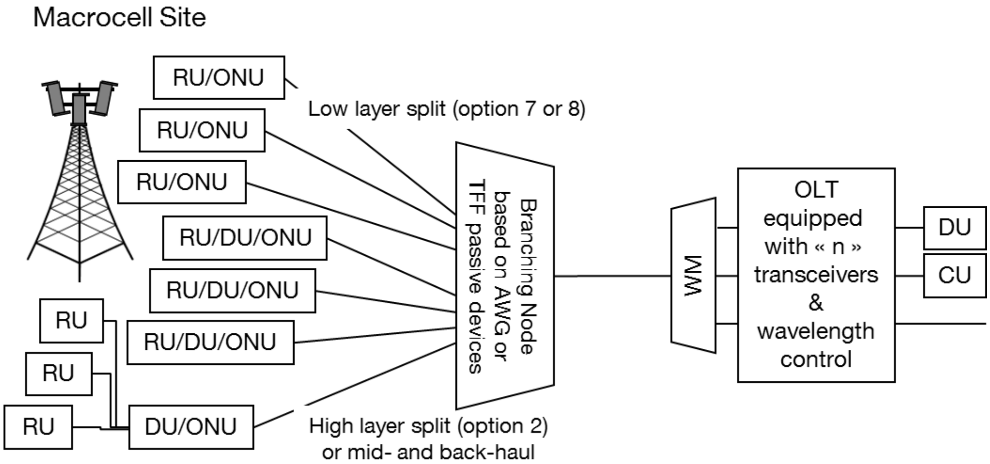

Figure 2-24 – Wavelength routed PtP WDM-PON.

Each ONU occupies a wavelength channel pair (or one wavelength in case of wavelength re-use technology scenarios). On the OLT side, a transceiver module is required for each ONU. On the ONU side, a colorless optical module that can work at any wavelength pair is essential. Inside a working-class which needs to be defined, different channels can support different protocols, data rates, and line coding thus carrying different services, not limited to fronthaul. But all these wavelength channels need to be controlled by an OLT (several OLTs could be considered for protection scheme with the help of Inter-Channel-Termination Protocol) to fix and control the wavelength allocation to prevent any rogue behavior in the concerned ODN.

Two classes of PtP WDM PONs could be defined, the Wavelength-routed (WR), and the Wavelength-selected (WS), more details about these network architectures can be found in Appendix A -TDM PON technologies suitability for fronthaul.

In G.989 series documents, the available wavelength spectrum for PtP WDM PON is limited to a spectrum that authorizes coexistence with legacy PON (G-PON, XG-PON, XGS-PON, RF video overlay, and TWDM PON). This wavelength plan, in case of coexistence, extends from 1603 to 1625 nm. An expanded spectrum is also proposed in the absence of any one of these coexistence systems ranging from 1524 to 1625 nm. It may seem odd that this expanded spectrum does not consider a wavelength range from 1260 to 1675 nm. However, we should remind that colorless ONUs, which intrinsically limit the full wavelength bandwidth, are required in G.989 to obtain the lowest cost PtP WDM ONU thanks to the use of the same technology bricks as the one used for TWDM (wideband option of TWDM is from 1524 to 1544 nm).

The feasibility of a new PtP WDM PON flavor that would support the full wavelength spectrum (1260 to 1675 nm) could become an open study for next-generation access. In this case, the colorless ONUs could be considered as an option depending on the wavelength allocation because they would be addressing a narrower market when targeting mobile applications, hence tolerating different operational constraints.

This possible new wavelength allocation could consider that fixed wavelength allocation is possible by using large wavelength channels (approaching the wavelength window definition of G-PON, XGS-PON in a coarse WDM type range). Colorless could be required only to increase the number of wavelength channels inside each of the large wavelength channels. Typically, the use of a sub-division based on a coarse WDM grid of the full spectrum is a candidate solution for: i) limiting the wavelength excursion of tunable sources for a colorless transmitter, ii) an alternative for bidirectional transmission based on fixed sub-channel CWDM.

Among many PONs technologies, WDM-PON can provide high inline bit rates on a single fiber using DWDM technologies and has the merit of potentially low latency, low jitter, and long transmission distance, making it very suitable for the scenario of high and low level split fronthaul with limited fiber resources.

2.4 Beyond 10G PON- 25GS-PON & 50G-PON[5]

With the publication of XGS-PON and NG-PON2 standards by ITU-T, FSAN has delivered on their previous roadmap, and in November 2016 a new standards roadmap was released [39], Figure 2-25.

There were a set of key requirements to be met to enable the successful and cost-efficient deployment of future optical access network (F-OAN) technologies, namely in terms of spectral efficiency (SE), flexibility, extended reach, open access, and heterogeneous service convergence. New technological solutions such as orthogonal frequency-division multiplexing (OFDM) PON or coherent ultra-dense WDM (UDWDM) PON can progressively be introduced in the network if they prove to meet the required cost and maturity [40].

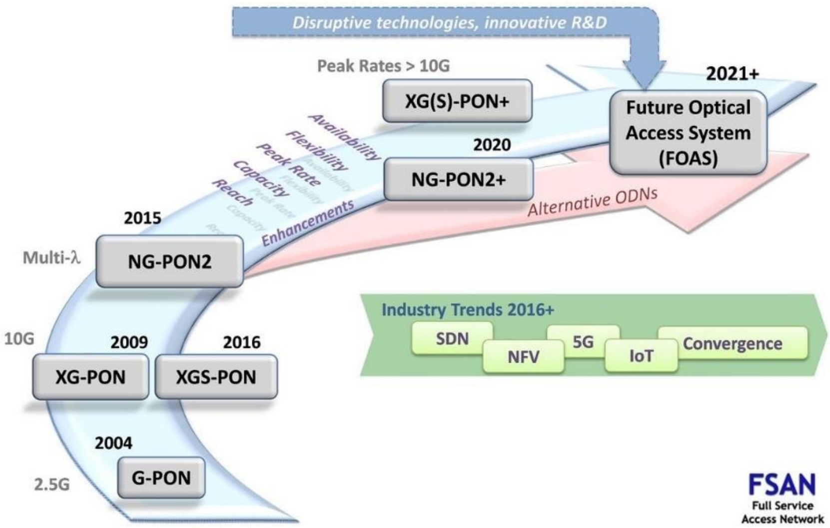

Figure 2-25 – FSAN Standards Roadmap 2.0 (released November 2016) [39].

Digital coherent systems have revolutionized the design of optical communications due to their extended wavelength selectivity and sensitivity. One potential solution for future

[5] This section of the thesis includes parts of the following articles "Ali Shahpari, Ricardo M. Ferreira, Fernando P. Guiomar, Sofia B. Amado, Somayeh Ziaie, Cláudio Rodrigues, Jacklyn D. Reis, Armando N. Pinto, António L. Teixeira, "Real-Time Bidirectional Coherent Nyquist UDWDM-PON Coexisting with Multiple Deployed Systems in Field-Trial (Invited) ", Dec 2015, Journal of Lightwave Technology." [40][40]; "Ali Shahpari, Ricardo M. Ferreira, Fernando P. Guiomar, Sofia B. Amado, Somayeh Ziaie, Cláudio Rodrigues, Jacklyn D. Reis, Armando N. Pinto, António L. Teixeira, "Field-Trial of a Real-Time Bidirectional UDWDM-PON Coexisting with GPON, RF Video Overlay and NG-PON2 Systems", ECOC 2015, Valencia, Spain, 27th Sep - 01 Oct. 2015."[41]

OAN combines coherent transceivers with Nyquist-shaped UDWDM in which the optical band per user is narrower than 10 GHz. Besides improving SE, Nyquist UDWDM-PONs enhance the mitigation of linear and nonlinear crosstalk between WDM channels due to back-reflections and Kerr nonlinearities. Recently, several research works have demonstrated the performance capabilities of Nyquist UDWDM-PONs in laboratory experiments including digital signal processing (DSP) both offline and in real-time [40], [41].

A coherent Nyquist UDWDM-PON field-trial transporting 64 downstream (DS) and 3 upstream (US) differential QPSK (DQPSK) channels at 2.5 Gb/s was demonstrated as a candidate for a FOAN [40], [41].

At the end of 2019, ITU-T released the ITU-T G.9804.1 that defines the requirements for the Higher Speed Passive Optical Networks (HSPON) [42]. The specifications of the physical medium dependent (PMD) layer for 50G single-channel PON systems, G.hsp-50Gpmd [43] stills under study, but it is already generating disagreement on the PON industry, where the downstream bandwidth is not gathering consensus and now seems probable that the world will divide into two manufacturing and purchasing camps, the Western and the Chinese [44], [45].

The basic architectures of higher-speed PON (HSP) systems can be split between TDM/TDMA based, and PtP based. In a higher speed multi-channel PON system, such as 50G TWDM PON, the OLT can be composed of multiple OLT CTs connected via a WM. In a 50G TDM PON, the OLT is a special case of a higher speed multi-channel PON system with just one channel in each direction [42].

A new PON-based 5G Mobile FrontHaul (PON-MFH) was included as services categories supported in higher speed PON scenarios. The OLT and ONUs provide transport between the control unit (CU) and a remote unit (RU). Ultra-low latency with the use of cooperative DBA function and quiet window reduction for the PON is introduced. An interface (named cooperative transport interface or (CTI) between the 5G scheduler and a PON OLT/scheduler is defined by O-RAN WG 4 group in collaboration with the ITU SG15 Q2 group [42].

50G TDM PON system, which operates over a single wavelength channel, shall be able to support a nominal line rate per fiber of approximately 50 Gbit/s in the downstream direction and up to approximately 50 Gbit/s in the upstream direction. A 50G TDM PON ONU shall be able to support the maximum service rate of approximately 40 Gbit/s. An asymmetric nominal line rate combination options per wavelength channel should also be possible: 25 Gbit/s in the upstream, 12.5 Gbit/s, or 10 Gbit/s in the upstream [42].

To facilitate coexistence, an HSP system must be capable of reusing existing legacy ODN PON and ideally operate in a usable spectrum not occupied by legacy PONs in a particular deployment. However, the new 50G-PON could re-use the spectrum allocated to legacy PON systems if it is not coexisting with those legacy PON systems on the fiber. In certain approaches, and to facilitate the reuse of spectrum by using a common wavelength band it could include multi-rate receivers. HSP systems must allow coexistence over the whole, end-to-end ODN including coexistence over the feeder fiber by use of a CEx (or equivalent WDM). Besides, higher speed TDMA systems such as 50G TDM PON can use a multi-PON module integrated into the OLT PON port when coexisting with a legacy PON system [42].

HSP systems must allow a technology migration on existing infrastructure without any prolonged service interruption. It must be capable of upgrading single customers' on-demand to maintain service operations

To realize the migration path, three options differ in the level of flexibility:

- **Straight two-step full migration to HSP**: this covers two-step straight full migration in line with the PON generation order from GPON to XG(S)-PON and then to HSP. This requires a full migration from GPON to XG(S)-PON before starting with the HSP upgrade. This migration option could be realized by removing all the GPON from the ODN and re-using the GPON wavelength windows to enable HSP technology to coexist with XG(S)-PON. The scenario has a double co-existence at any one time of two PON technologies.

- **Direct migration to HSP**: a direct migration covers a path from GPON to 50G TDM-PON. Migration requires an HSP system that can coexist with GPON, a double PON technology coexistence.

- **All-embracing migration to HSP:** coexistence of GPON, XG(S)-PON, and HSP. This option is the most challenging due to the limited optical spectrum and reduced inter-band guard band among the three PON technologies. Operationally, a triple coexistence is required to be managed by support systems, technician tools, and increased OLT port and ONU type inventory [42].

In any migration case including co-existence, the legacy ONU and OLT must remain unchanged and should not require any additional wavelength filters to protect them against HSP signals. If extra filtering is required, this should preferably be at the OLT where access may be easier and not the ONU to avoid truck rolls to many locations of the ONU [42].

In October 2020 was signed a 25G symmetric PON multi-source agreement (25GS-PON MSA) to promote and accelerate the development of 25GS-PON. The MSA Group defined the 25GS-PON specification needed to address the gap between 10G XGS-PON and 50G PON in the ITU-T. The MSA was created as the ITU-T SG15/Q2 group did not reach a consensus to standardize 25GS-PON, which is seen as a key technology by many of the world's top operators and vendors [44] [45]. The 25GS-PON MSA Group created a specification for 25GS-PON which includes optical specifications based on the IEEE 802.3ca 25G EPON standard, along with a Transmission Convergence (TC) layer that is an extension of XGS-PON [45].

A 25G TDM PON ONU shall be able to support the maximum service rate of approximately 25 Gbit/s in downstream and a symmetric nominal line rate of 25 Gbit/s upstream. It will be also possible the support of an asymmetric 10 Gbit/s in the upstream.

As stated before, coexistence scenarios are becoming more and more difficult and spectral scarcity is now a reality with already multiple generations of PON technologies on the field. Figure 2-26 presents and compares the wavelength candidates for HSP and 25GS-PON with current PON technologies.

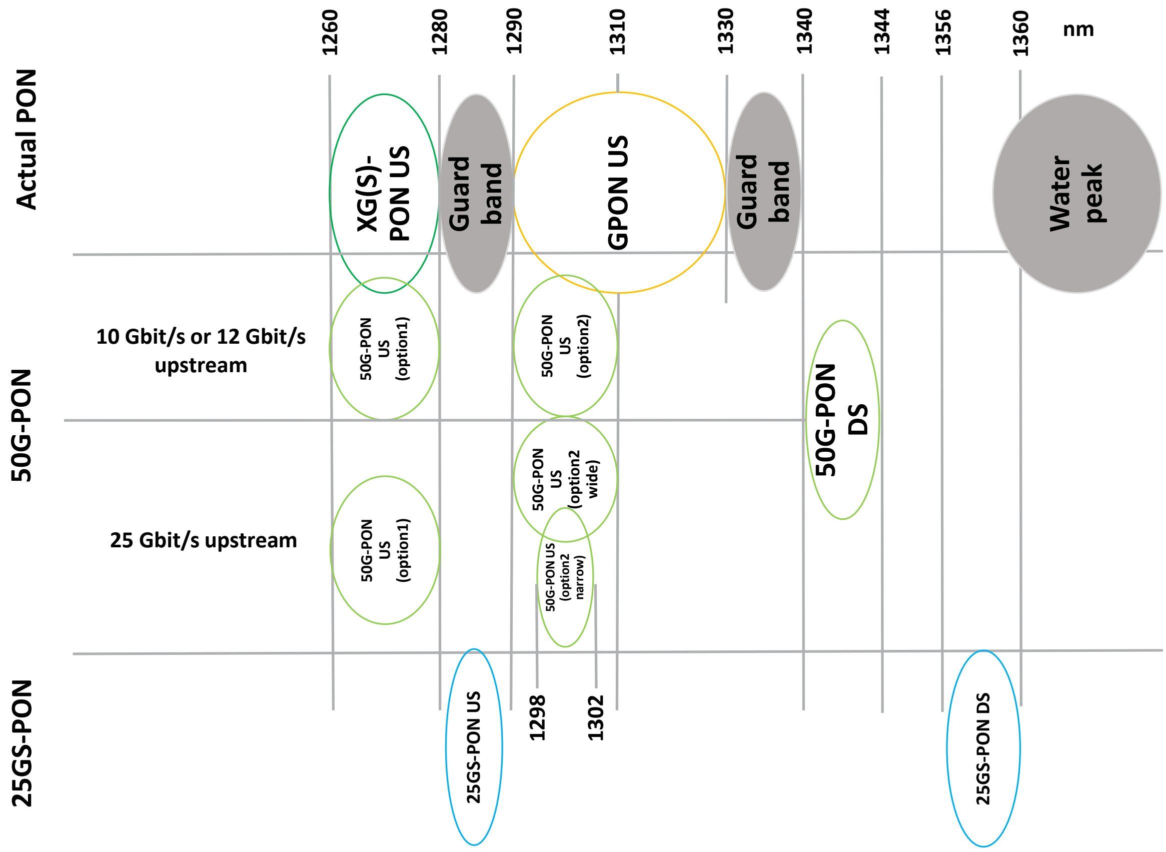

Figure 2-26 – Coexistence possibilities, legacy PON, HSP-PON, and 25GS-PON.

The 25GS-PON can benefit from the already optical technology employed in data centers that leverage the best cost solution, high capacity and fastest time-to-market, and simplest evolution path compared to the 50G-PON that will require a massive technology jump or long time to mature.

The question arises, what will be the next PON technology? With a minority coalition led by operators and vendors from China than objected to the proposal on the ground that 25G PON would pre-empt their futuristic vision of 50G PON, this is, announcing the support of a global standard for PON technology that operates at as high as 50 Gbit/s and can be used for fixed broadband, optical LAN, cellular backhaul/fronthaul, and even optical access uses; and a group of 18 ITU-T members (including ATT, BT, Korea Telecom, nbn Co, Telecom Italy, SK Telecom, Telus, etc.) in favor of initiating the 25GS-PON standardization project [46], [47].

The communications industry always benefit from volume shipments and consumers benefit from lower prices and new technology getting deployed sooner [46], [47], as so, it is necessary an agreement on the next PON technology deployment.

2.5 New optical technologies for PON[6]

Current PON optical technologies are based on bulk technology, like BOSA and it is also very common to have combined interfaces that allow multiple technologies to be handled within the same device, the so-called multi-pon module solutions.

Current low-cost laser and receiver technologies face some challenges to deliver higher data rates without increasing packaging or electronic costs for future 50G-PON or 25GS-PON. The current methods used for interconnecting devices with drivers and boards are typically based on wire bonding and flex printed circuit board (f-PCB). The latter has limited high-frequency performance and tough mechanical design challenges to meet the right soldering robustness, with an expected high impact on the electrical performance of assemblies and sub-assemblies [3].

Among PON future technologies, high interest has been given to the research/development of long-reach/high-speed transmission, where optical amplifiers, electrical domain digital signal processing (DSP) to enhance the link budget, and/or transceiver technology are predicted to be key factors [48].

Similar to what happened with integrated circuits' contribution to electronics development, PIC technology is one of the most attractive solutions to tackle the referred issues. Thus, integrated photonics can have a key role in the deployment of more flexible PON networks, as they can incorporate different optical components with various functions in a potentially cost-effective way without increasing the assembly process complexity [49], [50].

Photonic integration can provide advantageous solutions to PON by limiting the number of optical and electrical interconnections and thus overcoming some of the bulk packaging restrictions, such as bandwidth, power dissipation, and cost [18][51]. Nevertheless, complexities can arise with the use of this technology, namely fiber interfacing difficulties, number of electrical connections, and possible high-density of components per device, which demands a high power dissipation management [52]. The development of PIC solutions for access networks has already been reported, e.g., with an InP monolithic transceiver PIC for NG-PON2 applications [53], the proposed layout has the potential to be implemented as an OLT and with filter redesigning as an ONU. A photonic integrated apparatus for tunable multi-wavelength transmission was patented in 2017 [54], the time and wavelength division multiplexing (TWDM)-PON transmitter system proposed is tailored to support current and next-generation access technologies.

As addressed in previous sections, the major requirement for future PON technologies is the need for coexistence with current deployed PON systems [18], [52].

The longer the required reach, the more difficult it gets to find the laser technology able to support the demanded distance. As an example, for a 10 Gbit/s with a short reach like 10 km, almost all standard laser technologies can be used. If addressing the 2.5 Gbit/s markets, a medium reach like 40 km and further is still not a major limiting factor to the laser choice. However, if requiring a common GPON ODN which ranges 20 km including

[6] This section of the thesis is based on the following Journal article "Cátia Pinho, Francisco Rodrigues, Ana Maia Tavares, Carla Rodrigues, Cláudio Emanuel Rodrigues, António Teixeira," Photonic Integrated Circuits for NG-PON2 ONU Transceivers (Invited)". Appl. Sci. 2020, 10, 4024" [3] and in the patent "Teixeira, A.; Tavares, A.; Lopes, A.P.S.; Rodrigues, C.E. "Photonic Integrated Tunable Multi-Wavelength Transmitter Circuit," Patent no.2017/0331558, 2017"

splitters and handling dispersion penalty poses challenges to most of the 10 Gbit/s solutions. To achieve that target, the laser must be designed to perform a low penalty, typically below 1 dB to 2 dB, at the required distance. To meet those specs, specially designed direct modulated lasers (DML) are required, or even the migration to externally modulated laser (EML) technologies [49], [50].

Furthermore, ODN should support 128 users and a 20 km reach. These requirements lead to an ODN total loss greater than 32 dB. If we target 10 Gbit/s with APD receivers allowing a −26 dBm to −30 dBm receiver sensitivity, it leads to a minimum laser output power of 4 dBm. A possible alternative to overcome this requirement is to use an amplification stage in the path which removes the passivity of the ODN, however, it reduces the potential usage of EML-based solutions since its typical power does not exceed the 0 dBm.

To improve reach, several techniques are available and many stem from the laser (e.g., low dynamic chirp or frequency modulation efficiency), laser driving (pre-chirping or equalization), and wavelength selection (e.g., O-band instead of C and L bands) [52], [55]. O-Band has been used for supporting upstream and was adopted by some of the standards like GPON, XGSPON, and now for 25GS-PON and HSP. O-band, besides presenting low or null dispersion, only introduces slightly higher attenuation than C-band. To cope with the maturity of the technology and promote an easier and simplified entry into the market, initial PON technologies, like GPON, were set in large bandwidths for better yield in laser choice with the upstream in the O-band [49], [56]. The wavelength range of 20 nm to 30 nm per traffic direction was reserved for this technology, which allowed it to easily mature while still being competitive. This strategy proved to be solid since it resulted in the current GPON BOSA sitting in the few dollars range (as of today).

Furthermore, PON technology evolution can be achieved by data rate multiplication and more efficient use of the bands to promote further network evolution scenarios. Following this path, the XGS-PON standard was conceived with slightly smaller bandwidths for both upstream and downstream, which resulted in a four-times higher bitrate than GPON [20], [25]. Newer PON technologies, as NG-PON2 require finer tuning, as so, a more complex laser selection process. The qualification of a laser to operate in a certain wavelength range results from setting its maximum allowed wavelength at initial temperatures. The broad requirements of the technology in terms of the client locations may require industrial temperature ranges (−40 to 85°C), which bring extra requisites to the laser wavelength choice or thermal control mechanisms. Directly modulated lasers have good optical output power and are easy to drive and modulate. However, the inherent high wavelength fluctuation when modulated or the inherent chirp can result in propagation limitations. Laser design/control efforts are being made to minimize these effects and currently, there are already some devices in the market able to cope with some of the most stringent standard requirements [57], e.g., the NG-PON2. With an external cavity, EMLs result in a much lower chirp, however, having typically a more complex tunability mechanism when compared to the simple current or thermal tuning of the DML [49].

Photonic packaging technology has achieved a higher significance under optical communication systems' recent developments [58] by covering the optical and electronic connections in/out of the PIC. Packaging process developments are of great importance for the next generation of optical components [59]. Being one of the most complex segments of the integrated component viability, it can pose several challenges, such as limitations in terms of volume, cost, RF performance, power dissipation, and its high-volume manufacturing capability [58], which can highly impact the cost of the solution.

Currently, the packaging is seen as one of the most significant bottlenecks in the development of commercially relevant PIC devices [60], [61]. The packaging design flow is divided into three main areas: the optical design, the electrical design, and the thermal management of the module. Considering the typical wavelength gain band of an active device, ranging from 20 nm to 30 nm for the O- to L-bands, and the technology wavelength map, several approaches may be required to merge in a single device the upstream/downstream signals. There are several network standards, like XGSPON, which require upstream/downstream wavelengths spaced by more than 200 nm. A 200 nm spacing brings higher challenges and may require hybrid integration, which poses additional packaging challenges [49].

The different PON standards and technologies have their requirements in terms of complexity control, especially for tunable devices. When wavelength control is not essential, simpler actuation systems with lower power are required. Nonetheless, once the wavelength spectrum becomes more crowded, the options have to be restricted, and the requirements for more complex control increase [49]. A summary of the technology and expected power for its optoelectronic interfaces versus the complexity and requirements for a certain interface is depicted in Figure 2-27. A general sweep, from low data rate with large wavelength range to higher data rate with tighter wavelength range and longer reaches, is also presented in Figure 2-27. Additionally, the technologies with an approximate relative power requirement classification (from low to high power) are also identified. The x-axis represents the optical requirements, ranging from low data rate to long-reach DWDM and high data rate. The blue circles describe the complex steps from the system requirements.

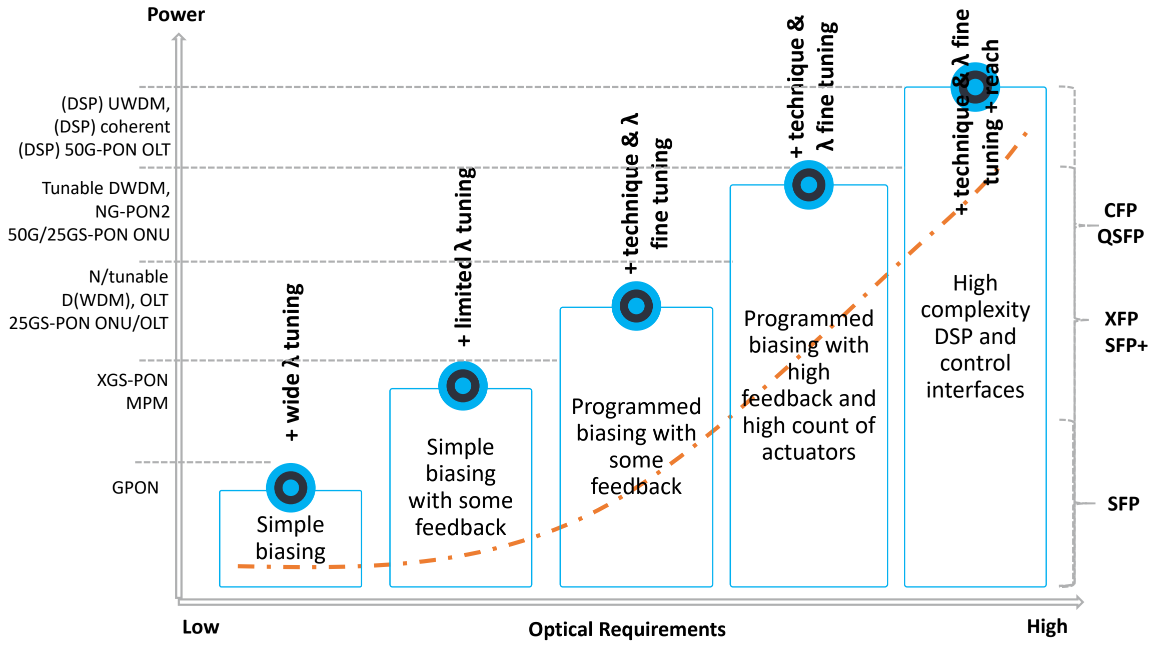

Figure 2-27 - Diagram of requirements in terms of control, complexity, and power for different technologies.

Potential form factor solutions able to cope with the required power dissipation are also presented in the far right of Figure 2-27. Technology evolution poses increasing challenges in the control complexity and required power. As the demanded power grows, a change in the form factor is needed. Form factors have two major characteristics: minimum volume and maximum dissipated power [62].

As it is possible to see in Figure 2-27 for the 50G-PON and 25GS-PON a high complexity is expected on both sides, mainly on the 50 Gbit/s NRZ processing, where DSP will play a major role to meet the high loss ODN requirements of PON. Also, tight control of the lasers working on the O band for both directions, due to the low spectral scarcity, will require complex techniques and careful laser selections.

An interesting point on the 25GS-PON is that currently available technology for 25G Ethernet and 100G Ethernet (4*25 Gbit/s) will speed up its deployment due to the high market availability for datacenters, as an example, a 100GBASE-ZR4 QSPF28 (4*25GbE for 80 km of fiber) already achieve sensitivities w/ FEC of -28dBm for O band at a bit error ratio of 5x10-5 and SFP28 25GBase-LAN-WDM already uses 25Gbit/s EML TO-CANs that met the 25GS-PON upstream requirements in terms of wavelength, temperature, and optical power. Unlike the 50Gbit/s downstream of HSP that will require a more complex structure in downstream, both at the transmission of OLT and reception of ONU, the use of NRZ signals poses high RF bandwidth of lasers and APDs and lasing technology only available nowadays on a limited laboratory availability of single wavelength 100G, 400G, and 800G Ethernet. High-speed Ethernet technology, namely 400GbE, 800GbE is moving from NRZ to PAM4 as so, this poses more challenges for the 50G-PON. An alternative is to use 25G optics with strong DSP capabilities.

The most cost sensitivity part of an HSP ONU is the optics for the 50 Gbit/s. As stated before, in the HSP system, 10Gbit/s and 25Gbit/s upstream look to be possible using conventional optics without wavelength control (20 nm width), unlike the 50Gbit/s upstream where the link budget is much overextended. There are several methods to solve the 50 Gbit/s upstream and downstream, power budget requirement and also enable coexistence with legacy systems and lower upstream line rate.

As presented in Table 2-9, based on [63]–[66], for 10 Gbit/s upstream transmitter based on DML, the cost of cooled transmitter is two and a half times of uncooled. For 25 Gbit/s upstream transmitter, due to lack of volume today, the cost of uncooled 25 Gbit/s DML is at least fifty percent more expensive than 10 Gbit/s DML, thus the cooled 25 Git/s DML transmitter is roundabout three times of uncooled (the absolute delta cost for cooled is generally same for 10G and 25G transmitter).

For 50 Gbit/s transmitter, is assumed the required launch power is at least +7dBm (to meet the ODN power budget), as so, we do not see an uncooled 50 Gbit/s DML can transmit such high power. For the 50 Gbit/s transmitter an SOA seems inevitable to reach such launch power. Currently, DML is very challenging to operate at more than 40Gbit/s, as so, an EML plus SOA seems the most feasible solution for 50 Gbit/s upstream, 50 Gbit/s DML+SOA may be possible in the future, but all of these need to be cooled.

An uncooled DML TOSA has a very simple structure and package, which points out that when the accumulated shipment volume becomes very high (such as ~10 million), the cost of uncooled 10 Gbit/s DML can be even lower, as in principle from the long term when volume goes very high, the cost of 10 Gbit/s DML will be infinitely close to 2,5 Gbit/s DML, the cost of 25 Gbit/s DML will be infinitely close to 10 Gbit/s. Like the 2,5 Gbit/s DML, 10 Gbit/s DML, and 25 Gbit/s DML are nearly in the same chip size, the cost mainly depends on the yield and how much the R&D cost need to be amortized.

ONU Upstream transmitter	Solution and Specification assumption Uncooled	Incremental Cost in Percent to cooled based	Solution and Specification assumption cooled
10 Gbit/s	10G DML, TX min= 4dBm	X 2.5	10G DML TX min= 4dBm
25 Gbit/s	25G DML, TX min= 5dBm	X 3	25G DML TX min= 5dBm
50 Gbit/s	No Technology >+7dBm	NA	EML+SOA or DML+SOA > +7dBm launch power

Table 2-9 – The added cost of temperature control of uncooled to cooled on Upstream transmission of ONU for HSP.

While for the cooled device, it needs a more complicated header and more complicated package process, cooled package do not have any yield issue or high R&D cost amortization, the delta cost is nearly constant even when the volume goes to very high. This means when the volume rumps up and is very high in the future, the cost difference between an uncooled transmitter and a cooled transmitter will become even higher.

In summary, for 10G and 25G upstream, the temperature control will bring a significant added cost for the ONU transmitter. The 50 Gbit/s upstream must be cooled to meet the required power budget.

Nowadays a 50 Gbit/s DML is not mature, due to the very small size of 50 Gbit/s DML chip, the uncooled 50 Gbit/s DML can only transmit very low launch power with very low ER, and is not likely to meet the power budget requirement for HSP PON upstream [66].

A more practical solution is to use a high launch power 50 Gbit/s EML or a 50 Gbit/s EML with an integrated SOA.

Regarding the receiver of the HSP ONU for 50 Gbit/s, there exist two possible solutions, 25 Gbit/s APD + TIA + DSP and a pre-amplifier receiver that is constituted by a SOA + Band pass filter+ 25 Gbit/s APD+ TIA + DSP. The cost of a pre-amplifier receiver is at least 20% more than the simple solution [66].

With the previous assumptions, a long technical way to reach a cost-effective solution for ONUs is expected to reach the requirements for the HSP for 50 Gbit/s.

A reduction in physical volume, number of sub-assemblies, and calibration steps are expected with the migration to PICs. These steps may greatly reduce the price of the subassemblies based on PICs when compared with traditional bulk BOSA [7,8]. As identified above, by having upstream/downstream on approximately the same wavelength band, NG-PON2 can be a great applicant for monolithic PIC. In such a case, ONU and OLT can coexist in the same PIC platform without further processing. XGSPON, besides being already stressed in price, may require O-band and L-band integration, which can entail extra processing and packaging steps, thus increasing the limitations of PIC viability in this wavelength range. DWDM is also included in the wavelength plan of NG-PON2 and is already an ITU-T standard being used for implementing several telecommunication systems, which also poses a good opportunity for the use of the PIC technology.

PICs are a promising technology with great potential in several fields including telecom, sensing, and bio-photonics. Depending on the requirements, the type of materials, and components, a tailored approach has to be carefully specified for the different PON technology standards. Several challenges must be considered when equating the introduction of PIC in the next-generation PONs, like productization, wideband wavelength range (O, C, and L-bands), laser control, and tunability mechanisms [3].

PON standards have different flavors that result in quite different requirements, especially regarding the wavelength ranges to be covered by the two traffic directions, i.e., the upstream and downstream. For instance, GPON and XGSPON have specifications of >200 nm spacing between upstream and downstream, while NG-PON2 requires around 60 nm for the same parameter. Due to technological inherent limitations of some technologies, hybrid integration may be required, e.g., XGSPON and GPON. Smaller bands will ease this process and therefore potentiate monolithic PIC implementation, simplifying packaging and deployment, e.g., NG-PON2 [3].

PICs have typically two major interfaces, electrical and optical, each with different requirements, techniques, and available materials to be used. Packaging and technical considerations such as size, power, RF compliance, and sealing are relevant. In a nutshell, manufacturability is anticipated to be one of the most critical steps for the technology to be successful, especially in PON. In our vision, the use of PICs in PON and other subsystems is very close to being an effective reality with prospective advantages [3].

2.6 Conclusions

This chapter presented an overview and summary of the different PON technologies. The capacity, technological limitations, and limits of PON were analyzed.

The need for different types of OLTs and ONUS with different capabilities, transport speed, and support services are emphasized. It is noticeable that depending on the scenario, PON technology can fulfill the requirements.

The metamorphosis of PON technologies to support from residential services, Wi-Fi, high resiliency services, high bit rate services, till RAN applications is notorious, what makes PON equipment's, namely OLTs and ONUs the most adaptive telecom equipment's to the preferable scenario and of the most diffused technology.

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Chapter 3: PON technologies breakthroughs

Telecom Industry is a complex process marked by the interactions between scientific advances and market demands. To model this phenomenon, we use economic theories of technical change and innovation management.

We examine the characteristics of technological breakthroughs and how they apply to PON technologies. What is the nature of radical innovations and how do they differ from other innovations? We map the path of radical innovations, from the first fundamental discoveries in the laboratory to mass dissemination through major demonstration projects. What is the configuration of the innovation process and how are the different stages linked? What are the factors involved in each of the phases? What are the uncertainties related to PON technologies investment? The policy role. What are the critical moments in the innovation process? The barriers to the development and diffusion of PON technologies on the market are investigated.

3.1 Innovation Cycles

The development of economies in history is associated with waves of innovation. Business cycles operate under long waves of innovation. As markets are disrupted, key clusters of industries have outsized effects on the economy. These innovation clusters normally appear around the main innovation responsible for breaking with the previous technological paradigms.

This section begins by revisiting the great technological waves in history. We then look at the study of major innovations, their distinctive characteristics, and socioeconomic repercussions.

3.1.1 Waves of technological innovations in history

The evolutionary concepts in the economy, which focus predominantly on technical progress, innovation, industrial development and market structure, business cycles, and growth in long waves dates back to the work of Schumpeter. This evolutionary character of the capitalist system is said to be the result of several reasons such as adaptation to a constantly changing social and natural environment, or the increase in population and capital. However, the main reason mentioned by Schumpeter [1] is the constant change in the economic structure. This transformation is manifested in a continuous movement of production of new objects of consumption, new production and transport procedures, new markets, and new types of industrial organization. The evolution of the economy would thus be the result of this process of "creative destruction", which describes the process that sees innovations replacing existing ones that rendered obsolete over time.

Innovation is at the center of Schumpeter´s theory. While the invention is seen as a gradual and continuous process, innovation is introduced at specific moments in history.

Schumpeter considers it likely that innovations will be introduced during periods of economic stability with less risk of failure.

Following the introduction of innovations, economic activity is moving away from equilibrium, eventually leading to a decrease in the step of innovative activity. In the meantime, the economy is characterized by a different production structure, with higher production and a lower price level. Business cycles would be explained by movements of innovation. Bases on Kondratieff cycles [2], Schumpeter identified long-cycles hypothesis: cotton, iron, and the steam engine (1780–1840), which was enabled by the first wave of the industrial revolution, followed by the age of railways (1842–1887), the second industrial revolution and the age of electricity (1898–1940) the start of which was the so-called technical revolution. A fourth and fifth were later on identified, the age of mass production and the rise of Information and Communications Technology and Network [3].

3.1.2 The typology of technical change

Technical changes do not, always, have the same magnitude. Besides simple changes in production techniques (for example, changing a machine), there are situations where the change is much broader with implications for the state of knowledge or even the organization of society. Freeman [4] therefore distinguishes between “technical” change and “technological” change. The first represents the change in tangible production methods, while technological change refers both to the tangible change in knowledge (the technique) and to the whole body of knowledge around the technique:

“…the expression ‘technical innovation’ or simply ‘innovation’ is used to describe the introduction and spread of new and improved products and processes in the economy and technological innovation to describe advances in knowledge.” ([4], p.24)

An important difference is drawn by Freeman and Perez [5], who distinguish incremental innovations and radical innovations, on one hand; and technological system changes and techno-economic paradigm changes on the other hand.

Incremental innovations are introduced more regularly. These are the result of a process of continuous improvement in performance, quality, and cost reduction. Thus, incremental innovations can be the result of action taken at the production level or by the fact of an increase in use (learning savings or "learning by doing" and savings in use or "learning by using", respectively).

In contrast, radical innovations are events that mark technological discontinuities, most often being the result of a deliberate process of research and development. These innovations are normally associated with a product, process, and organizational change. However, radical innovations benefit from incremental improvements in older technologies (for example, the nuclear power industry has benefited from technical advances in coal and oil-fired power plants).

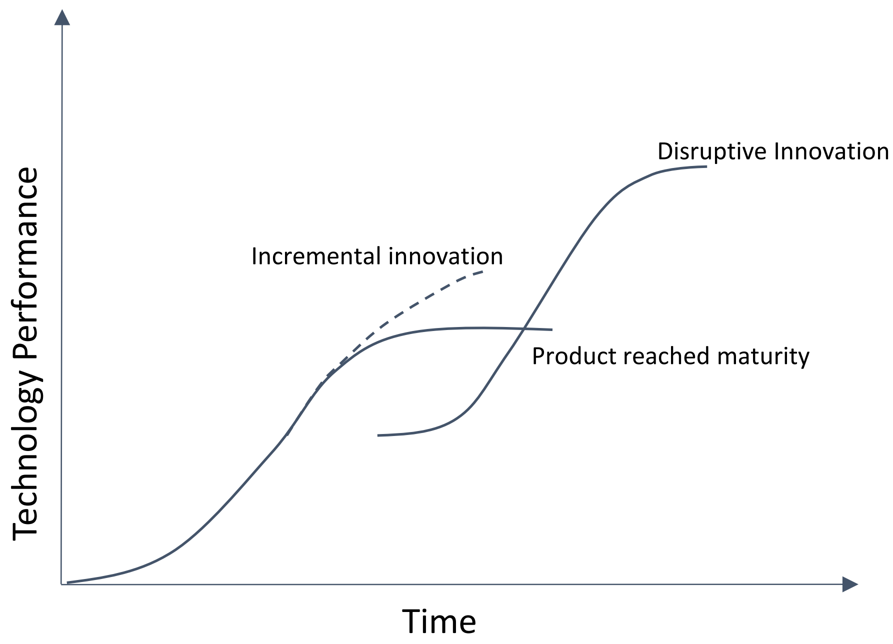

Figure 3-1 – Incremental and disruptive Innovations.

Figure 3-1 compares incremental innovations and disruptive innovations. Incremental innovation is generally comprehended as improvement of technology performance or product feature enhancement (in terms of quality or cost), which significantly expands its market potential. During the final phase of the s-curve, where the product reached maturity, this is reached physical or economic application limits, the major factors contributing to enhanced technological performance are now realized and exploited to a large extend [6].

Disruptive innovation is defined as based on technologies previously new to the world, combined with their effects on markets. Disruptive innovation is responsible for technological discontinuity. Although radical breakthrough innovations normally exhibit a more limited technological performance at the start compared to existing technologies, this gap is quickly overcome due to greater technological performance and economic potential compared to old technology.

Furthermore, we declare a change in the technological system when the effects of the change have a broad impact on several economic sectors. This is normally the result of a multitude of incremental and radical innovations that can lead to the creation of new economic activities.

Finally, the concept of a techno-economic paradigm shift applies to situations where the change in the technological system has major consequences in all areas of the economy. The new paradigm thus leads to contagion ('pervasive') effects for other sectors of activity as Freeman and Perez [5] state:

"…changes in the techno-economic paradigm have such widespread consequences for all sectors of the economy that their diffusion is accompanied by major structural crisis of adjustment, in which social and institutional changes are necessary to bring about a better 'match' between the new technology and the systems of social management of the economy — or 'regime of regulation'." ([5]*,p.871).*

The theory of techno-economic paradigms formulated by Freeman and Perez [5], identifies several technological waves in history, which is part of the Schumpeterian theories of long cycles of the economy and "creative destruction". Thus, new paradigms begin to develop before the end of the previous paradigm. The risk-taking and the cost of investing in a new paradigm become justified when the increase in productivity of the old paradigm is limited and profit expectations are reduced. Independently, a true technological revolution must meet certain criteria: drastic cost reduction; rapid and almost unlimited increase in production; and wave effects across the economy.

According to Dosi [7], the technological paradigm establishes the context for innovative activity by identifying the problems to be solved and the solutions available. The innovations follow a certain technological direction or trajectory throughout the dominant paradigm [7]. The paradigm shift is only made by a technological discontinuity [8]. Dosi relates knowledge evolution to the evolution of technology.

Note that the concept of techno-economic paradigm proposed by Freeman and Perez is macro-economic, comprising a set of technologies, while the technological paradigm, to which Dosi refers, characterizes the evolution of a single technology (approach microeconomic).

The innovations follow natural trajectories opened by a significant scientific or technical advance until the first signs of saturation. Natural trajectories also respond to signals received in the selection environment of firms.

It is therefore a continuous, orderly, and cumulative process aimed at the highest level of potential effectiveness. The cumulative experience in the production or use of the technology, as well as the dynamic effects of scale, contribute to the gradual improvement of the technical characteristics and performance of the technology along specific trajectories.

The relationship between the evolution of technology and industry has been studied by Abernathy and Utterback [9]. The authors explain the existence of an industry life cycle in which the first company enters the industry and try to innovate, but in most cases fails and leaves the market. However, after a while and after some cumulative efforts, a new idea begins to take hold and attract a significant share of the market. This is the gradual emergence of a dominant design that will impose itself on the entire sector. From the moment the market chooses a design, innovators and followers must adhere to the new format so that they can take a significant part of the market [10]. In this evolutionary framework, the first steps are very important for the formation of the dominant design and the technological variety disappears with the maturity of the industry.

The concept of "architectural innovations" applies to new technology which modifies the existing production system to offer new functionalities and new uses by users. This can be the basis for the reformulation of the sector or the creation of a new industry. The innovation then marks the basic configuration (architecture) in terms of techniques and marketing to be used by the rest of the industry.

The formation of an industry-standard reduces the variety of models and therefore the technological uncertainties for firms and consumers. Now the competition is no longer in terms of complex new technological architectures, but in terms of performance, costs, and product differentiation [11]. On the other part, the emergence of an industry standard simplifies the technology adoption process, otherwise, consumers would have to try out multiple technologies which may be difficult or expensive for some. Sometimes customers wait until the evolution of technology stabilizes. So, the emergence of technological architecture seems to be a necessary condition for mass production.

Clayton M. Christensen [12] distinguishes between sustaining technologies that improve the performance, cost, or quality of existing technology without, however, fundamentally changing its characteristics, and so-called disruption technologies which set a new industry standard, on the other hand. Technologies can be radical or incremental innovations; the important thing is that the innovation introduces new characteristics which prevail in the market compared to the previous technology (lower price, ease of use, etc.)

The classification of innovations can sometimes lead to some confusion. Radical innovation does not immediately lead to performance and cost gains.

3.1.3 The "push" of science versus the "pull" of the market

Market pull and technology push represents the innovation process in a linear model [13]. Kline and Rosenberg [14] advocated a shift from linear models of technology and demand for a more interactive model between these two potential sources of innovation. The innovation process is the result of an interactive process between demand and science.

According to the authors, linear models of innovation have difficulty representing the process of technical change. First, linear models do not consider feedbacks either during technology development or between users and the development company. Second, the early versions of the innovation are typically very faulty, and their performance falls short of maximum technical potential. Thus, for the technology to be successful, a process of continuous improvement and reconfiguration, taking into account the information ("feedbacks") between the various stages of development until commercialization, is essential. And also, which takes into account all the available knowledge.

Kline and Rosenberg's innovation model, Figure 3-2, is made up of a central innovation chain, through internal chain interactions ('loops') and external interactions with the market and knowledge and research (science).

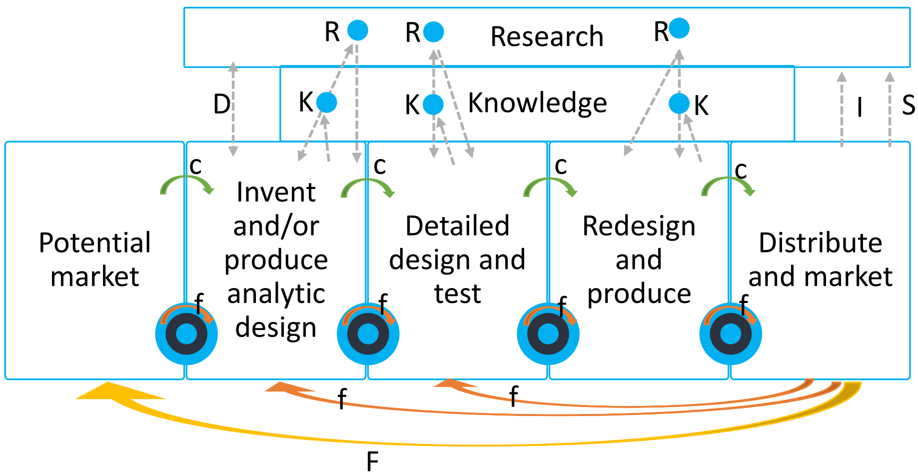

Figure 3-2- Chain-linked model from Kline and Rosenberg. Symbols on arrows: C = central-chain of innovation; f= feedback loops; F= particularly important feedback [14].

The innovation process starts with the design of the product which is determined by the unmet needs of consumers. Thus, the Kline and Rosenberg model can be associated with the “pull” theories of the market. However, the potential market may be opened up by a new product, or even a radical innovation. In this case, the innovation would rather be motivated by a technological push.

In this model, science is not the basis of the innovation process. Indeed, science supports the process throughout the central innovation chain as new technical needs arise and cannot be resolved in the current state of knowledge. At a given time, a research process is started to find the solution to the problems encountered during the development of the product. Science is also taking advantage of market feedback to improve products and redirect research toward future markets.

This integrated representation is particularly suitable for the representation of innovation in the passive optical networks sector. On one hand, the need for durable solutions, the physical network, calls for a transition to new technologies allowing to solve the problem of the need for bandwidth and the expected increase in demand for services. On the other hand, technological advances in photonics have opened new perspectives for new technologies.

The interactive visualization of the technical change process sees it as the result of both demand stimulus and the advancement of science. This has consequences for public policies. Support for basic and applied research is therefore essential to encourage innovation in the economy. But also, the creation of an institutional framework that facilitates interactions between science and innovation actors (businesses and consumers).

3.1.4 The evolutionary perspective of technical change

Long-term economic change is at the heart of evolutionary analysis. This is precisely the analysis of the selection mechanisms that favor the firms/technologies best suited to the selection environment.

For evolutionary authors, the behavior of agents does not result from the optimization of profits or utility but from an imperfect process of adaptation to changes in the selection environment. Unlike the neoclassical theory which considers that the best technologies ('best practice technologies') are chosen and that there is no uncertainty about the characteristics of the technology, evolutionary theory takes into account the indivisibility of factors [7].

The following points are explored the main characteristics of the evolutionary analysis of innovation: the hypothesis of limited rationality and uncertainty; the creation of variety and technological selection; path dependence; and the influence of cyclical factors of technological change.

- **Limited rationality**

A central assumption is the consideration of bounded rationality of agents. The agents have limited decision-making capacity, and they do not have access to all of the information necessary to make the decision. This assumption makes the analysis more realistic at the cost of greater operational complexity.

Nelson and Winter [15] note that companies do not use very sophisticated decision-making tools due to a lack of time or skills. Nonetheless, they also note that the outcome of all corporate decisions is approaching the optimal solution.

- **environmental uncertainty**

The consideration of limited rationality and uncertainty, especially in terms of technological adoption, takes into account the uncertainty of the different technologies to more realistically anticipate the progression of each on the market. In the neoclassical models, firms choose the best technologies with no uncertainty about the characteristics of the technology adopted.

- **The creation of technological diversity**

Innovation is the basis of technology development and the change of economic structures. It allows the assimilation of new products, processes, practices, etc., which increases the technological variety.

The concept of technological variety is a qualitative measure of economic change. The variety increases with the size of the market; and decreases with the competition when economies of scale are large and goods are substitutable [16].

Technological variety is limited by a set of forces that characterize technological selection. Not all innovations are successful; thus, old technologies are normally replaced by new, more efficient technologies. So, the increase in variety is often followed by the selection that reduces technological choices; both processes are the basis of the evolutionary explanation for technological change.

- **The selection environment**

In the evolutionary conception, companies and technologies are subject to an economic selection process identical to natural selection in biology. The market remains a fundamental barometer. The success of innovation in the market increases the profits of the innovator. The viability of product innovations is linked to the positive reaction from consumers. The success of a product innovation depends very much on its acceptance by the market.

But also, the selection environment includes actors with the power to influence the environment in which technological competition or between firms takes place [7]. The selection environment can be modified by government intervention through the funding of R&D, the establishment of mandatory standards, economic regulations, etc. Second, the selection environment is specific to each sector and each technology. It can be characterized by the availability and source (public or private) of capital, the need for additional goods (for example, physical infrastructure), the link between supplier and user (end or intermediate customer), the skills required, routines, consumer preferences and beliefs of innovators [17].

In evolutionary terms, companies and technologies are selected based on their adaptation to the environment. This concept may seem closer to the Darwinian theses where the ones most responsive to change survive.

From a dynamic point of view, the evolution of the market share of each of the technologies is determined by the selection environment [15]. On the one hand, it contributes to improving the productivity of innovation through the savings generated in terms of production and consumption. On the other hand, the selection environment influences the priority of companies' R&D projects in favor of the most profitable innovations. So it intervenes at the level of management of the marginal improvements expected in the future, by favoring a certain type of technology at the expense of others, a priori less profitable.

Adaptation through *selection* requires interactions of firms with the environment in a way that causes their differential replication. While innovation increases diversity, selection acts to reduce it. Selection operates primarily by imitation of other actors thus favoring the diffusion of some items at the cost of others [18]. Thus, the technology selection process is the basis for the emergence of dominant designs, which reduces technological variety[9]. The most widely adopted innovations benefit more from continuous improvements, allowing them to gradually close the market to competing technologies.

- **Path dependence and technological blockage by historical events**

The evolutionary explanation of the diffusion of technologies starts from a double observation: 1) the market does not always retain the best technologies, and 2) technological selection is the result of a dynamic process involving several factors. For evolutionary authors, technological adoption leads to cumulative dynamic effects over time by benefiting from the most adopted technology. In this perspective, the technological selection is more the result of an interactive process of technological choice and promotion of the adopted technology, than a predictable process of retention of superior technology.

From an evolutionary perspective, the complexity of technologies and limited rationality do not allow agents to accurately predict the market share of each technology in the long term. In addition, lack of information and uncertainty can be a barrier to the spread of the best technologies.

Technological evolution is, therefore, the result of a cumulative process influenced by the succession of historical events and by the choices of the past, that is, the result is not predictable at the outset and depends on the succession of adoption decisions [19][20].

- **The factors underlying technical changes in history**

Technological systems are not eternal, and they evolve in response to changes in the breeding environment. A technological change is a complex process and is determined by a series of factors such as technological bottlenecks; the scarcity of new entrants to production; growth and structure of demand; and political factors.

3.2 The dynamics of innovation and PON technologies

Telecommunication innovations normally require the mobilization of enormous resources (financial, human, etc.), which makes the innovation process more complex than in most sectors of the economy. We can identify several stages in the innovation process (3.2.1). First, the invention requires research and development (3.2.2). A critical moment for innovation appears at the level of the transition between the laboratory to the market (3.2.3). Technological Learning (3.2.4) is a key element for the competitiveness of technology, which will be decisive for its diffusion (Chapter 4).

3.2.1 The stages of technological change

Technological change is usually represented in the literature as a linear process composed of several successive phases. The origins of this vision go back to Schumpeter [1] who distinguished in the complex process of innovation three stages: the invention, the moment of the creation of the idea; innovation, the period of economic development of the new concept; and dissemination, through user adoption and imitation of competitors. Freeman [4] synthesizes this analytical treatment of the innovation process as follows:

« We owe to Schumpeter the extremely important distinction between inventions and innovations, which has since been generally incorporated into economic theory. An invention is an idea, a sketch or model for a new or improved device, product, process or system. Such inventions may often (not always) be patented but they do not necessarily lead to technical innovations. In fact the majority do not. An innovation in the economic sense is accomplished only with the first commercial transaction involving the new product, process, system or device, although the word is used to describe the whole process. »

Due to the high initial investments and infrastructure requirements, technical change in the telecommunication sector, namely on PON, is different when compared to other technologies.

Grubb [21] offers a representation of the innovation chain in the energy industries that integrates the interactions between demand and supply of technology, that can be applied to the telecommunications sector. The diagram below, Figure 3-3, also considers external influences such as the regulatory framework and the investment context. The author identifies six phases in the innovation process: 1) basic research and development; 2) technology-specific research, development, and demonstration; 3) demonstrations, full-scale tests, and first estimates of the technological economic potential; 4) marketing (entry into the market or 'start-up'); 5) the accumulation of markets; and 6) large-scale dissemination.

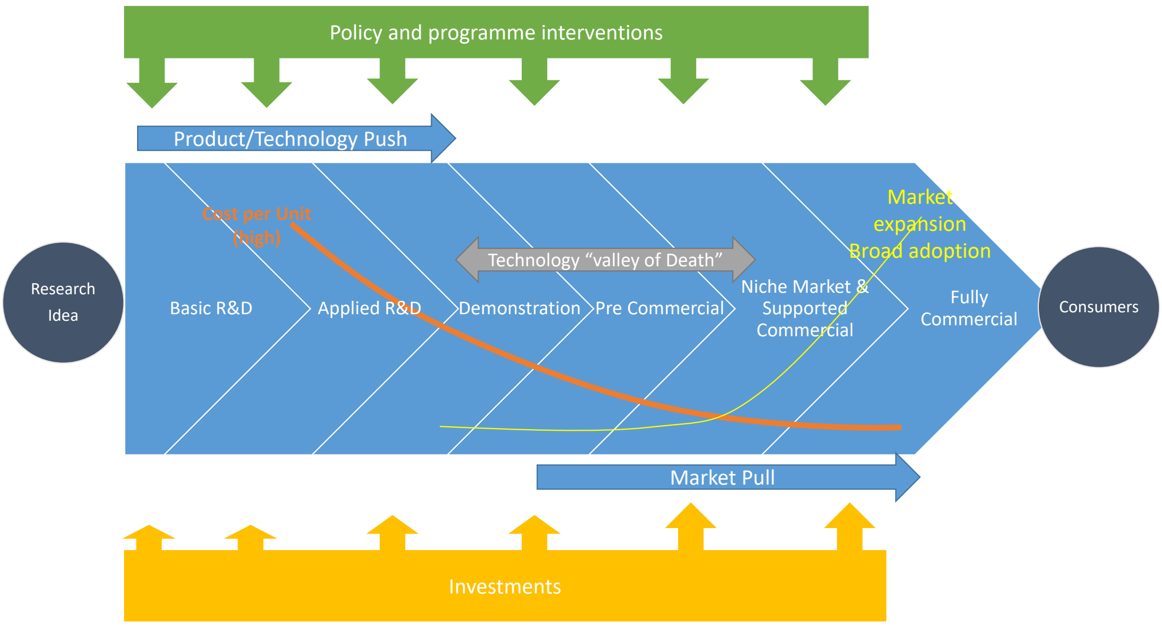

Figure 3-3 - The innovation chain.

3.2.2 Research and development (R&D)

Innovation and technical change are based on a certain stock of knowledge available in the economy. Theories of endogenous growth consider the stock of “knowledge capital” as one of the factors of economic growth. Research and development (R&D) fuel the stock of knowledge, and, through this, it is the basis of innovations and therefore indirectly of economic growth.

A first conceptual distinction must be made between basic research and applied research. Basic research concerns research whose results have the potential for practical application in the long term, while applied research leads to innovations (or technological improvements). During the development phase, the results of basic and applied research are used to design the prototypes of the technology, which will later be tested, augmented, and demonstrated in real life to potential customers.

3.2.2.1 The uncertainty associated with innovation

Firms invest in R&D intending to generate a profitable product or a process innovation. Investment in R&D has distinct characteristics compared to investment in tangible assets. First, the outcome of the research investment is more uncertain. The degree of uncertainty differs depending on the type and phase of the innovation. In the previous chapter, we saw that the innovations between the development phase and commercialization are marked by a multitude of uncertainties that make investments very risky.

Freeman [4] identifies three types of uncertainty: technical uncertainty; market uncertainty and the uncertainty of the business environment. The first type of uncertainty is technical and concerns the degree of confidence in the validation of the technical objectives set at the start of the innovation, during the development phase. Market uncertainty is linked to how innovation is accepted by the market. This is a type of fundamental uncertainty since commercial success dictates the success of innovation. Finally, uncertainty about the business environment is also important since it determines the ability of innovation to generate positive financial returns.

In general, the degree of uncertainty decreases during the development of the innovation. If not, the company may cease its innovation efforts to avoid the risk of accumulating losses.

In addition, the type of innovation influences the degree of uncertainty. The development of radical innovations is associated with greater uncertainty (technical, market, business context) in comparison with incremental innovations [4]. Basic research - necessary for major innovations - is considerably more uncertain than research applied to simple technical improvement. Likewise concerning the uncertainty linked to product and process innovation: the former is riskier because it is faced with at least two types of uncertainty (technical and market), while process innovation mainly faces technical uncertainty. In addition, market uncertainty is often less controllable by the innovator than technical uncertainty [4]. Table 3-1, adapted from Freeman [4], provides a summary of the different degrees of uncertainty concerning the type of innovation.

True uncertainty	Fundamental research
The very high degree of uncertainty	Radical product innovations Radical product innovations outside the firm
The high degree of uncertainty	Major product innovations Radical process innovations (in own firm)
Moderate uncertainty	New generations of established products
Little uncertainty	Imitation of product innovations Obtaining a license for developing an innovation Modification of products and processes Early adoption of established process
Very little uncertainty	New model Product differentiation Late adoption of an established process innovation Minor technical improvements

Table 3-1 –Degrees of uncertainty by Freeman [4].

3.2.2.2 The problem of research results appropriation

Another question arises concerning the appropriation of research results. Knowledge is a public good, that is to say, that, once produced, it becomes difficult for the innovator to exclude other firms from its use. The firm may try to keep the results secret, which is not a completely safe strategy. However, when it comes to product innovations, it must make the innovation available to the public so that it can make its discovery profitable. In doing so, the knowledge associated with the innovation is made (in whole or part) also public. This means that it becomes available to all competitors in the market.

3.2.2.3 Private R&D spending in a competitive environment

In a competitive environment, private investment in R&D faces a series of challenges. First, the problem of encouraging companies to invest in R&D when the results can be freely used by their competitors. Second, the uncertainty of the results and the long-term nature of certain projects will have an impact on the choice of projects to be developed by companies.

In a rational and optimized decision framework, firms choose research projects where the difference between the discounted flows of expected benefits and the discounted flows of costs is greatest [4]. Such a cost-benefit analysis favors technological improvements that can bring short-term benefits, despite major technical changes that require immediate investment and (uncertain) potential for longer-term benefits.

Thus, private spending on radical innovation R&D is expected at a socially sub-optimal level due to the uncertainties and the long-term nature of the project.

3.2.2.4 Public funding of basic research

The attention in policies targeting development innovative activity through framework conditions has grown in Europe over the previous decade, if only because restrictions on public spending have reduced the funding of more traditional research and innovation policies.

Public support is necessary for the development of technologies with significant expected long-term social gains. This requires long-term action planning, in a time horizon that is often too long for private investors. The state's vision and R&D investment are therefore important to make the technology available when it is needed.

3.2.3 From laboratory to market: going beyond the "valley of death"

The transition from the laboratory (original scientific research) to commercialization is a crucial phase for the success of innovation. This normally requires the performance of applied research and demonstration activities such as the construction of prototypes and first experimental versions of the technology on a full scale allowing a first estimate of the economic potential of the technology. However, this is a more capital-intensive stage when the risk of the project remains very high, which poses funding problems even when governments have increased the availability of financing and management support [22].

3.2.4 Technological learning

The concept of technological learning was born from the observation that the unit costs of technology decrease, and the performances improve with the increase in production. The decrease in technology costs through the learning effect was first identified by Wright [23].

"*Learning is the product of experience. Learning can only take place through the attempt to solve a problem and therefore only takes place through activity*. "([24], p. 155)

Indeed, learning increases factor productivity by reducing unit production costs. Arrow [24] (p.156) argued that the decline in production costs was a *consequence* of the accumulated experience, because "*it is very activity of production which gives rise to problems for which favorable responses are selected over time*."

Many technologies, notably semiconductors [25], are characterized by a reduction in costs with cumulative production. The reduction in costs may be due, in particular, to large-scale production or to learning savings. The first represents the savings generated by an increase in the quantity (scale) of production. The second is expressed by the experience (or learning) curves and represents a reduction in costs by the learning effect with an increase in cumulative production.

In general, new technology is initially much more expensive than the existing technologies, which have already benefited from learning gains when they were introduced and disseminated in the market. As the new technology is produced and marketed, the effects of increasing revenues are manifested in lower costs of the new technology. The decrease in costs can continue until the new technology becomes more efficient and cheaper than the existing technology.

Real-option models in general focus on the timing of investment [26]. For learning-curve technology, however, it is important to look at both timing and size of the investment, because a larger operating scale accelerates learning and the resulting cost reduction [27].

The learning curve has been used in various areas of manufacturing and is typically formalized by the relationship between unit costs and cumulative production.

As soon as new technology is deployed on the market and its cost is reduced to a competitive level, everyone benefits without having paid for its implementation, especially when its cost was still very high. In this case, firms and large consumers prefer to wait, which will delay the progress of the technology. In addition, the uncertainty surrounding cost reduction increases the risks of investing in learning.

Several types of learning curves have been studied: log-linear, Stanford-B, exponential learning factor, and sigmoid shape as presented in [28].

Optical components for PON require special wafer fabrication and processes. A Wafer fabrication facility (fab) requires huge capital investment. Its production line includes multiple steps and machines and is hired to produce advanced products at high yields within a short time to market [29]. Yield has a significant impact on cost and is associated with key performance measures such as throughput and flow time (noted cycle time).

Learning curve models have been used to describe tendencies in numerous areas of the semiconductor industry like Intel´s Moore Law [30] (projected that the number of transistors placed on a single chip will double every two years) and Intel's Noyce (shown that integrated circuit's cost per unit reduced log-linearly with the cumulative quantity of units produced).

It is well recognized that integrated circuits sale prices start high and decrease quickly [31]. Since yield has a dominant effect on semiconductor manufacturing economics, its ramp should occur quickly and then be maintained at a high level to maximize profits.

Several authors [31]–[36] present a sigmoid curve in support of the assumption that a wafer fabrication yield learning rate is not constant during the entire life cycle, but is rather slow in the development phase, increases in the ramp-up phase, and stabilizes in high volume production.

The experience curve simplifies the analytical processing of a complex reality - the dynamic gains of learning through production and consumption.

Indeed, lower costs (increased productivity) can be the result of several factors. It is therefore important to distinguish between learning effects and external factors of technological change. These external factors include economies of scale and scope, R&D results, spillovers, and fundamental innovations outside the industry.

3.3 Conclusions

The theory of innovation cycles was presented and discussed. The role of innovation and the typology of technical change were analyzed as well as the main drivers of technological change: the demand for technology or advances in science.

The most important phases of the telecom technology innovation process were explored. The elements covered were research and development, the transition phase between the laboratory and the market, technological learning, and dissemination.

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Chapter 4: Mathematical models that describe growth

In this chapter, we present the methodological framework for our analysis. This is provided by several relatively simple models originating from biology. All these models deal with processes of growth or decline of innovation and its interaction with the technological, economic, and social environment in which it is embedded.

The term "growth curve" represents a loose analogy between the growth in the performance of technology and the growth of a living organism. This chapter is presented several mathematical models that describe growth and help to organize the database that illustrates the patterns of PON development (described in Chapters 5, 6, and 7). While almost any conceivable growth curve might fit a special case, the focus here is on those most often found to describe technological innovation - the S-curves. These are characterized by slow initial growth, followed by a period of rapid growth, and finally by an asymptotic tapering to a limit.

4.1 Growth curves

All mathematical models that describe growth have a common biological theme, this is, the interaction of a population with its limiting environment, and the interspecies iterations among populations. These models have been applied to describe the dynamics of technological systems and their competition. By using this biological metaphor, we explore the origin of these models, that is, they are all either directly taken from biology or originate from it. By analogy, these models have been applied to describe the dynamics of technological systems and their competition for market shares.

These models serve as descriptive tools, and as such, they do not provide insight into the driving forces and causality of the evolutionary processes they describe. They are used merely as an instrument for the systematization and quantification of long historical development patterns and to provide consistency in international comparisons.

A quite general model of interaction of biological system competing for the same resource is provided by Lotka-Volterra equation [1]:

$$\frac{\partial N_i}{\partial t} = \alpha_i N_i - \frac{1}{\gamma_i}\sum_{j=1}^{n} \lambda_{ij} N_i N_j \,, \qquad i = 1, \dots n \tag{4-1}$$

The Lotka-Volterra competition equations, model the interaction of biological species, competing for the same resources and can also model parasitic and symbiotic relations. In this model, N_i represents the number of individuals of species i, the λ_{ij}´s are the coefficients of the interaction, the α_i´s and the γ_i´s are the parameters that depend on the environment [2].

In our study of this general model to the description of growth and change in the PON telecom sector we consider three aspects of interaction:

- The interaction of species N_i with its limiting environment in the form of a growth process.
- The competition between two species N_i and N_j inside a particular market in the form of substitution models.
- The competition between more than just two species is in the form of a multiple substitution model.

Several different models describe growth in interaction with a limiting environment. In our study, we concentrate only on models which have also found application in the description of technological change and economic modeling. All the functions presented below, contain three parameters, which have the following interpretation[3]:

I. As time, t, tends to infinity, $y = W(t)$ *(4-2)* approaches an upper bound that represents the level at which the growth process saturates, this is,

$$\lim_{t\to\infty} W(t) = A, \tag{4-3}$$

where A is positive and finite.

II. There exists a time, t_0, at which the curve has a point of inflection, this is,

$$\frac{d^2W}{dt^2}(t_0) = 0, \tag{4-4}$$

where the growth rate reaches its maximum. The curve is considered symmetric if it is symmetric around t_0, this is, $W(t_0 - t) = W(t_0 + t)$ *(4-5)*. A necessary condition for symmetry is:

$$W(t_0) = {}^{A}\!/_{2} \tag{4-6}$$

III. Δt, gives the length of the time interval needed to grow from 10% of A to 90% of A, more precisely, let t_p be defined as:

$$W(t_p) = \frac{p}{100}A\,, 0 < p < 100 \tag{4-7}$$

then Δt is given by:

$$\Delta t = t_{90} - t_{10} \tag{4-8}$$

Early models of technology diffusion used the metaphor of the spread of epidemics to represent the process of diffusion [4]–[8], and it is a common practice in empirical studies on the diffusion of innovations over time, to assume that the number of individuals that adopt an innovation follows an S-shaped curve [8]. After the introduction of the innovation, there is an initial stage where few individuals adopt the innovation. This early stage is followed by a period of the rapid growth of the number of adopters. Finally, the diffusion process reaches a maturity phase, in which the growth of the number of adopters slows down, and the total number of adopters gradually stabilizes.

The most used S-shaped growth curves in the empirical literature on diffusion are the logistic and the Gompertz curves. Despite their “good fit”, we will criticize later their mathematical properties, namely, their lack of flexibility concerning two important characteristics of the diffusion process, the inflection point, and the symmetry or asymmetry around the inflection point.

In this work, we propose a methodology to estimate the diffusion processes of PON equipment’s, ONTs/ONUs, and OLT ports, by considering different models that can accommodate a whole set of different S-shaped diffusion patterns, these models will be utilized in a comparative manner and the model which best fits the historical data of adoption will be subsequently used for forecasting the future uptake of the innovation. The reason for comparative evaluation is due to the generally accepted notion that no particular model is best suited for forecasting all innovations for all contexts, given that the models are found to be highly sensitive to the available dataset [9].

The first S-shaped growth curve we consider is the logistic function.

4.1.1 Three parameters Logistic Model

The three-parameter logistic curve is given by:

$$y = W(t) = \frac{A}{1 + e^{-K(t-t_i)}} \tag{4-9}$$

where $W(t)$ is the variable measuring the diffusion process in a period, t, this is, the number of ONT/ONUs or OLT ports at a given time. A define the maximum level of technology use (the equilibrium level at the end of the diffusion process, the market saturation) and k the diffusion speed, growth rate. They are positive parameters for estimation. The curve is symmetric around t_i, and the length of time interval to growth from 10% of A to 90% of A [3], is given by Δt (from equation (4-7)):

For t_{10}, $p = 10$:

$$\frac{10}{100}A = \frac{A}{1 + e^{-K(t_{10}-t_i)}} \tag{4-10}$$

Solving for t_{10},

$$t_{10} = \frac{Kt_i - ln9}{K} \tag{4-11}$$

For t_{90}, $p = 90$:

$$\frac{90}{100}A = \frac{A}{1+e^{-K(t_{90}-t_i)}} \qquad (4\text{-}12)$$

Solving for t_{90},

$$t_{90} = \frac{Kt_i - \ln\left({}^{100}/_{90} - 1\right)}{K} \qquad (4\text{-}13)$$

The Δt show that is related to the growth rate, K, by:

$$\Delta t = \frac{Kt_i - \ln\left({}^{100}/_{90} - 1\right)}{K} - \frac{Kt_i - \ln(9)}{K} = \frac{2ln9}{K_g} = \frac{1}{K}\ln(81) \qquad (4\text{-}14)$$

The parameter t_i specifies the time when the curve reaches its midpoint, this is ${}^{1}/_{2}\,A$ *(4-15)*.

Figure 4-1 plots the logistic curve for three different parameters of k. As is possible to observe it imposes a constraint that the inflection point occurs when half of the diffusion took place.

An equivalent form of the logistic equation can be defined as:

$$W(t) = \frac{A}{1+e^{-\frac{ln81}{\Delta t}(t-t_i)}} \qquad (4\text{-}16)$$

An Essay on the Principle of Population by the English economist Thomas Malthus (1766-1834) began the widespread practical application of the logistic function as a means to represent growth processes. The first reference to the logistic curve as a model of population growth can be found in the work of Pierre-Francois Verhulst. T. Brailsford Robertson in 1923 suggested using the function to describe the growth process in a single organism or individual. Raymond Pearl rediscovered the function for demographic forecasting [4], [5]. During 1925 and 1926, while working independently, Alfred J. Lotka and Vito Volterra generalized the growth equation to quantify competition among different species and coined the predator-prey equations. The logistic function can be derived from the general Lotka-Volterra equation for the two species competition assuming a limited environment, this is, $N_1 + N_2 = constant$ *(4-17)*. The interaction of the growth of species with its environment can also be presented by re-writing the logistic function with a linear right-hand side:

$$\ln\frac{y}{A-y} = K(t-t_i) \qquad (4\text{-}18)$$

This view is known as the Fisher-Pry transform [10]:

$$FP(t) = \left(\frac{F(t)}{1-F(t)}\right), \text{where } F(t) = \frac{W(t)}{A} \qquad (4\text{-}19)$$

Note that:

$$\ln(FP(t)) = \frac{ln81}{\Delta t}(t - t_i) \tag{4-20}$$

When plotted on a logarithmic scale yields a linear function that highlights in particular the early and late phases of the growth process. In Fisher-Pry transform, is the time in which the value is between 10^{-1} and 10^{1} is Δt. The time of inflection t_i is 10^0 [10].

The temporal derivative of the Logistic is the rate of growth, this is, new adopters. Differentiating equation (4-9) we have:

$$\frac{dW(t)}{dt} = \frac{AK_g e^{-K_g(t-t_i)}}{(e^{-K_g(t-t_i)} + 1)^2} \tag{4-21}$$

With this, we can know the number of new ONTs/ONUs, OLT ports per period. The maximum number of adoptions occurs at period $t = t_i$ *(4-22)* at which the inflection point occurs. Figure 4-1 plots the number of new ONTs/ONUs, OLT ports per period, $\frac{dW(t)}{dt}$ *(4-23)*, for various values of parameter k. An important feature is that the number of adoptions is symmetric around t_i. Values of k greater than 1 imply a fast adoption around the inflection time, and values smaller than 1 imply a smoother adoption.

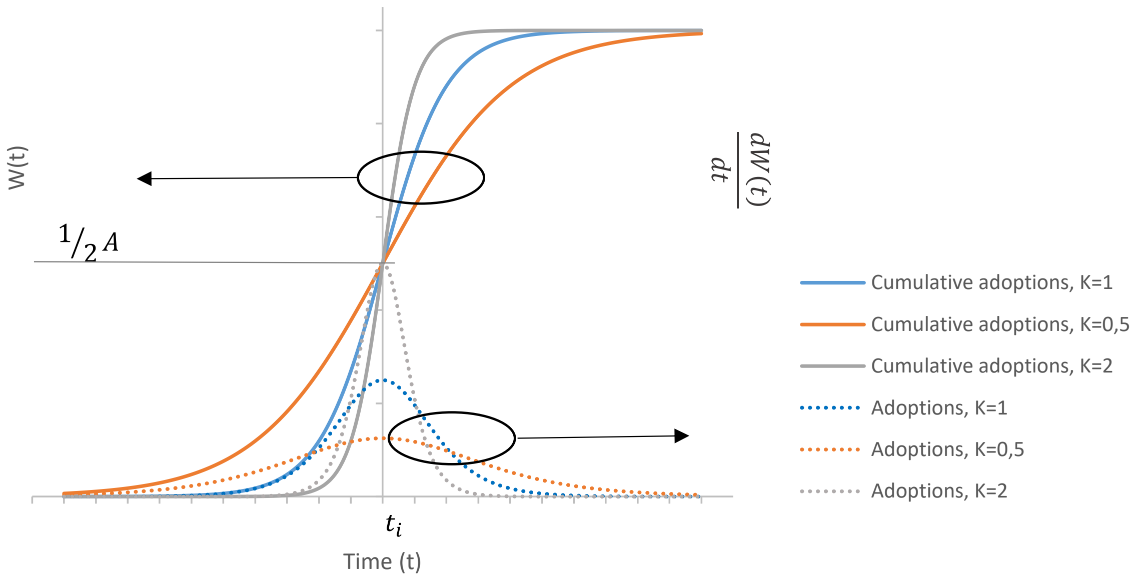

Figure 4-1 – Logistic curve plots for different values of growth rate.

4.1.2 Gompertz growth curve models

In 1825 Benjamin Gompertz published a paper in the *Philosophical Transactions of the Royal Society,* "On the Nature of the Function Expressive of the Law of Human Mortality", in which he showed the relationship between increasing death rate and age, "*if the average* *exhaustions of a man's power to avoid death were such that at the end of equal infinitely small intervals of time, he lost equal portions of his remaining power to oppose destruction*"[11], which has been in use as a growth model, both for biological and for economic phenomena.

The Gompertz growth curve model [12], is commonly used to define a growth curve for population studies in situations where growth is not symmetrical about the point of inflection [13]. Examples include trend of mobile broadband traffic profile [14], diffusion of digital mobile telephony [15], bandwidth growth on optical access network [16], demand and price forecasting on the photonic component industry [17], assessment of FTTH access networks [18][19], bacterial growth [20], and growth of cancer stem cell tumor [21].

Modeling the implementation of the offered services is a main characteristic of the standard business case analysis. Several mathematical models have been proposed to estimate the adoption of services and technologies, [16] has indicated the Gompertz adoption curve as the most suitable method to model the adoption of telecom business cases as a function of time, as so, in the next sections, several parametrizations and re-parametrizations of Gompertz curve will be modeled to the PON market.

Growth usually follows a sigmoid curve shape, as so, different candidate models, based on parametrizations and re-parametrization of the Gompertz model will be discussed. They can be divided into type I, based on the inflection-time parameter, T_i, and type II, W_0 – a starting point parameter. The focusing is on how their parameters affect curve characteristics.

In the type I models, a single parameter controls the time at which a specific point on the curve occurs. The point represents a fixed proportion (or percentage) of the upper asymptote, and the time at which this point occurs is not affected by the other parameters (though all other points along the curve are).[22]

In type II models, a single parameter controls the starting value for the curve (i.e., the intersection with the y-axis). In these re-parameterizations, the other parameters do not affect the starting point. Exists two type II models, type IIa where the starting value acts as a location parameter, keeping the upper asymptote constant, and type IIb where the starting value acts as a shape parameter [22]. One of the more important was suggested by Zwietering and colleagues [23]. The Zweifel and Lasker´s [24], a good example of a simple type II mode where the location parameter represents the absolute value of the starting point on the x-axis. Another prominent re-parametrization of the Gompertz model is the Gompertz-Laird model, proposed by Laird [25]. This model is considered especially useful when we want to discuss the initial value (starting point on the x-axis).

Another type II re-parametrization is also studied, suggested by Norton [26], due to its simplicity to interpret the parameters and control the curve characteristics.

The different models of the Gompertz curve are particularly important in our study because the PON market do not have the same behavior across the globe, this is, the equipment penetration is different on the studied geographies, the initial quantities of equipment on the market can influence the total market, the time when occurs inflection, as well as the how the market behaves over time.

The different studied models allow a deep study to describe diffusion patterns. Given the amount of effort devoted to the development of various asymmetric diffusion models, it is surprising that the flexibility of these models (in terms that they can describe a wide range of diffusion patterns) is achieved by paying a high theoretical price. No reasoning is given by any of the model developers as to why a particular diffusion pattern should follow their models or what the (economic or behavioral) explanation of the additional model parameters might be. The only remaining justification for these models appears to be that they can describe ex-post the diffusion patterns more accurately.

4.1.2.1 Traditional Cumulative Gompertz (type I)

A commonly found re-parametrization of the Gompertz growth curve is usually [27]–[29]:

$$W(t) = Ae^{-e^{-K_G(t-Ti)}} \qquad (4\text{-}24)$$

where $W(t)$ the estimated diffusion level at time t, this is, in our case this is, the number of ONT/ONUs or OLT ports at a given time. A represents the upper asymptote, saturation level i.e the final market potential, K_G is a growth rate coefficient (which affects the slope), and T_i represents the time at inflection. Figure 4-2 plots the Gompertz curve for two different parameters of growth rate and two different times of infection. As is possible to see T_i shifts the growth curve horizontally without changing its shape and is therefore what is often termed a location parameter (whereas A and K_G are shape parameters), which means that this is a type I model [22].

The Gompertz function shows the cumulative adoptions. Therefore, the temporal derivative is the new adopter. Differentiating we have:

$$\frac{dW}{dt} = AK_G e^{-e^{-K_G(t-T_i)}-K_G(t-T_i)} \qquad (4\text{-}25)$$

Differentiating again we have:

$$\frac{d^2W}{dt^2} = AK_G(K_G e^{-K_G(t-T_i)} - K_G)e^{e^{-K_G(t-T_i)}-K_G(t-T_i)} \qquad (4\text{-}26)$$

We see that there will be a point of inflection when

$$t = T_i \qquad (4\text{-}27)$$

The ordinate at the point of infection is:

$$W = \frac{A}{e} \qquad (4\text{-}28)$$

Or approximately, when 36,78% of the final growth has been reached. Figure 4-2 plots the number of new ONTs/ONUs, OLT ports per period, $\frac{dW(t)}{dt}$ *(4-29)*, for various values of parameter k and time of inflection. An important feature is that the number of adoptions is asymmetric around the inflection time. Values of k greater than 1 imply a fatter left tail than the logistic curve, and values of k smaller 1 imply a fatter right tail. Hense, as k increases, the slowdown in the adoption process after a period of time of inflection is increasingly pronounced.

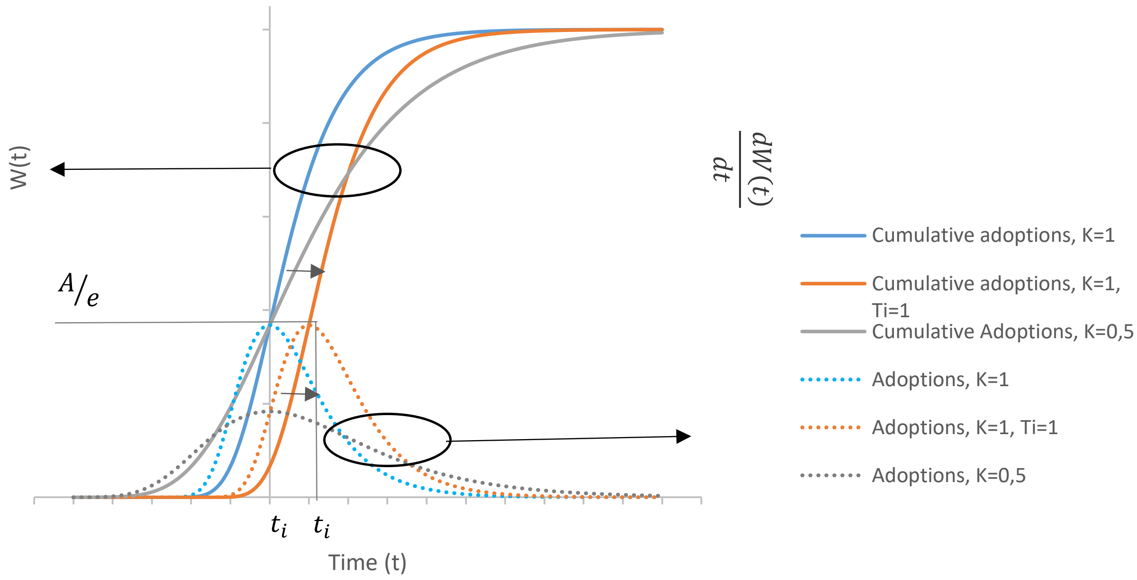

Figure 4-2 – Type I Gompertz model.

The curve is then asymmetric around T_i, and the length of time interval to growth from 10% of A to 90% of A [3], this is, Δt, where $W(tp) = {}^{p}/_{100}\, A$ *(4-30)*. Is given by:

$$\Delta t = \frac{Kt_i - \ln\left(-\ln\left({}^{90}/_{100}\right)\right)}{K} - \frac{Kt_i - \ln\left(-\ln\left({}^{10}/_{100}\right)\right)}{K} = \frac{1}{K}\ln\left(\frac{\ln(10)}{\ln(10/9)}\right) \qquad (4\text{-}31)$$

As for the logistic curve, the Gompertz curve can also be rewritten in a linear form.

$$-\ln\left(ln\frac{W(t)}{A}\right) = K(t - t_i) \qquad (4\text{-}32)$$

4.1.2.2 Zwietering modification of Gompertz curve (type I)

The Zwietering model[23] is a modification of the Gompertz curve and it is a type I Gompertz that is given as:

$$W(t) = Ae^{-e^{\left(\frac{eK_z}{A}\left(T_{lag}-t\right)+1\right)}} \qquad (4\text{-}33)$$

where K_z are the absolute growth rate and the "lag time", T_{lag}, always occur at 6,59 percent of the final growth, this is, the so-called lag time T_{lag} always occur at the same percentage of the upper asymptote: $W(t) = Ae^{-e}$ *(4-34)*. This means that the location parameter, Ti in the previous model, is modified to control some other than position than the inflection time.

Figure 4-3 shows the form of the curve for the case $A = 1$, $K_z = 0{,}368$, and different $T_{lag} = 0{,}1{,}2$; The new adopters per period, $\frac{dW(t)}{dt}$ *(4-35)*, are also plotted for various values of the cumulative adoption.

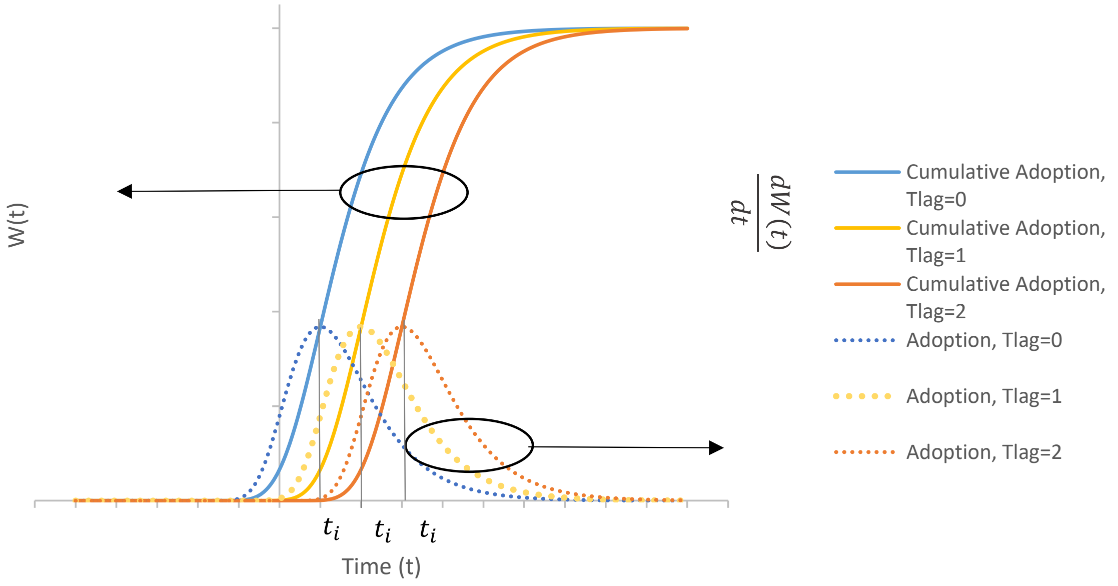

Figure 4-3 – Zwietering model.

Differentiating (4-33), to be able to know the number of new ONTs/ONUs, OLT ports per period we have:

$$\frac{dW}{dt} = K_z e^{-e^{\frac{eK_z(T_{lag}-t)}{A}+1} + \frac{eK_z(T_{lag}-t)}{A}+2} \qquad (4\text{-}36)$$

Differentiating again, to determine the inflection point, we have:

$$\frac{d^2W}{dt^2} = \frac{K_z{}^2\left(e^{eK_z(T_{lag}-t)+1} - 1\right)e^{-e^{\frac{eK_z(T_{lag}-t)}{A}+1} + \frac{eK_z(T_{lag}-t)}{A}+3}}{A} \qquad (4\text{-}37)$$

We see that there will be a point of inflection when:

$$t = \frac{e^{-1}(eK_z + A)}{K_z} \qquad (4\text{-}38)$$

An important advantage of the Zwietering re-parametrization is that the growth coefficient constitutes the absolute growth rate at inflection, and that A does not affect this parameter. Another important aspect for taking this curve into account is that the inflection time is dependent not only on A but also on the absolute growth, the main reason for using this curve in our study.

4.1.2.3 The Zweifel and Lasker re-parameterization (type IIb)

Zweifel and Lasker re-parameterization [24], is a type II Gompertz model, where the location parameter represents the absolute value of the starting point on the x-axis, this is the initial adoption of equipment at $t = 0$.

It is given by:

$$W(t) = W_0 e^{m(1-e^{(-k_g t)})} \tag{4-39}$$

where K_g is the growth coefficient and is comparable to the growth coefficient in the traditional cumulative Gompertz model. W_0 is a starting point parameter, the initial value, although it also modifies the upper asymptote, because it changes the beginning point by scaling the curve vertically. The interest of the study of this curve in our telecom case is mainly due to the presence of this variable, we intend to know the influence of initial equipment in the network and how it influences the upper asymptote. m, affect the upper asymptote (A) by scaling the model vertically.

The upper asymptote is found by $A = W_0 e^m$ *(4-40)* and both k_g and m affects the time of inflection.

The absolute growth rate, this is, the initial growth rate, at $t = 0$ is $W_0 k_g m$ *(4-41)* and the relative growth rate at $t = 0$ become $k_g m / e^m$ *(4-42)*. The maximum relative growth , at time of inflection $t = \ln(m)/K_g$ *(4-43)* is $e k_g m$ *(4-44)* [22].

The Zweifel and Lasker re-parameterization function shows the cumulative size, therefore the temporal derivative of the market size is the new adopters:

$$\frac{dW}{dt} = W_0 k_g m e^{m(1-e^{-k_g t})-k_g t} \tag{4-45}$$

Figure 4-4 shows the form of the curve for the case $W_o = 1,2,3$, $k_g = 1$, $m = 1$; The new adopters per period, $\frac{dW(t)}{dt}$ *(4-46)*, are also plotted for various values of the cumulative adoption. As is possible to observe, W_0 acts as a shape parameter, changing the upper asymptote.

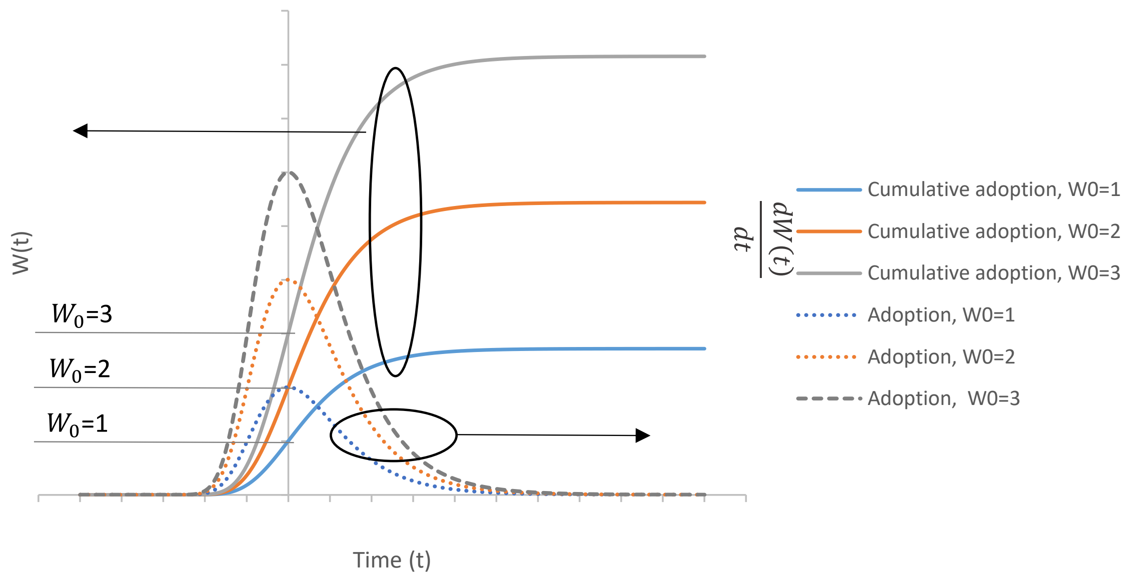

Figure 4-4 - Zweifel and Lasker re-parameterization

4.1.2.4 The Gompertz-Laird (type IIb)

Proposed by Laird in 1964 [25], with the notation of Aggrey [30], the Gompertz-Laird model becomes:

$$W(t) = W_0 e^{\left(\left(\frac{L}{K}\right)(1-e^{-Kt})\right)} \quad (4\text{-}47)$$

Where W_0 acts as a shape parameter comparable to the one in Zweifel and Lasker re-parameterization, but the other parameters are not.

This model is again unusual in that the W_0 parameter not only changes the interception with the x-axis (the initial adoption of equipment at $t = 0$) by repositioning the curve horizontally but rescales the x-axis so that all values increase or decrease proportionally [22].

In [30] the L parameter is the "*instantaneous growth rate*", K parameter "*is the rate of exponential decay of the initial specific growth rate, L (which measures the rate of decline in the growth rate)*". The L parameter affects the upper asymptote and the inflection time in addition to the growth rate ($W_0 L$).

The K parameter affects both maximum growth and the upper asymptote, however, it does not affect inflection time, nor the initial growth rate, as so, it influences how fast the growth curve levels towards its asymptote. Thus K parameter also affects the time of inflection, maximum relative growth rate, and upper asymptote.

L and K both affect maximum relative growth rate and time of inflection, whereas all three parameters, L, K, and W, together with control the upper asymptote [22], makes this curve interesting in our study due to the proprieties of the shaping parameters and the different characteristics presented by the Zweifel and Lasker re-parameterization.

The parameters derived for the inflection point, t_i; the W at the inflection point; and the asymptotic, W_A, are [30] :

$$t_i = \left(\frac{1}{K}\right) \ln \left(\frac{L}{K}\right) \quad (4\text{-}48)$$

$$W_i = W_0 e^{\left(\left(\frac{L}{K}\right)^{-1}\right)} \quad (4\text{-}49)$$

$$W_A = W_0 e^{\left(\frac{L}{K}\right)} \quad (4\text{-}50)$$

The temporal derivative of the Gompertz-Laird is the new adopters, of major interest on our study, and is given by:

$$\frac{dW}{dt} = LKe^{\frac{L(1-e^{-Kt})}{K} - Kt} \quad (4\text{-}51)$$

4.1.2.5 Norton´s re-parametrization (type IIa)

A re-parametrization where a single parameter controls the starting value for the curve is used, suggested by Norton [26] but in a simpler version proposed by Rogers [31].

Norton´s Gompertz equation is then presented as:

$$W\,(t) = W_0 e^{\ln\left(\frac{A}{W_0}\right)(1-e^{-k_g t})} \quad (4\text{-}52)$$

where the A corresponds to the final market potential, W_0 is the initial number of adopters for the definition of the origin of time, and parameter k_g is the rate of decrease in the initially exponential growth.

The traditional cumulative Gompertz (type I) (the T_i form) and Norton´s re-parametrization (W_o form) are complementary models because they together provide parameter values for four easily interpretable parameters, each controlling only one shape characteristic, this is, W_o controls the intersection with the x-axis (starting point), T_i controls the time at inflection (age time at maximum growth rate), k_g the slope at infection (maximum growth rate) and A the upper asymptote. By using the two models with the same constants to data they return values for the four parameters, W_o, k_g, T_i and A. The complementarity between the two models led us to include this model in our study.

For the initial stage, corresponding to small times, Norton´s re-parameterization reduces to an initial exponential growth $W = W_0 e^{u_0 t}$ *(4-53)* with rate:

$$u_0 = k_g \ln\left(\frac{A}{W_0}\right) \quad (4\text{-}54)$$

After a characteristic time, the growth begins to curve till the asymptotic final value given by the saturation parameter A.

The inflection time occurs at $t = \ln\,(\ln\,(A/W_0)/K_g$ *(4-55)*.

The exponential rate u_0 provides us with the relation between the parameter A and k_g. Therefore, we can also show the Gompertz model as a function of the parameter u_0 as:

$$W\,(t) = W_0 e^{\frac{u_0}{k_g}(1-e^{-k_g t})} \tag{4-56}$$

which is completely equivalent to Norton´s re-parametrization, however without the introduction of the final market potential, A.

The Gompertz function can be understood as the solution of the next couple of ordinary differential equations:

$$\frac{dW}{dt} = uW \tag{4-57}$$

which corresponds to exponential growth with a growth rate that is not constant but depends on time, it decreases exponentially with time:

$$\frac{du}{dt} = -k_g u \tag{4-58}$$

with a decreased rate k_g. The initial value of $u(t=0) = u_0$ *(4-59)* determines the initial exponential growth of W. However, the continuous decrease of the growing rate u permits the lost of the exponential growth till a complete saturation when u is close to zero.

The new adopters on Norton´s model is given by:

$$\frac{dW}{dt} = Ak_g ln\left(\frac{A}{W_0}\right)e^{-ln\left(\frac{A}{W_0}\right)e^{-k_g t}-k_g t} \tag{4-60}$$

This model has different parameters from the previous model, Laird´s and has the same growth rate coefficient and same starting point as Zweifel and Lasker re-parameterization.

4.1.3 Bi-S growth curve models – modeling uncertainties

Logistics and Gompertz curves, as previously discussed, are S-shaped because they are monotonous and present an inflection point where the curve change from concave to convex.

Growth curves are the solution to certain ordinary differential equations. In this sense, the associated models are deterministic and do not take into account the fluctuations or disturbances that might exist in the market under consideration. These disturbances can come from multiple factors, which are not always quantifiable or may even be unknown [32], this is, the emergence of new technology, incremental innovation, a financial crisis, or even pandemics. For this reason, in recent decades the aim of model formulation has been focused on modeling both the trend of growth processes and random environmental effects. The behavior of many dynamic real phenomena shows different phases, with each one following a sigmoidal type pattern. This requires studying sigmoidal curves with more than one inflection point.[33]

Assuming that double S-curves result from two consecutive growth processes, these can be obtained by the sum of two simple growth functions.

It is clear, that in general, the sum, or the average, of several Gompertz curves will not be a Gompertz curve, but it will be true that the sum of several Gompertz curves will often add to give something very close to a Gompertz curve [13].

4.1.3.1 The Bi-Logistic curve

A Bi-logistic model is presented for the analysis of a system that experiences two phases of logistic growth. This system with two logistic growth pulses, existing simultaneously or in succession, it's named —Bi-logistical by Meyer P. in [34].

In the case of a system with two well-defined Logistic growth curves, it is possible to split the time-series data set in two and model each set with a separate Logistic function. This method is restricted because it is frequently unclear exactly where to split the data. Rare cases appear where one process ends entirely before the second begins. Problems arise in assigning values from the "overlap" period to the first or second curve.

If we assume that double S curves are the result of two consecutive but overlapping growth processes, then the curves can be approximated as the sum of two Logistic growth curves, this is:

$$W(t) = \frac{A}{1 + e^{-K_g(t-T_i)}} + \frac{A_1}{1 + e^{-K_{g1}(t-T_{i1})}} \tag{4-61}$$

where A and A_1 are the upper asymptotes of each curve, K_g is the growth rate of the first curve and K_{g1} of the second curve. T_i and $T_{i1}$are the time of inflection for the first and second curves respectively. $0{,}1A$, $0{,}5A$ and $0{,}9A$ are break points of four stages, emergence, growth, maturity, and recession. The time to grow from 10% to 90% is given by:

$$\Delta t = \frac{1}{K_g} ln81 \tag{4-62}$$

And

$$\Delta t_1 = \frac{1}{K_{g1}} ln81 \tag{4-63}$$

for each curve respectively.

We can examine system-level behavior, or we can decompose it and examine the behavior of the discrete components, moreover, we can compare the two curves by normalizing them with Fisher-Pry transform.

The simple deconvolution can be defined as [34]:

$$W_{0i}(t) = W_i - \frac{A_1}{1 + e^{-K_{g1}(t-T_{i1})}} \tag{4-64}$$

$$W_{1i}(t) = W_i - \frac{A}{1 + e^{-K_g(t-T_i)}} \tag{4-65}$$

Where $W_{0i}(t)$ and $W_{1i}(t)$ are the component growth variables. The two data sets can be plotted linearly by using the Fisher-Pry transform. The linear form of the bi-logistic makes easier the morphological analysis and comparison of the two processes.

Perrin S. Meyer in [34], [35] described the taxonomy of bi-logistic curves. For the Bi-Gompertz and taking into account the similarities between both curves, this taxonomy is also valid. (Further information about the taxonomy can be found in Appendix C - Taxonomy of Bi-Logistic)

The temporal derivative of the Bi-Logistic is the rate of growth, this is, new adopters, this is particularly relevant to our analysis because we want to model the several oscillations of the annual markets. Differentiating we have:

$$\frac{dW(t)}{dt} = \frac{AK_g e^{-K_g(t-T_i)}}{(e^{-K_g(t-T_i)} + 1)^2} + \frac{A_1 K_{g1} e^{-K_{g1}(t-T_{i1})}}{(e^{-K_{g1}(t-T_{i1})} + 1)^2} \tag{4-66}$$

4.1.3.2 The Bi-Gompertz curve

In the case of a system with two well-defined Gompertz growth curves, it is possible to split the time-series data set in two and model each set with a separate Gompertz function. This method is restricted because it is frequently unclear exactly where to split the data. Rare cases appear where one process ends entirely before the second begins. Problems arise in assigning values from the “overlap” period to the first or second curve.

Following the same reasoning of *Lowell J.Reed and Raymond Pearl* for the logistic curve [4], [5], and the Bi-logistical from Meyer P. in [34], if the total growth-curve is represented by:

$$W(t) = Ae^{-e^{-K_G(t-Ti)}} \tag{4-67}$$

And the growth curves for the two components of the total are given by:

$$W_0(t) = Ae^{-e^{-K_G(t-Ti)}} \tag{4-68}$$

$$W_1(t) = A_1 e^{-e^{-K_{G1}(t-Ti1)}} \tag{4-69}$$

If we assume that double S curves are the result of two consecutive but overlapping growth processes, then the curves can be approximated by the sum of two Gompertz growth curves, this is:

$$W(t) = Ae^{-e^{-K_G(t-Ti)}} + A_1e^{-e^{-K_{G1}(t-Ti1)}} \tag{4-70}$$

where $A + A_1$ *(4-71)* is the upper asymptote, K_G and K_{G1} are the growth rate coefficients and Ti and T_{i1} represents the times of inflections.

As for the Bi-Logistic, for the Bi-Gompertz we can examine system-level behavior, or we can decompose it and examine the behavior of the discrete components, moreover, we can compare the two curves by normalizing them with Fisher-Pry transform.

The simple deconvolution can be defined as:

$$W_{0i}(t) = W_i - A_1e^{-e^{-K_{G1}(t-Ti1)}} \tag{4-72}$$

$$W_{1i}(t) = W_i - Ae^{-e^{-K_G(t-Ti)}} \tag{4-73}$$

where $W_{0i}(t)$ and $W_{1i}(t)$ are the component growth variables. The two data sets can be plotted "linearly" by using the Fisher-Pry transform. The linear form of the Bi-Gompertz makes easier the morphological analysis and comparison of the two processes.

The rates of change of the component Gompertz provide clues to the mechanisms propelling the composite Gompertz. Analyzing the rates of change is often useful when yearly tabulations are applicable, as in the case of market data.

Taking into account the previous equation, the instantaneous growth of the Bi-Gompertz is given by its derivative for time:

$$\frac{dW}{dt} = AK_Ge^{-e^{-K_G(t-T_i)}-K_G(t-T_i)} + A_1K_{G1}e^{-e^{-K_{G1}(t-T_{i1})}-K_{G1}(t-T_{i1})} \tag{4-74}$$

4.1.4 The Multi-Gompertz and Multi-Logistic curves

Following the same reasoning presented by Meyer in [35] where growth is the sum of n simple logistics, in our case, n simple Gompertz, the generalization of the Bi-Gompertz and Bi-Logistic model to a multi-Gompertz and a multi-Logistic is:

$$W(t) = \sum_{i=0}^{n} W_i(t) \tag{4-75}$$

where,

$$W_i(t) = A_ie^{-e^{-K_{Gi}(t-Tii)}} \tag{4-76}$$

for the Gompertz model, and:

$$W_i(t) = \frac{A_i}{1 + e^{-K_{gi}(t-T_{ii})}} \tag{4-77}$$

for the Logistic model, respectively.

If we want to fit a Gompertz or Logistic curve of n components to a model, then it will require 3 n parameters, that could be represented by a matrix $n \times 3$ as the one presented below, where the ith row describes the ith components:

$$M = \begin{matrix} A_0 & k_{g0} & T_{i0} \\ \dots & \dots & \dots \\ A_n & k_{gn} & T_{in} \end{matrix} \tag{4-78}$$

As for the Bi-Gompertz and Bi-Logistic, we can decompose it and examine the behavior of the discrete components, moreover, we can compare the n curves by normalizing them with Fisher-Pry transform:

$$FP_i(t) = \left(\frac{F_i(t)}{1 - F_i(t)}\right), \text{where } F_i(t) = \frac{W_i(t)}{A_i} \tag{4-79}$$

Taking into account the previous equations, the instantaneous growth of the Multi-Gompertz is given by its derivative to time:

$$\frac{dW}{dt} = \sum_{i=0}^{n} \frac{dW_i}{dt} = AK_G e^{-e^{-K_G(t-T_i)} - K_G(t-T_i)} + A_i K_{Gi} e^{-e^{-K_{Gi}(t-T_{ii})} - K_{Gi}(t-T_{ii})} \tag{4-80}$$

For the multi-logistic:

$$\frac{dW(t)}{dt} = \sum_{i=1}^{n} \frac{dW_i}{dt} = \frac{AK_g e^{-K_g(t-T_i)}}{(e^{-K_g(t-T_i)} + 1)^2} + \frac{A_i K_{g1} e^{-K_{gi}(t-T_{ii})}}{(e^{-K_{gi}(t-T_{ii})} + 1)^2} \tag{4-81}$$

4.2 Research Methodology

The methodology followed in our research, has three major components, Figure 4-5: the diffusion and rate of growth analysis of GPON technologies (Chapter 5), the analysis of uncertainties on the diffusion and the rate of growth (Chapter 6), and the forecast of NG-PON equipment´s in EMEA, North America and Globally (Chapter 7).

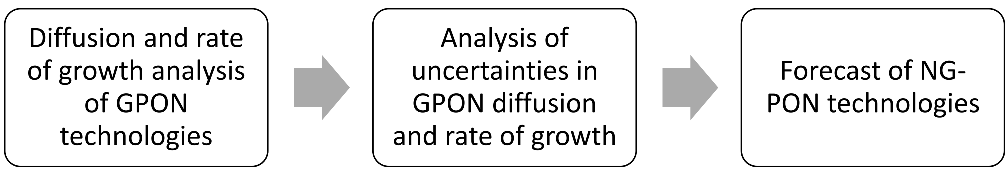

Figure 4-5 – Research methodology.

The summary of the steps for the first major component is summarized in Figure 4-6.

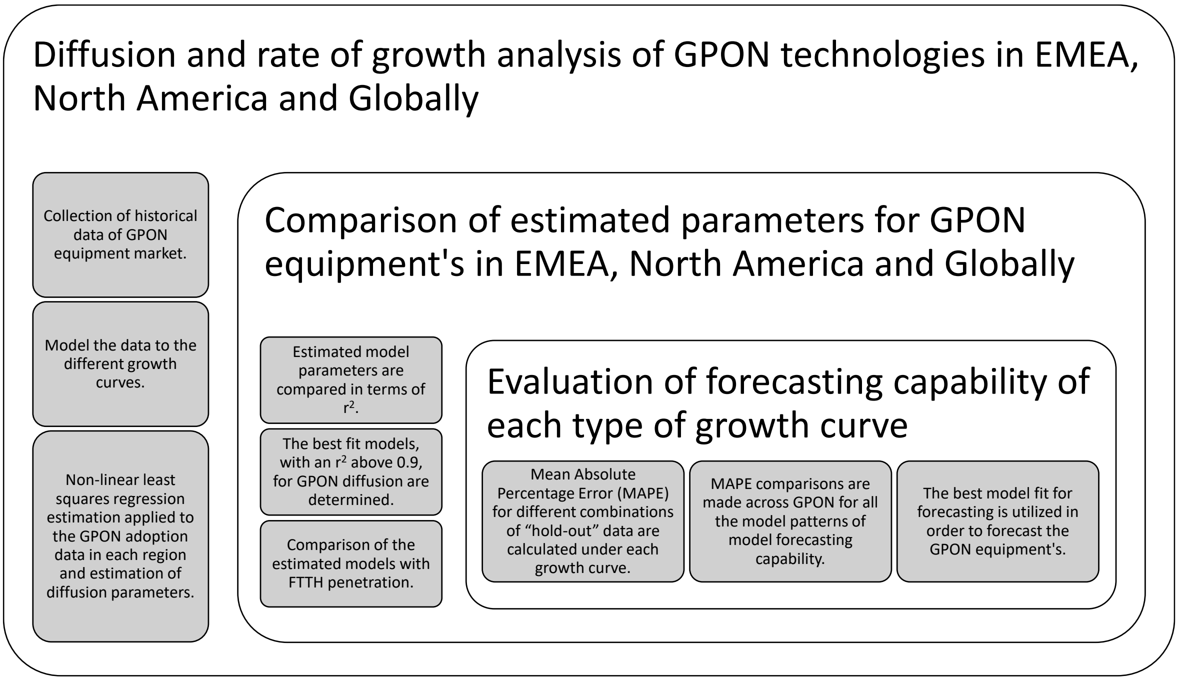

Figure 4-6 – Summary of steps in the analysis for the first component.

The yearly adoption of PON technologies is collected for the three regions, to begin with. OMDIA market share 2Q20 for PON, DSL, GFast, and CMTSC and CAP [36] presents the worldwide fixed broadband access equipment market from 2008 till the second quarter of 2020.

The global optical access components market is divided into the following four regions:

- North America (NA);
- Europe, Middle East, and Africa (EMEA);
    - Asia-Pacific (AP): China, Rest of Asia-Pacific (RoAP);
- Caribbean & Latin America (Cala).

The regional definitions can be found in Appendix B Regional Definitions.

Total ONT/ONU and OLT market share is constituted by 2.5G GPON, 1G EPON, XG-PON1 & XGS-PON, NG-PON2, and 10G EPON. In our study, we will only focus on ITU-T technologies, namely GPON, XGS-PON, and NG-PON2.

For the diffusion and rate of growth analysis of GPON technologies in these regions, we utilize the previously presented growth models, namely, Logistics, Gompertz, Zwietering, Zweifel and Lasker, Gompertz-Laird, and Norton. Since the chosen models are non-linear, we perform a non-linear–least squares regression (NLS) based on sequential quadratic programming. It consists of finding a nonlinear model of the relationship between the dependent variable and a set of independent variables. Unlike traditional linear regression, which is restricted to estimating linear models, nonlinear regression can estimate models with arbitrary relationships between independent and dependent variables.

The modeling of the different Gompertz equations to data was done using IBM SPPS Statistics version 26 with an estimation method based on sequential quadratic programming.

Some considerations on the different simulations have been taken into account, due to the nonlinear regression problems often presented in computational difficulties:

- The choice of initial values for the parameters influences convergence, as so, reasonable initial values were considered, closed to the expected final solution:
  - Growth rates, inflection times, the maximum level of technology use, and number of adopters are always positive;
  - the maximum level of technology use bigger than presented data at the end of 2019;
  - W_0 (Initial number of adopters) equal or smaller than the one presented in available data in 2008.
- When iteration stops only because the maximum number of iterations has occurred (999 iterations), the "final" model is probably not a good solution, as so, the selection of use starting values from the previous analysis was performed to continue the iteration.
- Models that require exponentiation due to large data values [37] can cause overflows or underflows (numbers too large or too small for the computer to represent), as so, this was avoided by suitable choice of initial values and by imposing constraints on the parameters.

Regarding parameter uncertainty, the saturation level is the parameter that is the most sensitive to changes in the data. Subsequently, we are not presenting statistical measures of the performance of fit for the results obtained with the different models. Sensitivity analyses with different models and estimation algorithms have been performed throughout the study and only the results with the best statistical fit are given.

From the empirical results presented in the different analyses performed, we will only accept fits of models that are quite satisfactory, this is models with an *r square* above 0,9, indicating that at least 90% of the variance of the dependent variable are explained by variance of the independent variable.

When dealing with growth models, where the saturation level of the market is not known *a priori*, statistical uncertainty in the parameter estimates can be substantial.

As stated by Arnulf Griibler[3] :

"In principle, the minimization algorithms used provide the matrix of the second derivatives, and therefore allow the determination of the standard deviations of the values of the parameters and the corresponding confidence levels. However, this method of determining the confidence levels is not suitable, since it assumes that the errors in the parameters are normally distributed and, in addition, that they are uncorrelated. There is no compelling reason why such a restrictive assumption is warranted and as demonstrated by Debecker and Modis, 1986, there is in fact evidence that these standard statistical assumptions do not hold for estimating parameters of S-shaped growth curves."

Debecker & Modis [38] conclude for a given length of historical data and data estimation error that uncertainties are higher in the asymptote parameter than for the rate parameter and so also Δt. Uncertainties in estimated saturation level increase quickly for data series that have not passed the inflection point, this, has not reached less than 50% of saturation. This is instinctively understandable as the logistic function at this stage is indistinguishable from an exponential function. As an example, a logistic model fitted to data points with 5% estimation errors covering 1-60% of the asymptote has parameter uncertainties of ±7.9% (asymptote), ±3.2% (rate), and ±0.15% (inflection point), all with 95% confidence intervals. [39].

As Arnulf Griibler [38] stated, and from the research in the bibliography, for other growth curves, no similar information is available and no information was found. Uncertainty estimates for the estimated parameters will not be presented.

The estimated diffusion and rate of growth model parameters from the previous step are compared with each other in terms of their capacity to explain the diffusion of GPON in terms of growth and concerning their changes over time. We chose the *r square* as the indicator measuring model robustness and fit. The specific implications on the behavioral dynamics behind the adoption of the innovation under examination and its characteristics, such as speed of diffusion, time to grow from 10% to 90% are explained, therefrom.

To verify the consistency of the modeling, a comparison with past and future FTTH/B subscribers was performed for the European and North American markets. Based on an FTTH Council Europe report from September 2019 [40] was possible to have historical data and a growing trend for EU28 countries and EU39 countries (EU39 = EU28 (excl. Cyprus) plus 4 CIS countries, Russia, Kazakhstan, Belarus, and Ukraine plus Andorra, Iceland, Israel, North Macedonia, Norway, Serbia, Switzerland, Turkey), from 2012 till the end of 2019 for FTTH/B subscribers and FTTH/B Homes passed. FTTH Council Middle East and North Africa (MENA), also provides a report in September 2019 [41] with the historical data and growing trend of FTTH/B subscribers and FTTH/B Homes passed from 2012 till the end of 2019.

FTTH Council Europe-2020 presented the FTTH forecast for Europe, 2020-2026 [42], where is presented the forecast for FTTH/B homes passed and FTTH/B subscribers for EU 38+UK.

For the NA market, was only possible to obtain data for the FTTH/B Homes passed for the United States of America [43]. For the FTTH/B subscribers, was available the data for the United States of America from Fiber Broadband Association [43] and total fixed broadband subscription and forecast from OMDIA [44].

The model best-fit to the historical data does not need necessarily be the model with the better forecasting capability, as so, we evaluate the forecasting capability of each model, by comparing the forecasted values under a given time horizon with the know samples from historical data (known as the hold-back data) for the same horizon. We calculate the Mean Absolute Percentage Error (MAPE) indicator, which is used as the measure of forecasting performance [45]. MAPE is calculated as shown below:

$$\text{MAPE} = \frac{100}{n} \sum_{i=1}^{n} \frac{|x_i - W(t)|}{W(t)} \qquad (4\text{-}82)$$

where x_i is the actual value at time t, $W(t)$ is the forecasted value at time t, and n is the number of observations. MAPE is the average of the absolute percentage errors of the forecast. These measurements depend on the residuals, showing the deviation between the real data and the forecasted data. The smaller the MAPE the better the forecast [46]. The best fit model according to the MAPE criterion is chosen for forecasting the GPON technologies in the different regions.

The second major component of the research methodology, this is, the analysis of uncertainties in GPON diffusion and rate of growth is presented in Figure 4-7.

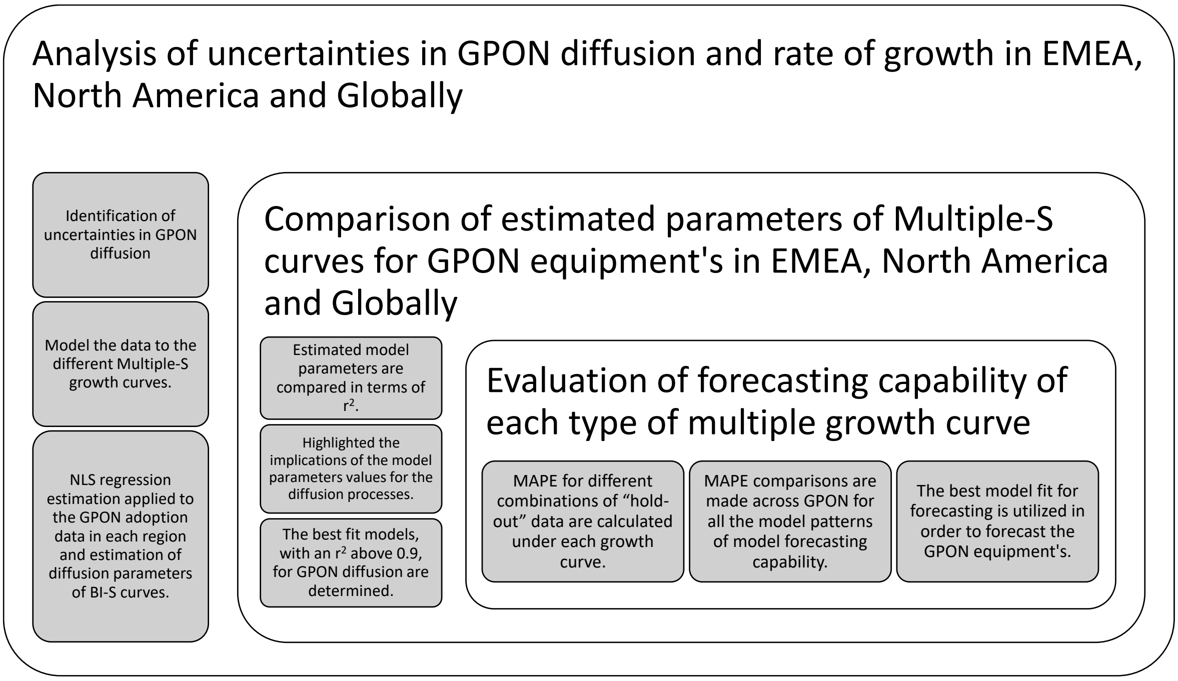

Figure 4-7 - Summary of steps in the analysis for the second component of research methodology.

Here, the main uncertainties related to investment in PON technologies are identified. A Bi-S curve model, based on Logistics and Gompertz is proposed to model the uncertainties of the PON adoption and diffusion. As in the first component of the research methodology, an NLS regression is performed based on the Bi-S curves to the data and the estimated diffusion and rate of growth model parameters are compared with each other in terms of their capacity to explain the diffusion of GPON in terms of growth, and in relations of their changing over time. As before, we chose the *r square* as the indicator measuring model robustness and fit. A model based on Multi-Gompertz and Multi-Logistic is also proposed and its fit and robustness are analyzed.

The best fit model according to the MAPE criterion is chosen for forecasting the GPON technologies in the different regions taking into account the market uncertainties.

The forecast of NG-PON technologies follows the research methodology summarized in Figure 4-8.

As for the ONU and OLT GPON diffusion, for the next generation market study, we will also focus on the global analysis, NA, and EMEA. The regional definitions can be found in Appendix B - Regional Definitions and the NG-PON equipment adoption for ONT/ONU – XG(S)-PON and NG-PON2 for Global level, EMEA and NA from OMDIA market share 2Q20 for PON [36] in Appendix D- XG(S)-PON market share.

For the diffusion and rate of growth analysis of NG-PON technologies in these regions, we utilize the Logistics and Gompertz growth models and perform an NLS. Since the data available for the NG-PON technologies is limited and to perform a longer forecast to the NG-PON2 technologies, Bi-S curves were applied considering the diffusion and adoption of GPON, this is, different forecast scenarios were defined by using the historical behavior of GPON adoption. A simple logistic substitution model was also applied for comparison proposes.

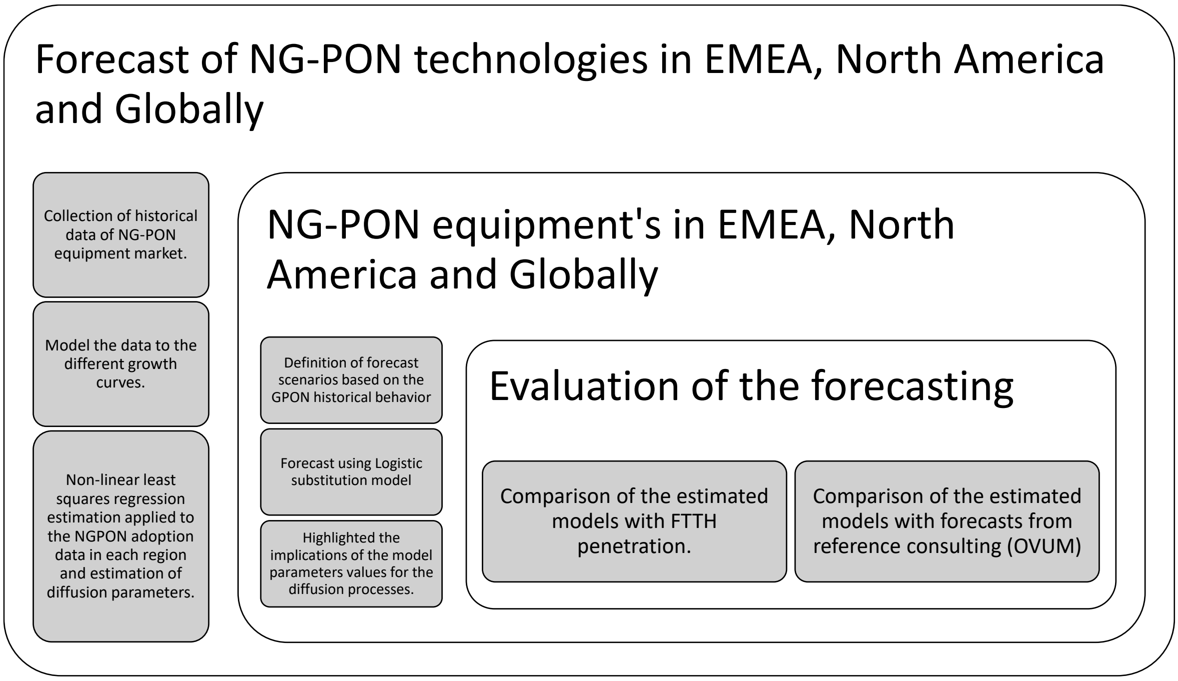

Figure 4-8- Summary of steps in the analysis for the third component of research methodology.

For the case of market substitution models, where no technology can exceed 100% market share, parameter uncertainty is not considered a major problem [3]. We will rely on *r square* or leave the judgment to the human eye to assess how well a model performs in mapping the empirical data.

To evaluate the forecast models for NG-PON, a comparison is done with the FTTH penetration and with a reference forecast, the wireline broadband access equipment forecast from Ovum, March 2019 (pre-pandemic)[47] and the forecast from OMDIA 2019-2025, July 2020 [48].

4.3 Factors influencing and shaping the evolutionary processes

Figure 4-9 created by Nicholas Felton of the New York Times shows how long several categories of products take to achieve different penetration levels in the United States.

From the analysis of the graph, we can find empirical regularities on the diffusion process. First, technology diffusion is a long process spanning several decades. Between the first use of the technology and the moment when it reaches a large part of the potential market (say 90%), it can take anywhere from 5 to 50 years, or even longer. In general, the broadcast has become faster recently. However, we can identify different groups in the set of innovations presented in the graphic above. For example, technologies needing the implementation of dedicated infrastructure (electricity, car, telephone, radio) normally took longer to broadcast.

A common characteristic of almost all of the technologies presented in Figure 4-9 is the form of diffusion. When the evolution over time of the penetration of technology on the market is represented graphically, the result is a logistic diffusion curve in S. This curve illustrates the low initial diffusion rates followed by a more sustained growth rate until at the inflection point from which the growth rate slows again.

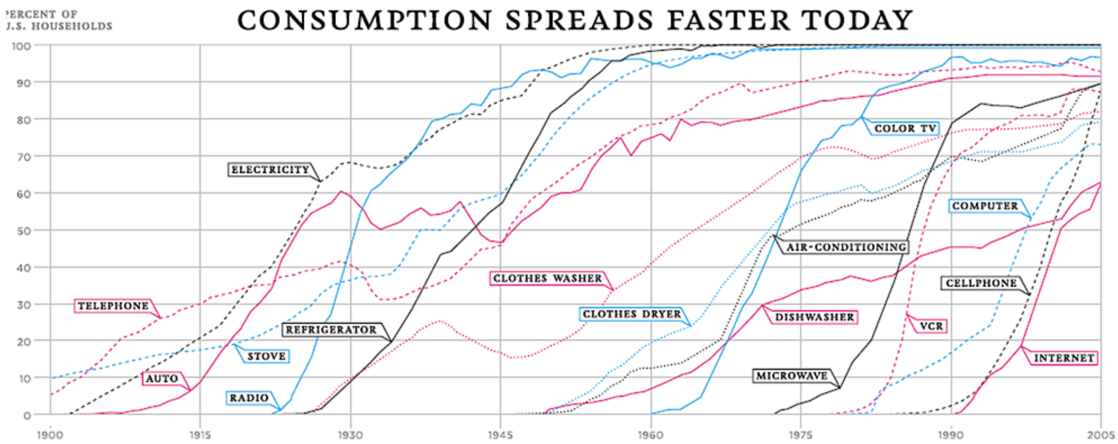

Figure 4-9 – Penetration levels of different products in the United States.

The characteristics of technologies tend to change during the diffusion process. As technology reaches maturity, it is usually accompanied by improved performance and lower prices.

Technology users also have different characteristics throughout the diffusion process. Rogers [49] analyzed the different groups of people that make up the potential market for innovation. The author identifies several groups of consumers with different attitudes, whose delayed entry into the market would explain the stylized behavior of spreading.

In his work on the diffusion of innovation, Rogers [49] offers an analysis of the social factors underlying the adoption of new technology. This approach emphasizes the information dissemination process and the attitude of different individuals towards innovation.

The dissemination mechanism is based on the contagion and the processing of information by each agent. The adoption (or rejection) of innovation is the result of a decision-making process consisting of several stages: 1) becoming aware of the innovation; 2) the formation of an attitude towards innovation; 3) the adoption (or rejection) decision; 4) the implementation of innovation, and 5) confirmation of the decision.

The author also proposed a categorization of the population likely to be interested in a certain innovation. Agents are classified according to their willingness to adopt the innovation which depends on the perception of the technological advantage, its compatibility with existing technologies, its complexity, the possibility of experimentation, and its visibility. Rogers distinguishes five groups of potential consumers:

- Innovators are the primary users of innovation. They are attracted by technological innovations ("technology enthusiasts"). Precursors are typically richer and willing to take the risk of innovation. By their adoption, they influence the choice of the following consumers;
- Early adopters closely follow the decisions of innovators. It is a normally younger and educated group that seeks to stay one step ahead of the rest of the population. This type of consumer is at the beginning of the diffusion wave, and they normally have an active role in persuading their neighbors;

- The precocious majority form a more conservative group of consumers who are still open to new ideas. This group is influenced by the adoption of a growing number of people;
- A late majority are a risk-averse group. He does not buy the innovation before it is used by a wider base of people to be reassured about the quality of the technology;
- The laggards are the last to use innovation. They are typically not interested in the latest news.

Based on sociological studies, Rogers [49] concluded that the population of potential consumers of innovation is normally divided between the different categories analyzed. The author uses standard deviations from the mean of the normal distribution curve to distribute the population between innovators (2.5%), early adopters (13.5%), early majority (34%), late majority (34%), and latecomers (16%).

"The adoption of an innovation follows a bell-shaped curve when plotted over time on a frequency basis. If the cumulative number of adopters is plotted, the result is an S-shaped curve." [49], Figure 4-10.

Thus, innovation begins to diffuse slowly at the start of the period and the pace accelerates as the early and late majority adopt the technology until only the laggards remain to buy technology.

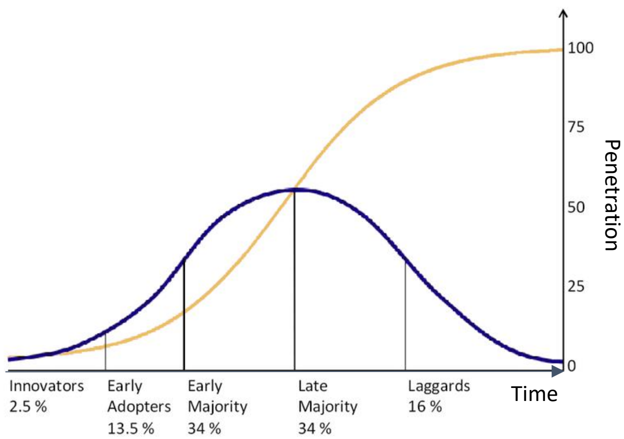

Figure 4-10 – The diffusion curve. [49]

Technical change is a dynamic process. The increasing adoption of technology is improving performance and reducing costs. For evolutionary authors, an analysis of the factors that determine the evolution of technology is essential to understand the result.

Without a clear forecast of the future, it is impossible to predict the result of technological competition with certainty because it depends on the path of diffusion [50]. This path dependence gradually limits the choices available, which ultimately leads to a market lock on the dominant technology ('lock in') [51].

The evolutionary representation considers that competition between technologies is affected by dynamic factors likely to lock the market by inferior technology [50]. There are multiple equilibria and not a single equilibrium towards which the system converges. The result is therefore unpredictable in the sense that we cannot predict exactly the market share of each technology.

This is particularly the case when the diffusion of technology contributes to reinforcing its attractiveness (cost, performance, quality, etc.). Increasing returns to adoption are positive externalities generated by the adoption of technology that increase the likelihood of adoption as it spreads [51], for instance, the more a technology is adopted the more will be improved and be productive. Several factors contribute to the existence of such positive feedback. Arthur [52] identifies five sources of increasing returns adoption returns:

- **Learning by using**: technology becomes more efficient with adoption and especially with use, which makes it more attractive to non-users;
- **Network externalities**: technology becomes more attractive as the number of users increases [53]. Typical examples are the telephone or the Internet, the arrival of new members of the network increasing the communication possibilities of all users (apart from the congestion effects which appear later on from a certain size);
- **Scale economies in production (increasing yield in production)**: the increase in the volume of production can allow a reduction in unit costs, as well as the accumulation of experience which reduces more costs[54] ;
- **Informational increasing returns**: the growing adoption of new technology increases general knowledge about this technology, which reduces the uncertainties that block diffusion;
- **Technological interrelatedness**: the more the technology is adopted, the more compatible goods are made available to users. It is particularly a question of services and physical supports (infrastructures) auxiliary to consumption. Thus, technologies compatible with infrastructure has more conditions to develop in the market; at the same time, incompatible technologies have to face more barriers.

Technology diffusion is not linear when the probability of technology adoption increases with market share [51].

The emergence of new technologies becomes more difficult in the presence of increasing returns adoption. New technologies that have not been widely used have not yet benefited from adoption externalities, which limits their attractiveness (poor performance, high cost, little known, etc.). In this way, these technologies are at a disadvantage vis-à-vis mature technologies that have already benefited from the positive effects of diffusion.

Epidemic models normally hypothesize that there are potential adopters for a certain technology. These potential adopters are considered constant over time. Likewise, the technology remains unchanged during the broadcast process. The essential mechanism of dissemination is the transmission of information. Diffusion begins with a small number of adopters of the technology. These adopters are in social contact with non-adopter. The increase of adopters over time makes it more likely the transmission of information and through this the accession of a larger number of people. However, as and when the diffusion progresses, the number of potential adopters decreases. The rate of growth in the number of adopters then depends on the relative effect of increasing the likelihood of contact versus decreasing the population of potential adopters. The first effect is stronger initially and the second becomes stronger over time.

However, these technological diffusion models are not unlimited, which derive from the initial assumptions. Thus, the criticisms normally formulated concerning the model are as follows [55][3]:

- the mathematical properties and the adequacy of the application to describe the diffusion process, namely the symmetry of the logistic curve and the fact the model is derived from biology;
- the process of dissemination in epidemic models lies in the transmission of information. The model thus ignores other sources of information such as advertising;
- the adoption does not depend on a rational economic choice but exposure to information;
- the number of potential customers A remains constant throughout the dissemination process and is found exogenously to the model. On one hand, the number of potential customers may change during the process due to a demographic reason (e.g. rising birth rate), or some other factor responsible for the increase in the number of people potentially interested in the technology. On the other hand, there are no explanations to the factors that condition this variable and how to find it;
- the model considers that the users are homogeneous and does not take into account the existence of differences in the population of potential members. For example, the fact that early consumers may be interested in buying the technology faster than the later ones is not captured by the model. The effective probability of contact remains unchanged throughout the diffusion process;
- The technology does not change during the broadcast. The model does not foresee the possibility of improving performance and reducing costs, which is unrealistic (no learning effects).

Mansfield (1968) proposed an extension of the original epidemic models by accounting for the uncertainty during the diffusion process. According to this approach, the level of uncertainty inherent in the adoption of the innovation is the main determinant of the dissemination process and not the mere reception of the information. Uncertainty is measured by the market share of the innovation: the greater the innovation, the more learning by use and by doing, and the less uncertainty there will be in the performance of the innovation.

Geroski [8] further reports the existence of other extensions of the original epidemic model that have been introduced in the literature. Taking into account different subsets in the population of potential users, in particular through the use of decreasing count rates, as well as the increase in the potential market, have generally led to diffusion curves asymmetric.

The models presented in this work are relevant to explaining the behavior of the technology on the market and to overcoming the previous criticisms. The models will show the strength and weaknesses of the application of epidemic models in the diffusion of PON technologies. In response to mathematical properties criticism, several mathematical models are proposed that can accommodate different S-shaped diffusion patterns. The simplification, in an economic context, of the binary nature of the diffusion models regarding the adopting population is justified, as we are mainly interested in the impact of the adoption decision with its resulting economic consequences. The critique regarding the missing multidimensionality of influencing factors, this is, the static nature of the influencing variables, in reality, is not true, since these variables change continuously over time and interact, in our case, PON technologies performance is increased, prices go down and the uncertainties in the application is reduced over time.

4.4 Conclusions

In this methodological chapter, we have presented several mathematical models to describe the growth, from the perspective of the interaction between a system and its environment. These models are at the base of our PON diffusion study, analysis of uncertainties, and forecast of NG-PON technologies. We point out, that the diffusion models are a useful tool for systematization and organization of empirical data to describe the long-term development pattern.

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Chapter 5: Diffusion and rate of growth analysis of GPON technologies

This chapter is addressed the diffusion and rate analysis of GPON equipment, and what is the expected evolution of current GPON technology on the market.

A historical view of the PON market is presented and the current fiber developments and market shares are analyzed. The 2.5G GPON ONU market is modeled to the different growth curves presented in the previous Chapter, namely, Logistics, Gompertz, Zwietering, Zweifel and Lasker, Laird, and Norton´s. The best fit models for GPON diffusion are determined. As the ONU market differs from the OLT market, since OLT market depends on the operator willing to invest, the OLT 2.5G GPON market is also modeled, but only using the models that present the best fit in 2.5G GPON ONU. The relationship between fiber penetration and market shares is analyzed and an evaluation of the forecasting capability of each type of growth curve is realized.

5.1 Fiber Development and Market share

In 2007 the lifecycle of GPON technology was being born, vendors were expecting to see the maturation of technology, including cost optimization, component vendors integrating functions into application-specific circuits. Interoperability was as the technology, in its early stage. GPON was already standardized but was lacking service-oriented standards, FSAN has already looked at and defined security and QoS but transparent LAN or VoIP was undergoing. GPON was pushed by Verizon in North America and in Europe by France-Telecom [1].

A historical view of the FTTH market, Appendix B - PON and FTTH a historical view, is provided to map the uncertainties and market variations observed in the different curves.

Fiber rollout developments around the world play a major role in the optical components market since it boosts the use of optical components for PON applications.

An analysis of the fiber development around the Globe will be presented here to map the PON forecast models with the actual FTTH/B deployment.

“Fiber to the Home” is defined as an access network architecture in which the connection to the subscriber’s premises is optical fiber, “Fiber to the Building” is defined as an access network architecture in which the final connection to the subscriber’s Premises. The fiber optic communications path is terminated within the building to carry communication services for a single building with potentially multiple subscribers.

FTTH/B includes several types of typologies, namely, PTP, P2MP, and ring.

The OMDIA Fiber Development index from October 2020 tracks and benchmarks fiber development across 81 countries, all data used is from December 2019 [2].

628.5 million FTTx subscribers worldwide were identified in December 2019. The different types of FTTx will be presented, namely, the FTTH penetration (FTTH subscription household penetration), the FTTB penetration (the FTTB subscription against total enterprise connections), the FTTH population coverage (percentage of households that ate covered by FTTH), and the FTTS fiber penetration (percentage of total mobile cell sites that are fiber covered).

Figure 5-1 presents the FTTH penetration (%), for the countries that have more than 20% of take-up of FTTH services. NA cluster, Canada and USA, do not appear on the graphic since their FTTH percentage is 16% and 13% respectively, showing that such a big market has a trend to expand and take benefit of the already installed fiber.

Regarding the EU39 countries (EU39 = EU28 (Appendix B - Regional Definitions) plus 4 CIS countries, Russia, Kazakhstan, Belarus and Ukraine plus Andorra, Iceland, Israel, North Macedonia, Norway, Serbia, Switzerland, Turkey), is possible to identify 18 countries that present already a very significant FTTH penetration.

Regarding the African market, Qatar, UAE, and Bahrain, all present an FTTH penetration superior to 40%.

At the Global level, Singapore is the leader country.

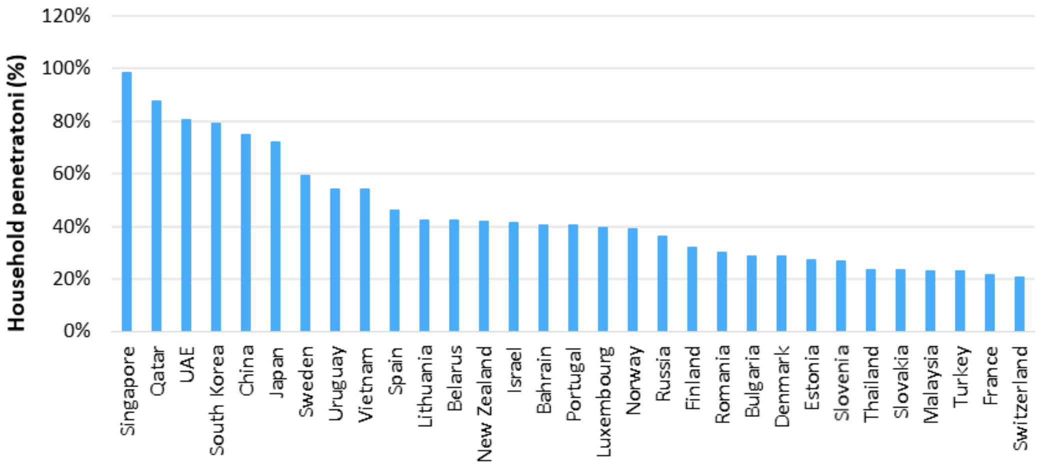

Figure 5-1 – FTTH penetration for the countries with more than 20% of take-up [2].

As takeaways, countries like Austria, the UK, Germany, and Belgium appear currently with less than 20% of FTTH coverage, which means low current potential for FTTH connections, meaning that only a small selection of households and businesses have access to the benefits of the fiber networks. These countries will benefit from the installation of FTTH, as so, they have a big potential to grow in terms of PON equipment in coming years as they increase their FTTH networks and population coverage. US and Canada present an FTTH/B population coverage of more than 40% and 35% respectively, but their FTTH/B subscription household penetration is low.

Asia market together with Qatar and UAE presents the higher FTTH population coverage. Spain, Norway, and Portugal are the leaders for European countries with more population coverage by FTTH.

Figure 5-2 presents the FTTB penetration that represents the current take-up of FTTB services. China, Russia, and Thailand are the countries that have a higher number of businesses that are taking advantage of FTTB services.

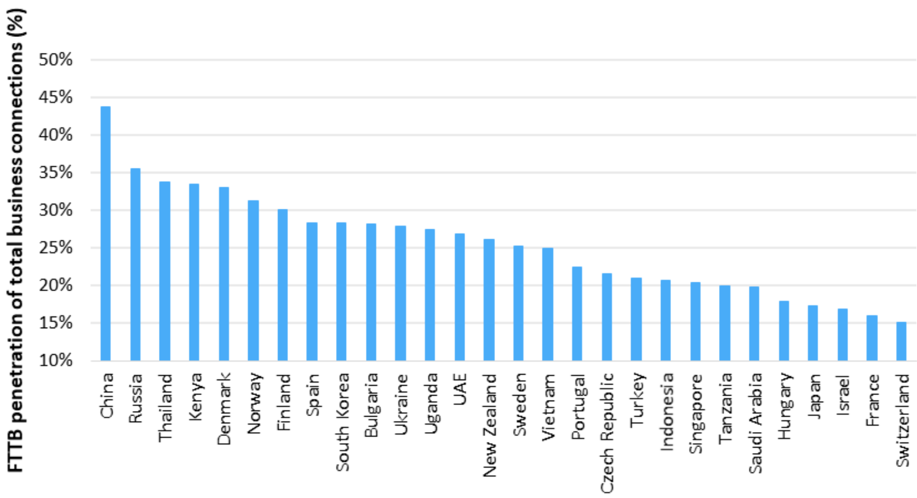

Figure 5-2- FTTB penetration [2].

Another important metric on this analysis is the FTTS fiber penetration, this is the percentage of total mobile sites that are fiber-connected. Mobile cell sites need high-speed backhaul capabilities. A high FTTS penetration will therefore signal a more optimized mobile data network, as fiber is today the only medium able to guarantee the high-speed necessities for mobile services. For 5G cell sites, high-speed fiber connections are mandatory and in countries that present today high FTTS penetration can speed up the 5G can have a major role.

Figure 5-3 are presented the countries with greater than 40% of FTTS penetration.

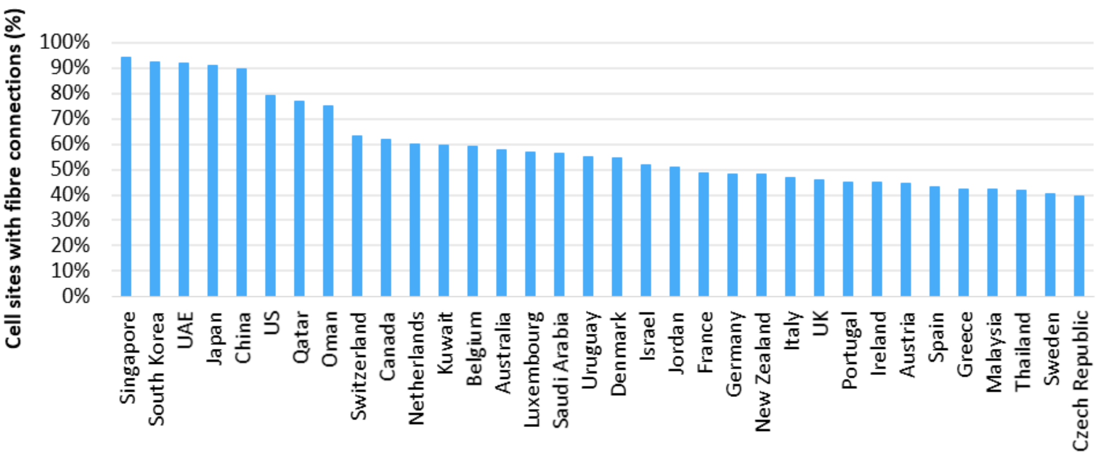

Figure 5-3 – FTTS fiber penetration for the countries with more than 40% of penetration [2].

FTTH, FTTB, and FTTS are directly related to the quantity of equipment installed, as more fiber connections exist, more equipment will be needed.

OMDIA market share 2Q20 for PON, DSL, GFast, and CMTSC and CAP [3] presents the worldwide fixed broadband access equipment market from 2008 till the second quarter of 2020.

Total ONT/ONU and OLT market share is constituted by 2.5G GPON, 1G EPON, XG-PON1 & XGS-PON, NG-PON2, and 10G EPON. In our study, we will only focus on ITU-T technologies, namely GPON, XGS-PON, and NG-PON2.

As regards the global equipment market share, Figure 5-4, is possible to observe that EPON ONU is losing market share for 2.5G GPON since 2008. The 2.5 GPON ONUs have currently a market share of more than 75%. New PON technologies, as 10GEPON and XG(S)-PON started to appear in the market in the year 2011 and 2015 respectively, and therefore with a very low market share globally. 10GEPON raising from 0,01% in 2011 to 0,14% in 2019 and XGS-PON from 0,01% in 2016 to 0,06% in 2019. NG-PON2 started to appear in the market in 2018 and the global market share in 2019 is 0,001%.

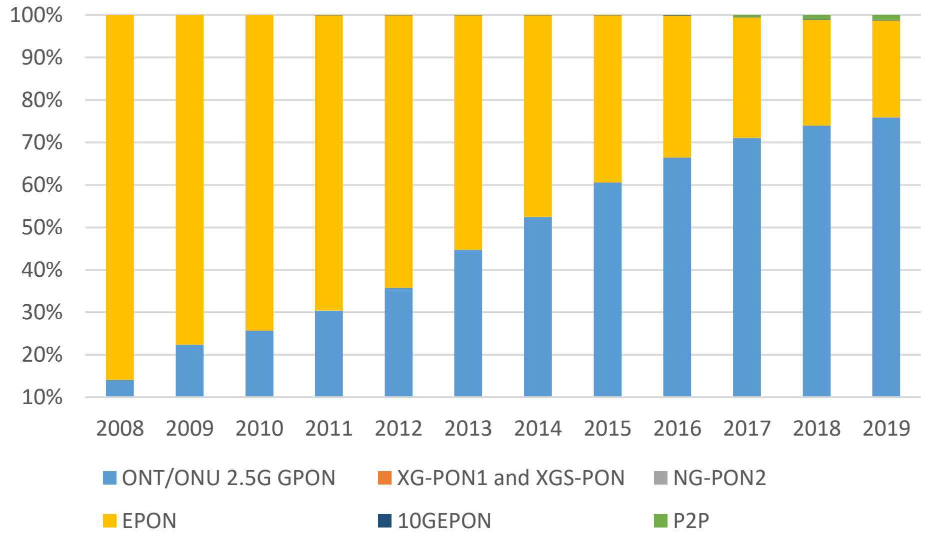

Figure 5-4- Global equipment market share, 10GEPON – from 0,01% in 2011 to 0,14% in 2019, XGS-PON from 0,01% in 2016 to 0,06% in 2019. The global market share of NG-PON2 in the year 2019 is 0,001%.

For the EMEA market, in Figure 5-5, GPON ONU/ONT has total dominance of the market. New PON technologies, as XG-PON1 and XGS-PON started to appear in the market in 2015, but yet, with a very low market share, 0,05% in 2019. P2P at the end of 2019 presented already a market share of about 10%. Regarding NG-PON2, no market share was observed in EMEA.

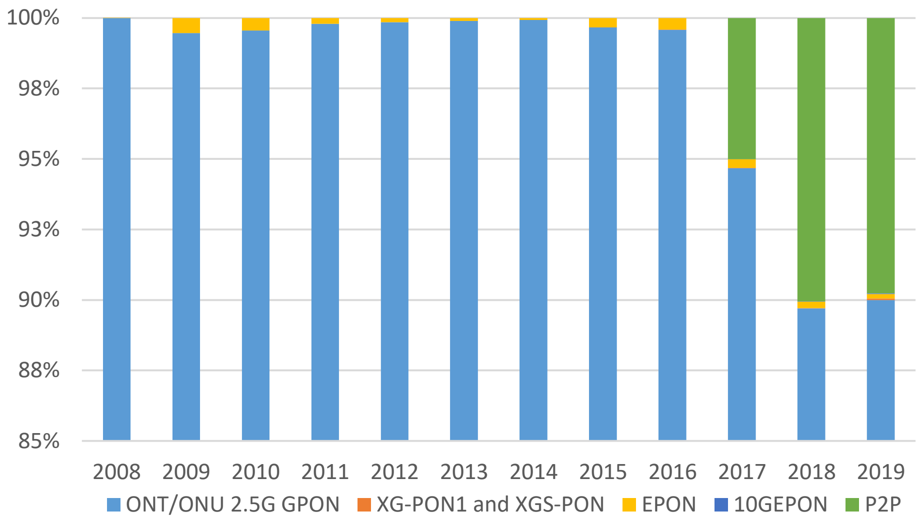

Figure 5-5 – EMEA equipment market share. XGS-PON - 0,05% in 2019.

In Figure 5-6, NA market, GPON ONT/ONU are the dominant equipment. EPON technologies have a constant small market share. XG-PON1 & XGSPON, as well as NG-PON2, are starting to appear in the market, in 2016 and 2018 respectively, but still 10GEPON as the new PON technology with the biggest market share. XG-PON1, XG(S)-PON, and NG-PON2 have a market share of 0,02% at the end of 2019. P2P represents about 7% of the market.

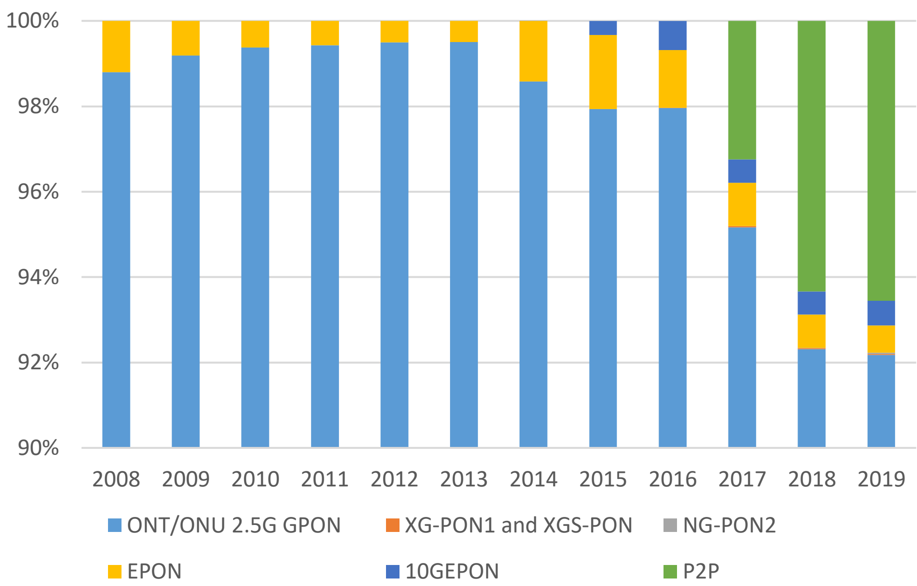

Figure 5-6- NA equipment market share. XG-PON1, XG(S)-PON, and NG-PON2 have a market share of 0,02% at the end of 2019.

5.2 Growth curves to model the ONT/ONU GPON Market

The different parametrizations and re-parametrizations of Gompertz equations presented in section 4.1 were fitted using an NLS regression to the vendor units data for ONT/ONU – 2.5G GPON for Global level, EMEA, and NA from OMDIA market share 2Q20 [3] (Appendix B- GPON Market Share) to analyze market behavior and to define the best parametrization.

To compare the performance of the fitting obtained with IBM SPPS Statistics version 26, a software tool [4], to estimate the parameters of technological growth from the International Institute for Applied Systems Analysis (IIASA) was used. The different market data was fitted to three-parameter logistic, Gompertz (as the one presented in section 4.1.3), Sharif-Khabir, and Floyd.

Figure 5-7 presents the fit of the different growth models to the global vendor units for ONT/ONU -2.5G GPON. The parameters defined for the NLS regression can be found in Appendix B - Modeling the PON Market, Gompertz to model GPON terminals, Zwietering modification to model GPON terminals, Zweifel and Lasker to model GPON terminals, Gompertz-Laird to model GPON terminals, Norton´s re-parametrization (type IIa) to model GPON terminals and Logistic, Gompertz, Sharif-Khabir, and Floyd to model GPON terminals.

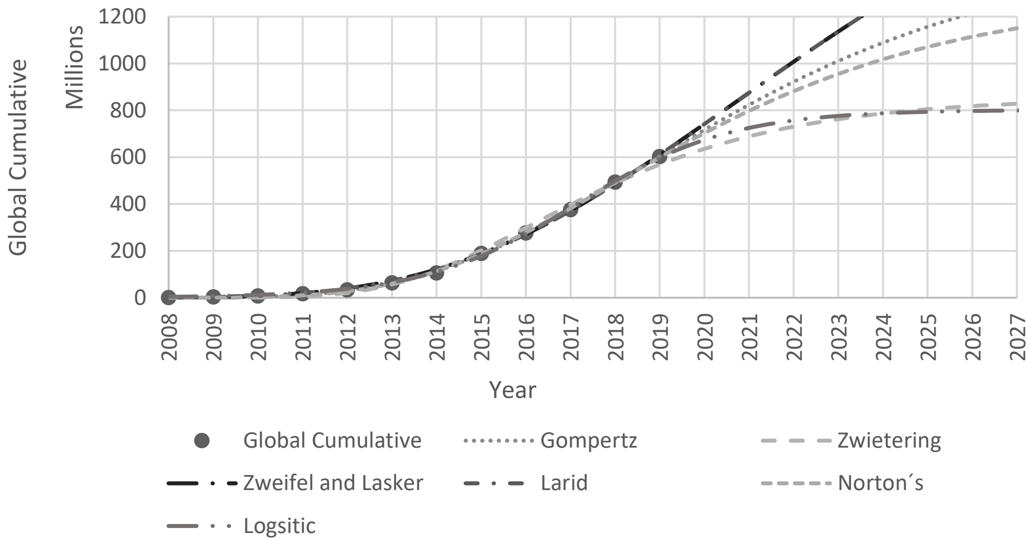

Figure 5-7 – Growth curves fit the global vendor units for ONT/ONU – 2.5G GPON.

In Table 5-1 is possible to compare the results of the different Gompertz equations model to GPON ONT/ONU vendor units for the different analyzed regions. The results of the NLS regression suggest the general suitability and sufficiency of all the growth models towards explaining the adoption of the GPON technology across the three studied regions. This is evident from the high values of their adjusted *r square* – the metric used to evaluate the model fitness criteria. The *r square* in the cells highlighted in dark grey present the best model fit to the data.

	Market Potential (millions)	Time of inflection (years)	Cumulative market *r square*	Annual Market *r square*
Global vendor units for ONT/ONU – 2.5G GPON				
Gompertz (type I)	1504	10,5	1,000	0,965
Zwietering (type I)	855	9,6	0,994	0,832
Zweifel and Lasker (type IIb)	2261	12,6	0,990	0,955
Gompertz-Laird (type IIb)	2241	12,6	0,999	0,146
Norton´s	1302	9,9	1,000	0,961
Logistic (IIASA)	802	9,1	0,999	0,943
Gompertz (IIASA)	1511	10,5	0,999	
Sharif-Khabir (IIASA)	877	8,6	0,997	
Floyd (IIASA)	1009	8,6	0,998	
EMEA vendor units for ONT/ONU – 2.5G GPON				
Gompertz (type I)	100	9,2	0,985	0,680
Zwietering (type I)	110	15,3	0,984	0,689
Zweifel and Lasker (type IIb)	171	11,8	0,992	0,846
Gompertz-Laird (type IIb)	170	11,8	0,992	0,543
Norton´s	196	12,5	0,992	0,868
Logistic (IIASA)	145	12,2	0,997	0,928
Gompertz (IIASA)	48	28914,8	0,887	
Sharif-Khabir (IIASA)	87	8,7	0,987	
Floyd (IIASA)	100	8,8	0,997	
NA vendor units for ONT/ONU – 2.5G GPON				
Gompertz (type I)	71	10,2	0,980	0,746
Zwietering (type I)	69	17,2	0,978	0,955
Zweifel and Lasker (type IIb)	725	26,6	0,997	0,955
Gompertz-Laird (type IIb)	755	26,7	0,997	-
Norton´s	172	15,7	0,992	0,915
Logistic (IIASA)	148	15,0	0,999	0,947
Gompertz (IIASA)	261040	88,4	0,999	
Sharif-Khabir (IIASA)	84	11,6	0,997	
Floyd (IIASA)	103	12,0	0,997	

Table 5-1 – Summary of modeling of different growth models to vendor units for ONT/ONU – 2.5G GPON.

As far as the market potential estimates are concerned, we can infer that Zweifel and Lasker model yields the most optimistic estimate for the three studied markets.

The Logistics estimates of the market potential remain conservative across all three regions when compared to the different Gompertz models. This particular result offers an interesting insight into the capabilities of the growth models to explain, both, the short-term diffusion process of GPON in the early growth stage, as well as the long-term diffusion process of GPON whose growth curves have crossed the inflection point and are approaching saturation. Based on the estimates of the market potential reported in Table 5-1, the Logistic model most certainly qualifies to explain well the diffusion process in regions falling in the latter category, whereas the Gompertz model is suited to the GPON diffusion in the growing stage.

In terms of the model best fit to explain the adoption dynamics of GPON, the following could be observed after taking into account the *r square* and the feasible market potential estimates. For the global market, the best fit to data is obtained by using the traditional Gompertz, Norton´s re-parametrization, and Logistic. For the EMEA and NA markets

Zweifel and Lasker re-parametrization, Norton´s re-parametrization, and Logistic present the best fit to data.

The fit of the traditional Cumulative Gompertz to the Global vendor units can be observed in Figure 5-8. A potential market forecast of around 1,5 billion units for GPON ONU/ONT globally was determined. The maximum growth rate was 20,7% and the market inflection point happened in the middle of the 2018 year. The time interval to grow from 10% to 90%, this is, Δt, is 14,9 years. From this model analysis is possible to conclude that GPON ONU is already on the decline phase, being consumed by a late majority risk-averse group.

From the 1st derivative using cumulative constraints is possible to determine a potential market forecast of around 1,4 billion units for GPON ONU/ONT globally. The maximum growth rate was 21,9% and the market inflection point happened in 2018.

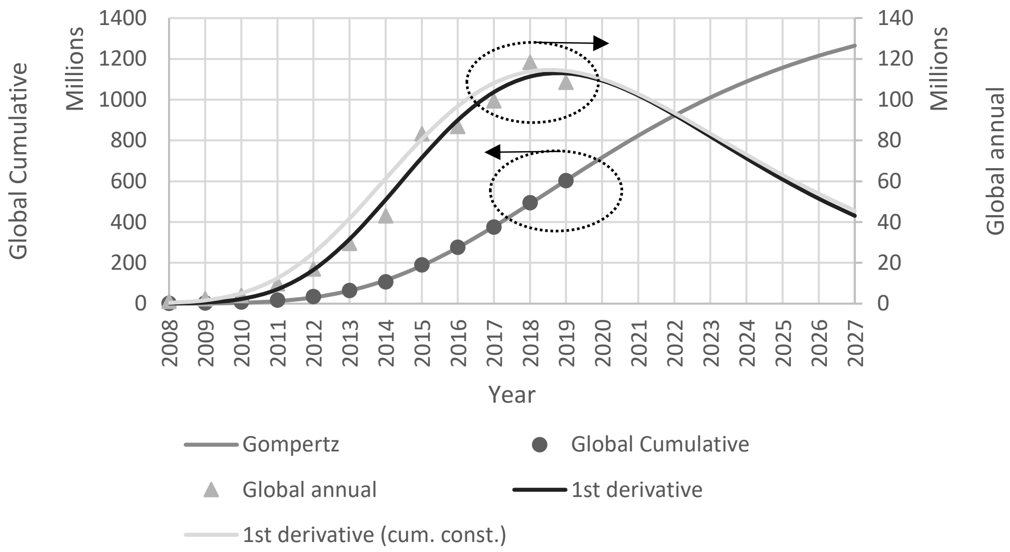

Figure 5-8 – Traditional Cumulative Gompertz fit to the global vendor units for ONT/ONU – 2.5G GPON.

As regards the global market, the logistic curve, asymptote value, gives a potential market forecast of 802 million units, with an inflection point in the year 2017 and a time interval to grow from 10% to 90% of 7,5 years. The data and the corresponding logistic curve plotted are presented in Figure 5-9. In the same figure, left side top is possible to observe the growth plotted linearly using the Fisher-Pry transform.

In the Fisher-Pry transform is observed the long-term diffusion process of GPON whose growth curves have crossed the inflection point and are approaching saturation.

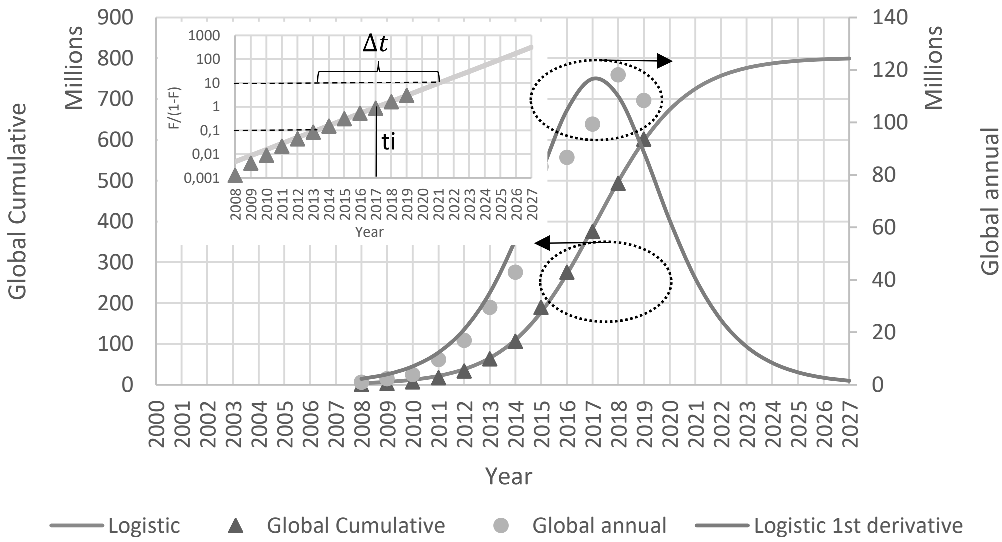

Figure 5-9- Logistic growth model fits the global vendor units for ONT/ONU – 2.5G GPON. The inset shows the growth curve after using the Fisher-Pry transform.

Figure 5-10 presents the fit of Norton´s growth model to the EMEA vendor units. For the first simulation, a potential market forecast of around 56 million units was found and the market inflection point happen in the middle of the 2014 year. The maximum growth rate is 27,5%. The optimization modeling gives a potential market forecast of 196 million units a growth rate of 15,7% and the inflection point happen in the middle of the year 2020. Using the constants obtained from the optimization for the cumulative market, fitting to the annual market, this is the new adopters per year, making Norton´s model account for much more variability in the dependent variable.

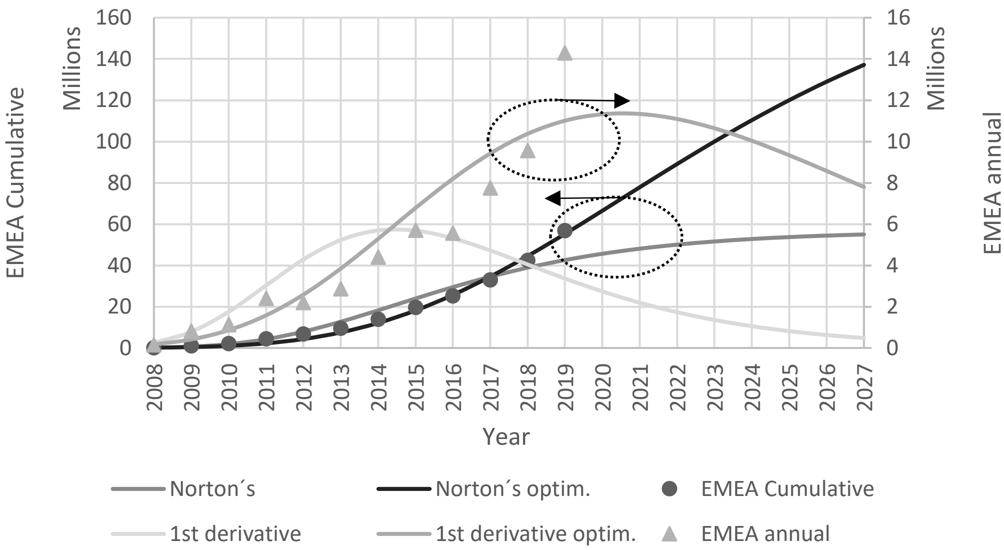

Figure 5-10 – Norton´s fit to the EMEA units for ONT/ONU – 2.5G GPON.

For the EMEA market, the logistic curve, asymptote value, gives a potential market forecast of 145 million units, with an inflection point in the year 2020 and a time interval to grow from 10% to 90% of almost 12 years. The data and the corresponding logistic curve plotted are presented in Figure 5-11. In the same figure, left side top is possible to observe the growth plotted linearly using the Fisher-Pry transform.

The Logistic model, for the rate of growth (annual growth), has the best model fit compared to the other models, but as is possible to see, from 2016 till 2019 the estimates remain far from ideal.

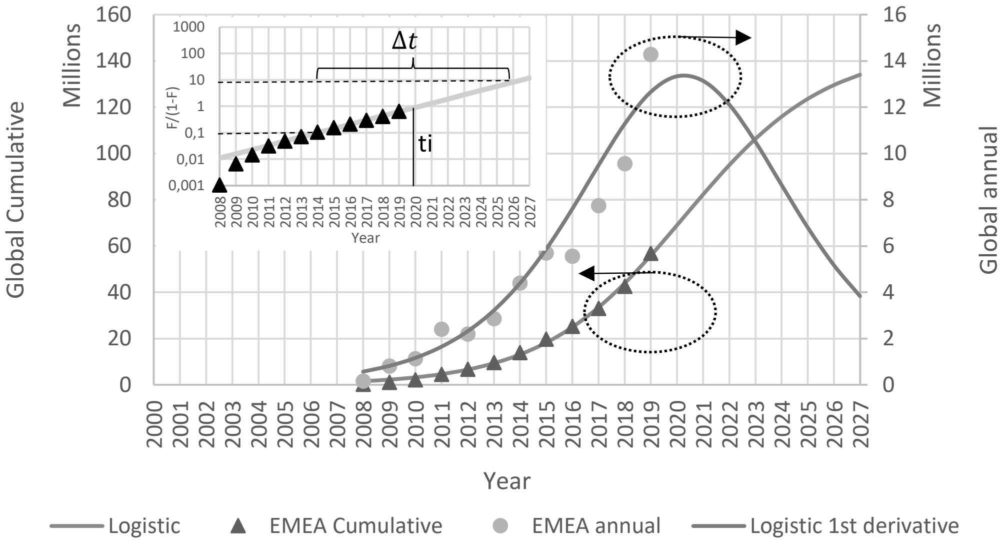

Figure 5-11 - Logistic growth model fits the EMEA vendor units for ONT/ONU – 2.5G GPON. The inset shows the growth curve after using the Fisher-Pry transform.

As regards the NA potential market forecast using Zweifel and Lasker is 725 million units. The maximum growth rate is 7,3% and the market inflection point will happen in the middle of 2034. The annual market presents a lower fit to data compared to the cumulative, this is mainly due to large variations of the annual market over time due to specific uncertainties. This will be discussed in detail in Chapter 6: Analysis of uncertainties in GPON diffusion and rate of growth

For the annual GPON equipment adoption, using the cumulative constants, and to analyze the fitting of the curve, the NA market potential prevision is 3 billion. The maximum growth rate was 5,4% and the market inflection point will happen in 2047. This value is misaligned with the fast market adoption of PON technology as well as, with the upcoming adoption of NG-PON. We have to consider the Zweifel and Lasker model inadequate to predict the market behavior, despite presenting reasonable results, Figure 5-12.

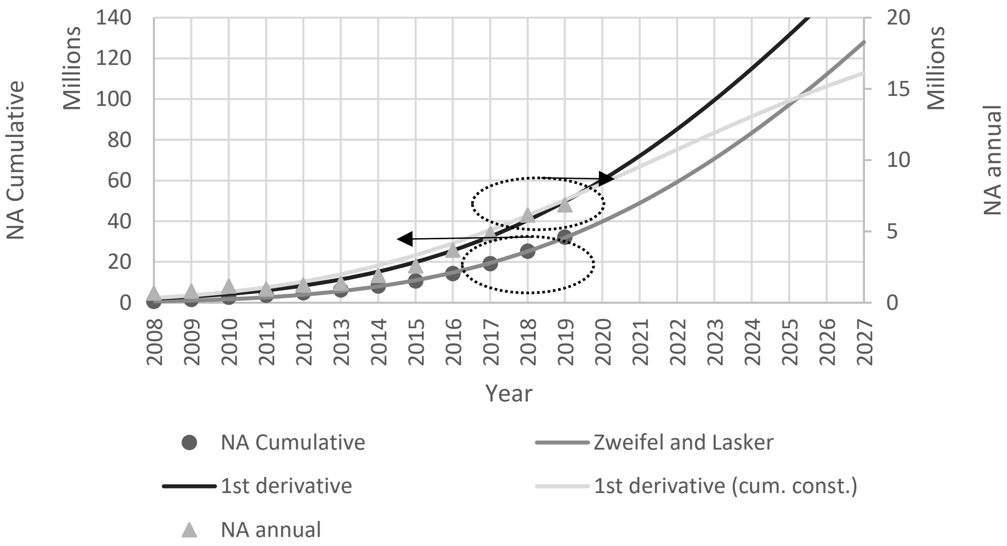

Figure 5-12- Zweifel and Lasker fit to the NA vendor units for ONT/ONU – 2.5G GPON.

The Logistic curve, asymptote value, gives a final market forecast of 148 million units, with an inflection point in the year 2023 and a time interval to grow from 10% to 90% in 14 years. The data and the corresponding logistic curve plotted are presented in Figure 5-13. In the same figure, left side top is possible to observe the growth plotted linearly using the Fisher-Pry transform.

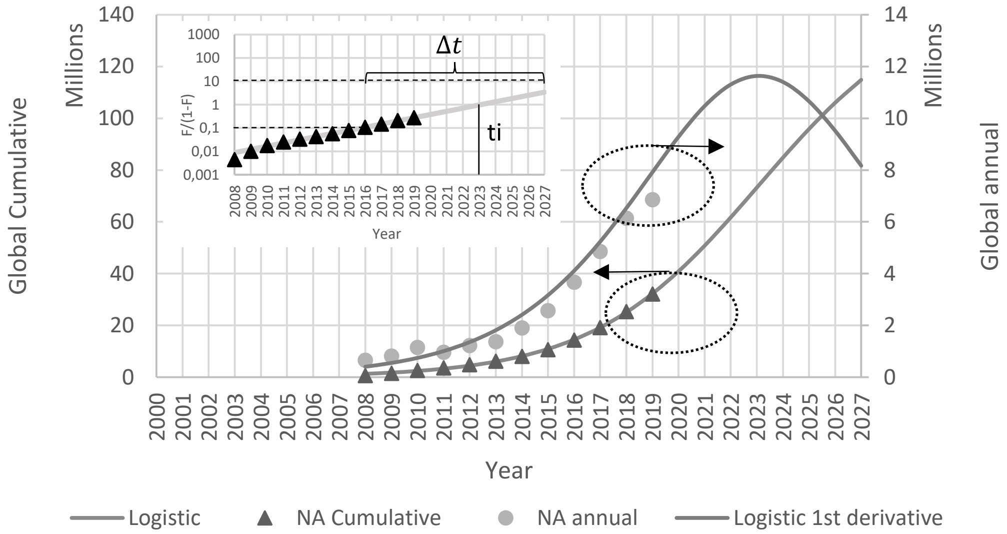

Figure 5-13 - Logistic growth model fits the NA vendor units for ONT/ONU – 2.5G GPON. The inset shows the growth curve after using the Fisher-Pry transform.

It is clear from the results that when it comes to explaining the diffusion of GPON, no model is superior to the other model in all the cases. Therefore, to make any generic claims regarding the best-fit model for GPON diffusion we take help of the accuracy of the forecasts generated by each model for establishing their relative suitability for representing the diffusion process by using MAPE.

To evaluate the forecasting accuracies of each of the models, we segregate a portion of the know data points from the historical data and keep them aside as the “hold-out” data. We then forecast the GPON adoption figures, over the same period as the hold-out data, using the NLS determined coefficients of the growth models. Finally, the MAPE values are evaluated for the corresponding periods, by comparing the forecasted values with the real GPON adoption values. The MAPE indictor thus obtained, helps in establishing the forecasting capabilities, both the long and short-term of the models, in a rigorous manner.

Table 5-2 presents the results of the MAPE calculations for the different growth models that fit the vendor units for ONT/ONU -2.5G GPON. We have chosen 3 scenarios with varying hold-out periods consisting of 4 (MAPE4), 6 (MAPE 6), and 12 (MAPE12) years, respectively.

ONT/ONU	Cumulative Market			Annual Market		
	MAPE4 (%)	MAPE6 (%)	MAPE12 (%)	MAPE4 (%)	MAPE6 (%)	MAPE12 (%)
Global vendor units for ONT/ONU – 2.5G GPON						
Gompertz (type I)	0,57	2,02	20,04	7,33	12,53	26,19
Zwietering (type I)	5,07	6,28	37,08	19,18	26,57	44,07
Zweifel and Lasker (type IIb)	1,52	3,54	7,50	9,03	13,13	32,83
Gompertz-Laird (type IIb)	1,52	3,54	7,50	49,35	62,10	197,27
Norton´s	0,83	1,86	25,93	7,46	12,85	26,29
Logistic (IIASA)	1,35	2,51	42	15,78	15,84	35,99
EMEA vendor units for ONT/ONU – 2.5G GPON						
Gompertz (type I)	7,64	5,94	27,18	27,25	28,27	34,40
Zwietering (type I)	7,40	6,98	15,47	24,96	23,84	29,65
Zweifel and Lasker (type IIb)	4,57	5,46	19,30	24,05	23,35	26,21
Gompertz-Laird (type IIb)	4,57	5,46	19,30	43,50	51,87	69,49
Norton´s	3,62	5,82	20,51	25,15	23,33	25,85
Logistic (IIASA)	1,87	3,39	94,89	22,19	15,32	34,88
NA vendor units for ONT/ONU – 2.5G GPON						
Gompertz (type I)	6,76	7,39	29,01	19,70	32,76	43,97
Zwietering (type I)	8,10	10,26	23,27	22,31	32,04	41,75
Zweifel and Lasker (type IIb)	1,54	1,75	10,41	6,06	15,23	24,17
Gompertz-Laird (type IIb)	1,52	1,74	10,42	96,03	96,63	98,04
Norton´s	3,86	4,25	18,15	9,43	20,77	30,84
Logistic (IIASA)	0,69	0,94	12,45	10,43	15,29	20,51

Table 5-2 – MAPE (%) for different hold-out periods for the different growth models fit the vendor units for ONT/ONU – 2.5G GPON.

Regarding the forecasting performance of the models, we can observe from the table that for the cumulative and annual Global market the Gompertz and Norton´s model presents the best performance, for both the short and mid-term adoption.

As regards the EMEA and NA cumulative market, the logistic model-based forecast presents the best performance for short-term and mid-term adoption and Laird in the long-term adoption.

The Gompertz and logistic model-based forecasts are consistent across the three regions for both the cumulative and annual markets presenting a good forecast model for both short-term and mid-term adoption. As regards the model best fit to explain the pattern adoption dynamics of GPON, Table 5-1, and the best model forecasting performance for both short term and mid-term adoption, Table 5-2, we point out Gompertz for the Global market and Logistic model for EMEA and NA.

To verify the consistency of the modeling, a comparison with past and future FTTH/B subscribers is performed for the EMEA market.

Based on an FTTH Council Europe report from September 2019 [5] is possible to have historical data and a growing trend for EU28 countries and EU39 countries (EU39 = EU28 (excl. Cyprus) plus 4 CIS countries, Russia, Kazakhstan, Belarus, and Ukraine plus Andorra, Iceland, Israel, North Macedonia, Norway, Serbia, Switzerland, Turkey), from 2012 till the end of 2019 for FTTH/B subscribers and FTTH/B Homes passed.

FTTH Council Middle East and North Africa (MENA), also provides a report in September 2019 [6] with the historical data and growing trend of FTTH/B subscribers and FTTH/B Homes passed from the 2012 year till the end of the 2019 year.

FTTH Council Europe-2020 presented the FTTH forecast for Europe, 2020-2026 [7], where is presented the forecast for FTTH/B homes passed and FTTH/B subscribers for EU 38+UK.

In Figure 5-14 is possible to observe the current EU39 and MENA FTTH/B subscribers (blue columns), the EMEA vendor units for GPON ONU/ONTs (yellow dots), the fit of the two S curves (Gompertz and Logistic) the forecast for EU38+UK 2020-2026 from FTTH council (green columns) and the total fixed broadband subscription and forecast from OMDIA [8] (orange columns). Is possible to conclude that GPON ONT/ONU will maintain its market share in the FTTH/B subscriptions, but of course, the emergence of new PON technologies will start to occupy space in the subscription market.

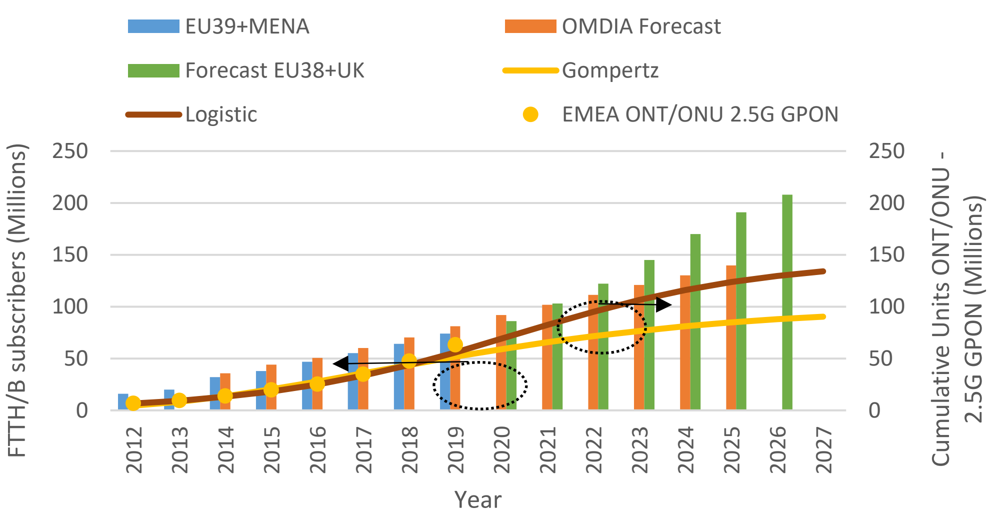

Figure 5-14 - FTTH/B subscribers, cumulative units ONT/ONU 2.5G GPON and the fit of Gompertz and Logistic.

The observed discrepancy between the growth models and the presented forecasts could be due to:

- the data used to model the EMEA market includes reported vendor results and OMDIA estimates [3];
- the data used to fit the growth models include the major GPON equipment vendors, but it is noticed that other smaller vendors, with a significant presence in EMEA, are not included;
- the data from FTTH council include operator data FTTH/B subscription, this means different data sourcing (vendors vs operators);
- reconditioned equipment is not considered in our model.

Regarding FTTH/B Homes passed, Figure 5-15, the market will maintain its "fiberalization", as well as the tendency of percentage market adoption of such technology by the population.

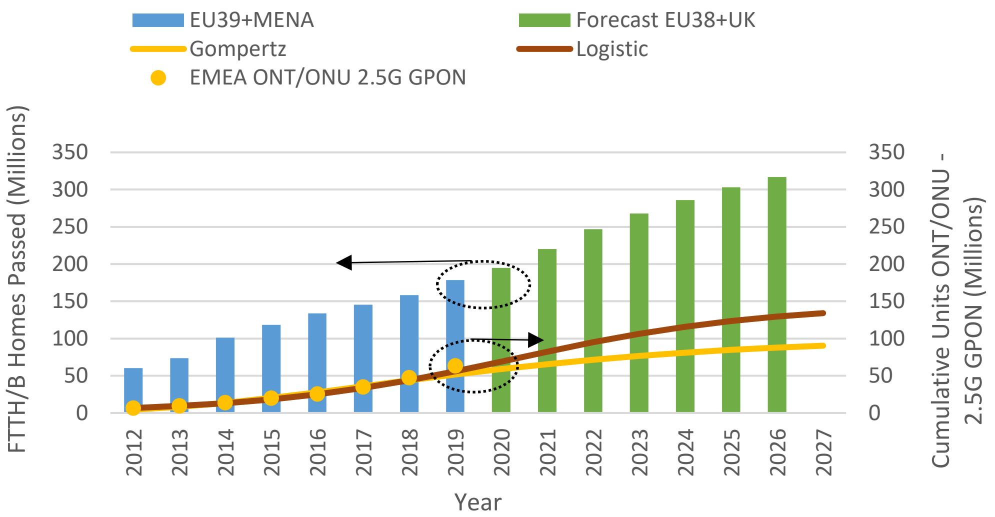

Figure 5-15 - FTTH/B homes passed, cumulative units ONT/ONU 2.5G GPON, and the fit of Gompertz and Logistic.

For the NA market, Figure 5-17, was only possible to obtain data for the FTTH/B Homes passed for the United States of America [9]. For the FTTH/B subscribers, Figure 5-16, is available the data for the United States of America from Fiber Broadband Association [9] (blue columns) and total fixed broadband subscription and forecast from OMDIA [8] (orange columns). Is possible to notice that the quantity of equipment sold to the NA market is always superior to the total quantity of network subscribers.

The observed discrepancy between the growth models and the presented forecasts could be due to:

- the data used to model the NA market includes reported vendor results and OMDIA estimates [3];
- the data used to fit the growth models include the major GPON vendors equipment, but it is noticed that other smaller vendors in the NA market are not included;
- the data from Fiber Broadband Association include operator data FTTH/B subscription, this means different data sourcing (vendors vs operators);
- the data from Fiber Broadband Association include major operators data FTTH/B subscription and smaller regional/local operators are not taken into account;

- reconditioned equipment is not taken into account on our model;
- warranty and operational equipment substitution after some specific period of operation in the field.

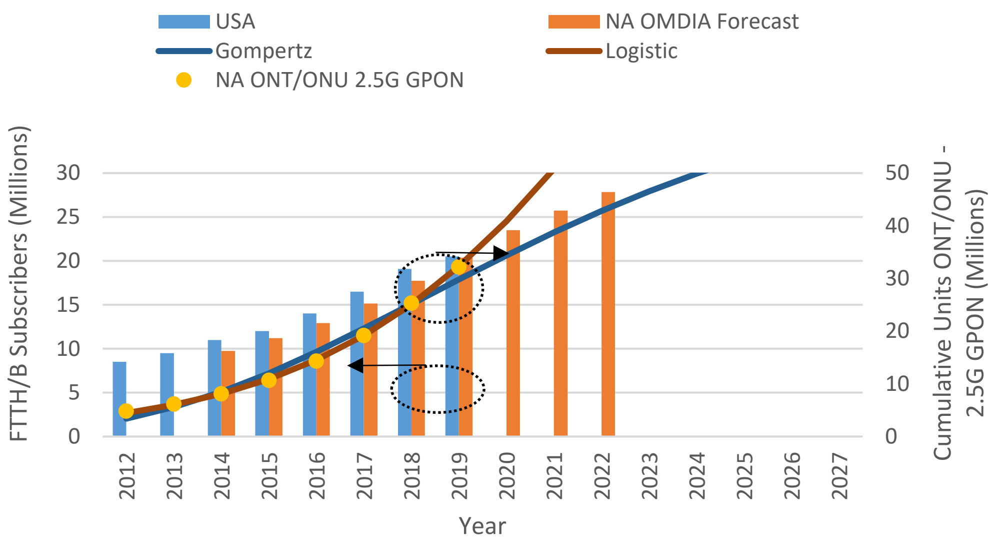

Figure 5-16- FTTH/B subscribers, cumulative units ONT/ONU 2.5G GPON and the fit of Zweifel and Lasker, Norton´s, and Logistic

In Figure 5-17 is possible to observe the current USA FTTH/B homes passed, the NA vendor units for GPON ONU/ONTs, and the fit of the two S curves, Gompertz and Logistic.

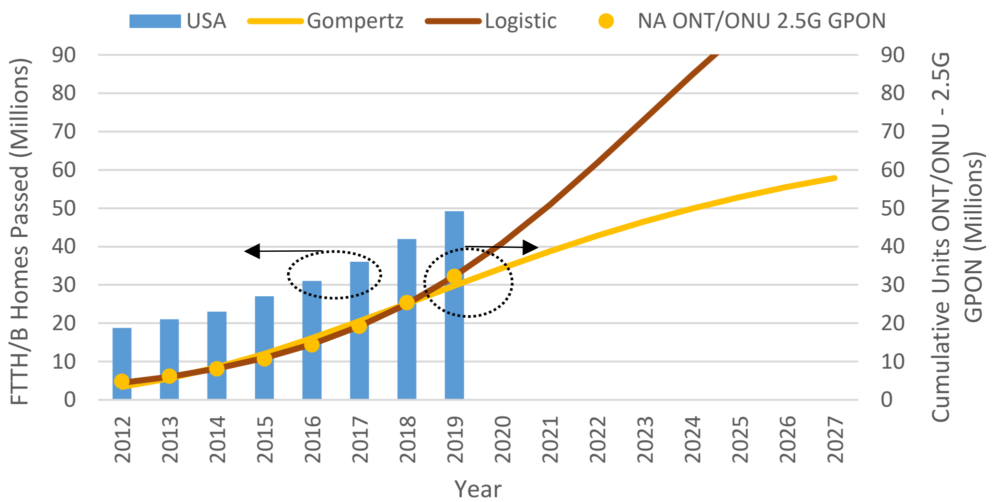

Figure 5-17- FTTH/B homes passed, cumulative units ONT/ONU 2.5G GPON and the fit of Zweifel and Lasker, Norton and Logistic

It is expected that the market continues to use GPON ONT/ONU as more FTTH Homes are passed, and as in Europe, XGS-PON will start to increase market share as well as NG-PON2 that will continue to move forward slowly.

5.3 Growth curves to model OLT GPON Market

As for the ONU GPON market, for the OLT market share our study we will also focus on the global, NA, and EMEA market.

The vendor units for OLT – 2.5G GPON for Global level, EMEA, and NA from OMDIA market share 2Q20 for PON [3] are presented in Appendix B- GPON Market Share.

To compare the performance of the fitting done in SPSS by using an NLS regression, a software tool [4], to estimate the parameters of technological growth from the International Institute for Applied Systems Analysis (IIASA) was used. The different market data was fitted to the different growth models presented before.

Figure 5-18 presents the fit of the different growth models to the global vendor units for OLT-2.5G GPON. The parameters defined for the NLS regression can be found in Appendix B -Zweifel and Lasker to model OLT - 2.5G GPON, Norton´s to model OLT - 2.5G GPON and Logistic, Gompertz, Sharif-Khabir, and Floyd to model OLT - 2.5G GPON.

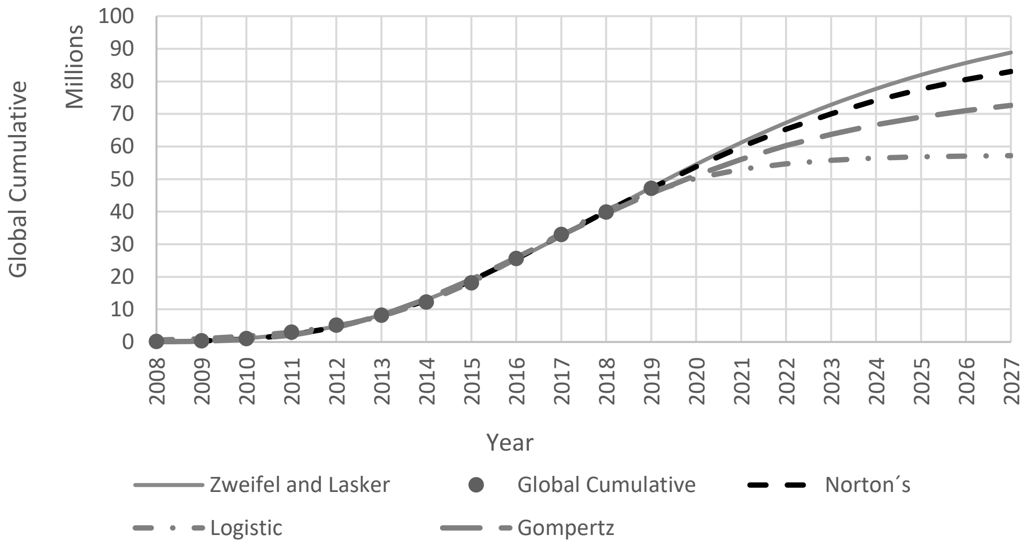

Figure 5-18 - Growth curves fit the global vendor units for OLT – 2.5G GPON.

The GPON ONT/ONU market is directly related to the number of OLT ports installed, where a GPON OLT port can serve typically 32, 64, or 128 terminals in a splitter-based network architecture. The market share of OLT ports is associated with the service provider business case, this is, their capacity and will of rolling out FTTH/B in different areas, and their will to invest in GPON OLT equipment for the central offices. Despite the ONT/ONU market being fully dependent on the OLT market, the ONT/ONU market depends on the adoption of the technology by the end-users, as so, the reinvestment of the service provider in new areas for installation for OLT ports is conditioned by the success of the previous adoption on other areas. This emphasizes the importance of the growth models studied for GPON ONT/ONU 2.5G GPON.

In Table 5-3 is possible to compare the results of the different Gompertz equations model to GPON OLT vendor units for the different analyzed regions. The results of the NLS regression suggest the general suitability and sufficiency of all the growth models towards explaining the adoption of the GPON technology across the three studied regions. This is evident from the high values of their adjusted *r square* – the metric used to evaluate the model fitness criteria. The *r square* in the cells highlighted in dark grey presents the best model fit to the data.

	Final market Volume (millions)	**Time of inflection (years)**	**Cumulative market *r square***	**Annual Market *r square***
Global vendor units for OLT – 2.5G GPON				
Zweifel and Lasker	105	9,8	0,999	0,956
Norton´s	94	9,2	0,999	0,952
Logistic (IIASA)	57	8,3	0,999	0,906
Gompertz (IIASA)	78	8,4	0,998	
Sharif-Khabir (IIASA)	64	7,9	0,998	
Floyd (IIASA)	72	7,8	0,998	
EMEA vendor units for OLT – 2.5G GPON				
Zweifel and Lasker	10,0	9,6	0,984	0,576
Norton´s	9,8	9,5	0,981	0,665
Logistic (IIASA)	5,9	8,8	0,992	0,529
Gompertz (IIASA)	13	11,8	0,995	
Sharif-Khabir (IIASA)	5,2	7,1	0,980	
Floyd (IIASA)	5,9	7,0	0,981	
NA vendor units for OLT – 2.5G GPON				
Zweifel and Lasker	10,0	14,6	0,991	0,079
Norton´s	4,2	9,0	0,986	0,699
Logistic (IIASA)	3,1	9,1	0,996	0,808
Gompertz (IIASA)	10,0	14,6	0,992	
Sharif-Khabir (IIASA)	No valid results		-	
Floyd (IIASA)			-	

Table 5-3 – Summary of modeling of different S models to OLT – 2.5G GPON vendor units.

As far as the market potential estimates are concerned, we can infer that Zweifel and Lasker model yields the most optimistic estimate for the three studied markets.

The Logistic estimates of the market potential remain conservative across all three regions when compared to the different Gompertz models. The Logistic model most certainly qualifies to explain well the diffusion process in regions that have crossed the inflection point and are approaching saturation, whereas the Gompertz model is suited to the GPON diffusion in the growing stage.

In terms of the model best fit to explain the adoption dynamics of GPON, the following could be observed after considering the *r square* and the feasible market potential estimates. As regards the global market, the best fit to data is obtained by using the Zweifel and Lasker re-parametrization. For the EMEA and NA market, Norton´s re-parametrization presents the best fit. The Logistic curve presents the best fit to the NA market.

The fit of the Zweifel and Lasker re-parametrization to the Global vendor units for OLT – 2.5G GPON can be observed in Figure 5-19. It predicts a potential market forecast of 105 million units for GPON OLT globally. The maximum growth rate is 19,3% and the market inflection point happens at end of the year 2017.

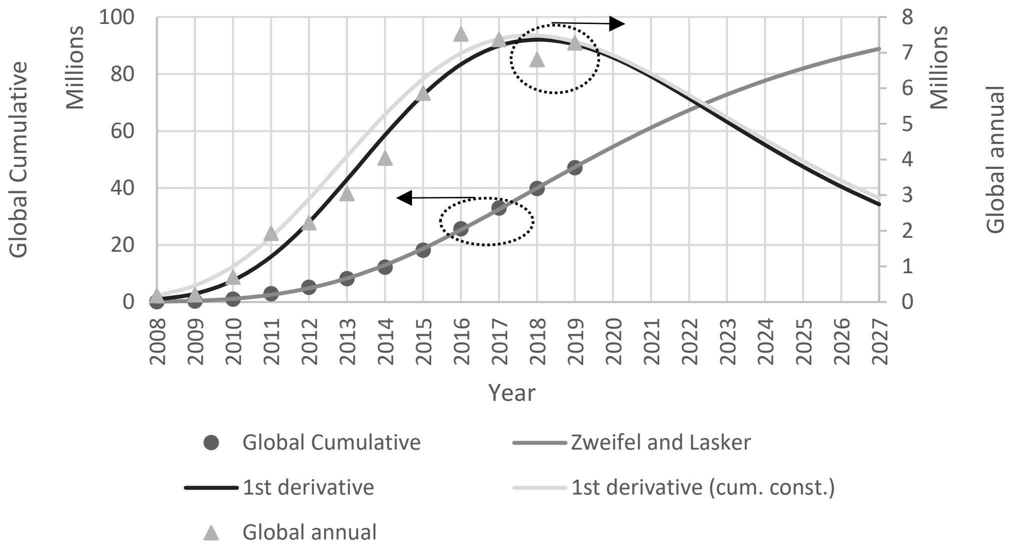

Figure 5-19- Zweifel and Lasker re-parametrization fit to the global vendor units for OLT – 2.5G GPON.

Figure 5-20 presents the fit of Norton´s growth model to the EMEA vendor units. The EMEA potential market forecast is 9,8 million units. The maximum growth rate was 20,1% and the market inflection point happened in the year 2017. Regarding the annual OLT port GPON equipment adoption in EMEA, none of the models can cope with the market oscillations and increase adoption between the years 2018-2019, their *r square* is low regarding what is intended.

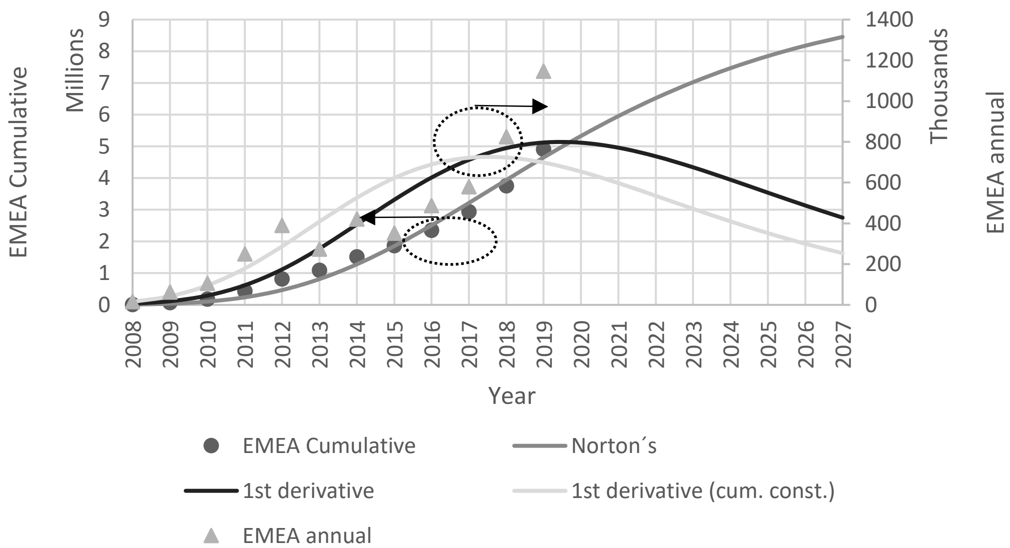

Figure 5-20 - Norton´s re-parametrization fit to the EMEA units for OLT – 2.5G GPON.

The growth model fit for the NA market is presented in Figure 5-21, a potential market forecast of 4,2 million units was found. The maximum growth rate was 19,9% and the market inflection point happened in the year 2017. As it happens for the EMEA market, for the NA market, none of the annual adoption growth models was able to model the OLT port adoption between the years 2015-2016 and the decline in adoption between the years 2017-2019.

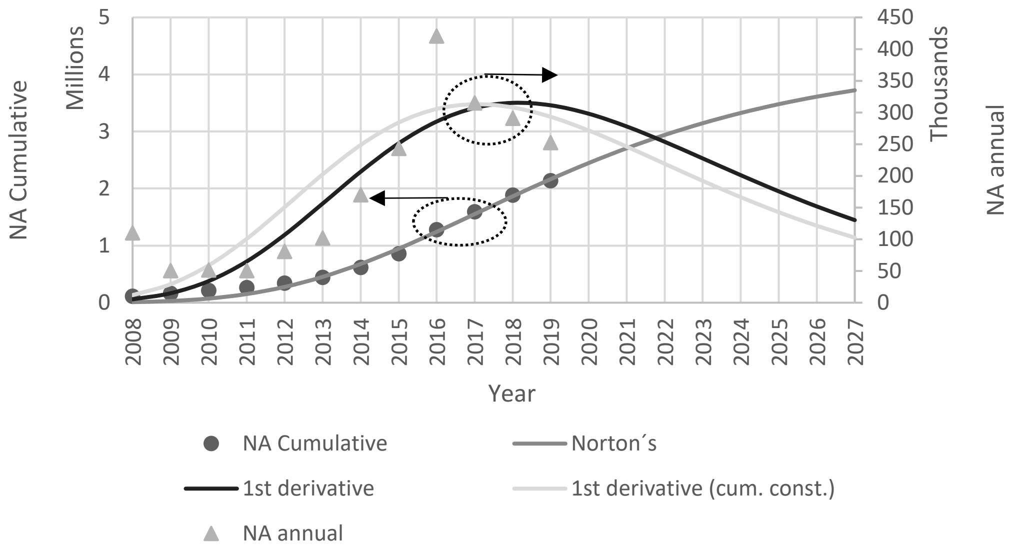

Figure 5-21 - Norton´s re-parametrization fit to the NA units for OLT – 2.5G GPON.

As regards the logistic curve, the model gives a potential market forecast of 3,1 million units, with an inflection point in the year 2017 and a time interval to grow from 10% to 90% in 10 years. The data and the corresponding Logistic curve plotted are presented in Figure 5-22. In the same figure, left side top, is possible to observe the growth plotted linearly using the Fisher-Pry transform where is notorious the market oscillation.

The logistic model, for the rate of growth (annual growth), has the best model fit compared to the other models, but as is possible to see, the estimates remain far from ideal due to the market adoption oscillations.

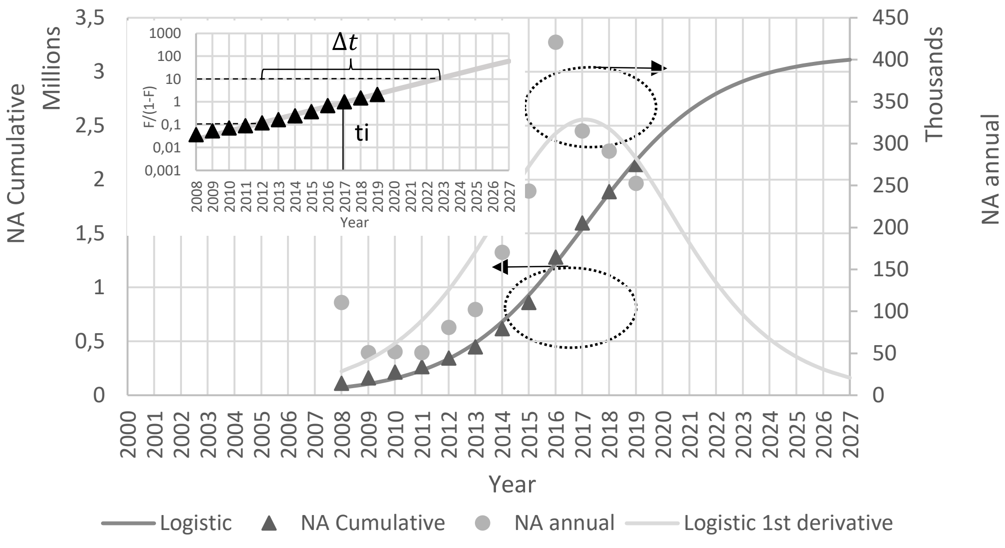

Figure 5-22 - Logistic growth model fits the NA vendor units for OLT – 2.5G GPON. The inset shows the growth curve after using the Fisher-Pry transform.

It is clear from the results that when it comes to explaining the diffusion of OLT GPON ports, no model is superior to the other model in all the cases happening the same as in the diffusion of ONT/ONUs GPON. Therefore, to make any generic claims regarding the best-fit model for OLT GPON diffusion we take the help of the accuracy of the forecasts generated by each model for establishing their relative suitability for representing the diffusion process by using MAPE.

As for ONT/ONU GPON, to evaluate the forecasting accuracies of each of the models, we segregate a portion of the know data points from the historical data and keep them aside as the "hold-out" data. We then forecast the GPON adoption figures, over the same period as the hold-out data, using the NLS determined coefficients of the growth models. Finally, the MAPE values are evaluated for the corresponding periods, by comparing the forecasted values with the real OLT port GPON adoption values. The MAPE indictor thus obtained, helps in establishing the forecasting capabilities, both the long and short-term of the models, in a rigorous manner.

Table 5-4 presents the results of the MAPE calculations for the different growth models that fit the vendor units for OLT -2.5G GPON. We have chosen 3 scenarios with varying hold-out periods consisting of 4 (MAPE4), 6 (MAPE 6), and 12 (MAPE12) years, respectively.

OLT	**Cumulative Market**			**Annual Market**		
	MAPE4 (%)	**MAPE6 (%)**	**MAPE12 (%)**	**MAPE4 (%)**	**MAPE6 (%)**	**MAPE12 (%)**
Global vendor units for ONT/ONU – 2.5G GPON						
Zweifel and Lasker (type IIb)	0,94	1,97	6,42	4,43	9,11	24,24
Norton´s	0,56	1,58	12,5	4,71	10,22	22,83
Logistic (IIASA)	1,16	0,92	39,78	10,51	14,43	33,95
EMEA vendor units for ONT/ONU – 2.5G GPON						
Zweifel and Lasker (type IIb)	6,59	6,69	17,41	36,36	49,53	37,81
Norton´s	6,44	7,10	23,64	29,36	36,50	30,94
Logistic (IIASA)	6,28	5,68	95,22	28,54	28,50	49,39
NA vendor units for ONT/ONU – 2.5G GPON						
Zweifel and Lasker (type IIb)	4,28	6,63	15,65	26,17	21,93	40,30
Norton´s	1,99	4,73	27,56	12,47	18,78	45,22
Logistic (IIASA)	2,5	4,76	12,46	12,86	15,68	33,66

Table 5-4- MAPE (%) for different hold-out periods for the different growth models fit the vendor units for OLT – 2.5G GPON.

Regarding the forecasting performance of the models, we can observe from Table 5-4, that for the cumulative and annual Global market the Zweifel and Lasker model in a general form presents the best performance for the short-, mid- and long-term adoption.

As regards the EMEA and NA cumulative market, the logistic model-based forecast presents the best performance for short-term and mid-term adoption.

The logistic model-based forecasts are consistent across the three regions for both the cumulative and annual markets presenting a good forecast model for both short-term and mid-term adoption. As regards the model best fit to explain the pattern adoption dynamics of GPON, Table 5-3, and the best model forecasting performance for both short term and mid-term adoption, Table 5-4, we point out the Logistic model as the most consistent for the three markets.

FTTH Council Europe-2020 presented the FTTH forecast for Europe, 2020-2026,[7] where is presented the forecast for FTTH/B homes passed and FTTH/B subscribers for EU 38+UK as well as the history from the year 2012 till 2019, Figure 5-23. In the same figure is possible to observe the ratio of homes passed over subscribers, and is seen that from 2012 till 2019, the number of subscribers per home passed is increased. This means that in 2012 for each 4 (3,7) homes passed one have a subscriber, in 2019 for each 3 (2,5) houses passed one has a subscriber, this tendency is expected to increase till 2026 where for each 2 (1,5) houses passed one will have a subscriber.

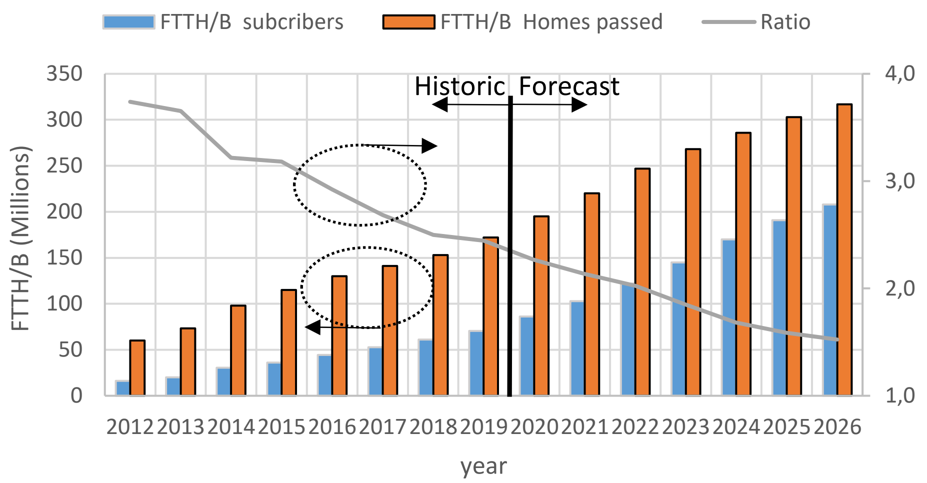

Figure 5-23 – FTTH/B subscribers and homes passed, the ratio between homes passed and subscribers.

A telecom operator has to prepare its network, from a CO point of view, to account for all homes passed. The number of OLT ports has to be proportional to the homes passed and consequently oversized.

From OMDIA market share 2Q20 for PON [3], we calculated the number of ONT/ONU – 2.5G GPON per OLT- 2.5G GPON, Figure 5-24.

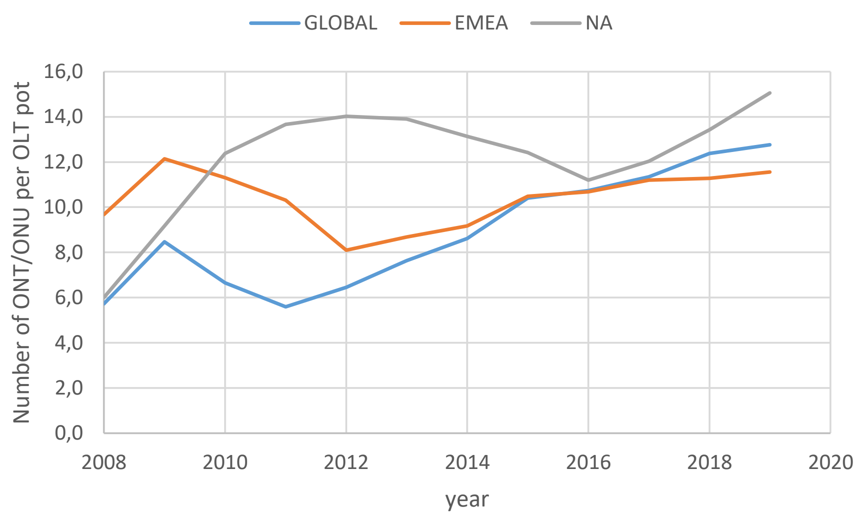

Figure 5-24 – ONT/ONU 2.5G GPON per OLT-2.5G GPON port.

We can see that the number of ONT/ONU- 2.5G GPON per OLT port is increasing. Taking this reasoning from the ratio of homes passed over subscribers, we can conclude that, as the number of subscribers per home passed is increasing, the number of ONT/ONU 2.5G GPON per OLT port should also increase.

The same line of thought was used for the different S curves models. As so, the number of ONT/ONU per OLT port is calculated for each type of S curve, this is, the cumulative number of ONT/ONU 2.5G GPON were divided by the cumulative OLT 2.5G GPON OLT ports for Gompertz, Zweifel and Lasker, Norton´s and Logistic, considering the best forecast models.

Figure 5-25, Figure 5-26, and Figure 5-27 present the number of ONT/ONU- 2.5G GPON per OLT port for the global, EMEA, and NA market respectively.

As regards the Global market, Figure 5-25, was particularly used the Gompertz model for the ONT/ONU divided by the Zweifel and Lasker for the OLT, as these models present the best forecast models from the MAPE calculations. It is possible to see, the tendency is to maintain the number of terminals connected to the OLT port but with a slight growth over time. From the models' forecast is possible to conclude a potential market of around 14 ONT/ONU per OLT port.

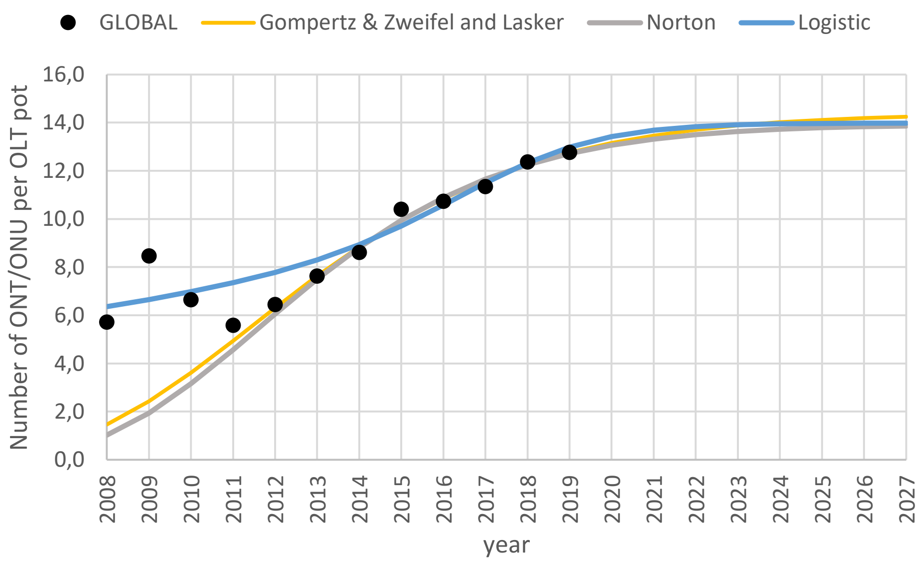

Figure 5-25 –ONT/ONU 2.5G GPON per OLT-2.5G GPON port for the Global market.

For the EMEA market, Figure 5-26, and reinforcing the previous line of thought, an increase in the number of subscribers per home passed is noted. The models also demonstrate that the number of ONT/ONU per OLT 2.5G GPON port will continue to increase.

The discrepancy observed in the number of ONT/ONU per OLT port by using the Logistic model is noticeable from the forecasting performance of the model, Table 5-2 - ONT/ONU and Table 5-4 - OLT, where this model, on the long term forecast (MAPE12), have the worst model value.

As regards the model forecast is possible to conclude a potential market of between 13 to 17 ONT/ONU per OLT port in the long term.

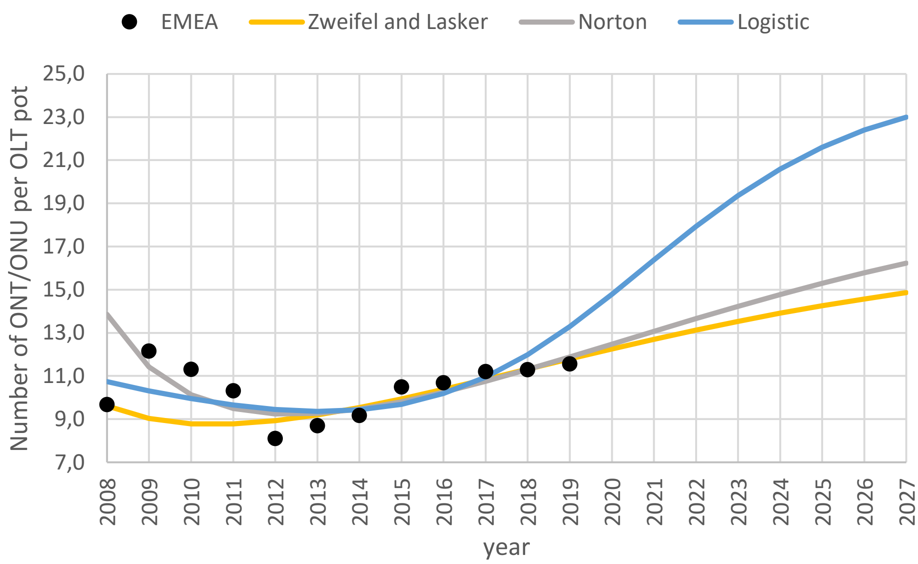

Figure 5-26 - ONT/ONU 2.5G GPON per OLT-2.5G GPON port for the EMEA market.

For the NA market, in Figure 5-27, the modeling is showing that the number of ONT/ONU per OLT 2.5G GPON port will continue to increase. Norton´s model failed to map the initial adoption of OLTs, between 2008 and 2010, Figure 5-21, and consequently, the number of ONT/ONU per OLT port is very high in this time frame (dash circle).

As what regards the logistic model and from all models presented, it predicts the lowest potential market forecast for GPON OLT port in NA, consequently the number of ONT/ONU per OLT port, in the long term, overcome a typical PON network of 32 ONT/ONU, a possible number, but an unlikely high number.

The Zweifel and Lasker and Norton´s model predict a forecast of 23 ONT/ONU per OLT port on the long term.

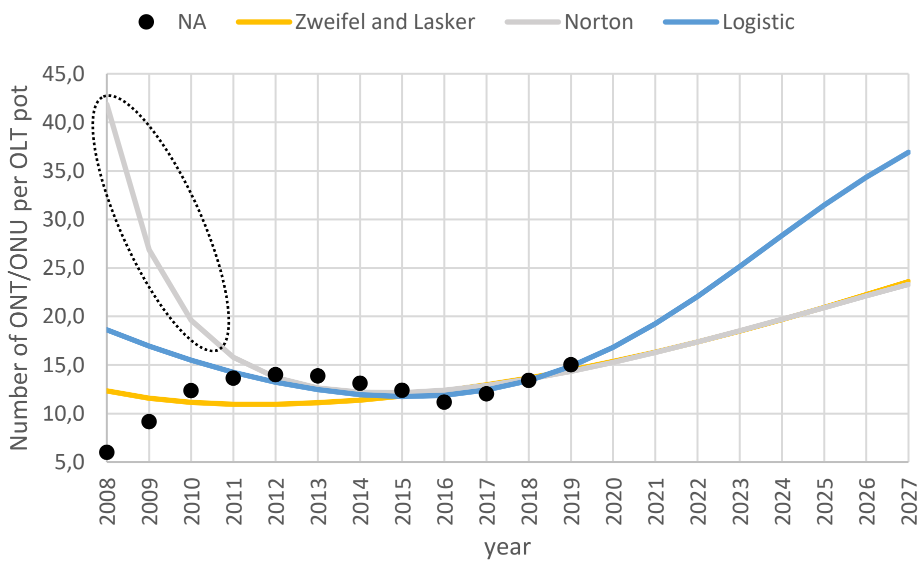

Figure 5-27 - ONT/ONU 2.5G GPON per OLT-2.5G GPON port for the NA market.

5.4 Conclusions

This chapter presented and analyzed the diffusion and rate of growth analysis of GPON ONT/ONU and OLT ports in EMEA, North America, and Globally. The data was modeled to the different studied growth curves by using an NLS regression. The estimated model parameters were compared, and the best fit models were determined. An evaluation of the forecasting capabilities of each type of growth model was also performed and a comparison of the estimated models with FTTH/B penetration was also done.

As regards the model best fit to explain the pattern adoption dynamics of ONT/ONU GPON and the best model forecasting performance for both short-term and mid-term adoption, we point out Gompertz for the Global market and Logistic model for EMEA and NA.

With regards to OLT GPON, the Logistic model presents the best fit to explain the pattern adoption dynamics and the best model forecasting performance for both short-term and mid-term adoption.

5.5 Bibliography

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Chapter 6: Analysis of uncertainties in GPON diffusion and rate of growth

This chapter has analyzed the uncertainties in GPON diffusion and rate of growth in EMEA, NA, and globally. The uncertainties in GPON diffusion are identified and different multiple S growth curves are modeled to the data. A comparison of the estimated parameters of the multiple S curves is realized and an evaluation of the forecasting capability is done.

The uncertainties related to PON investments are explored with Bi-Gompertz and Bi-Logistic models as well as a multi-Gompertz and multi-logistic.

6.1 Uncertainties related to the development of PON technologies

The development of innovation follows different phases before commercialization which are normally synthesized in four stages [1], [2]: predevelopment, take-off, breakthrough (acceleration), and stabilization. The initial steps are crucial. During the predevelopment phase, the novel idea is improved to give practical application. In the take-off phase, firms must not take a different direction from the industry because of technological interconnections, network and learning economies [3].

Different types of uncertainties dominate depending on the phase of dissemination and the role of stakeholders. Uncertainties can have several origins. In this chapter, we follow the typology proposed by [4]. Thus, the main uncertainties affecting the PON technology sector relate to progress in the technology, the PON infrastructure, demand trends, policies, competitiveness, the existence of physical resources, and supplier uncertainty. Figure 6-1.

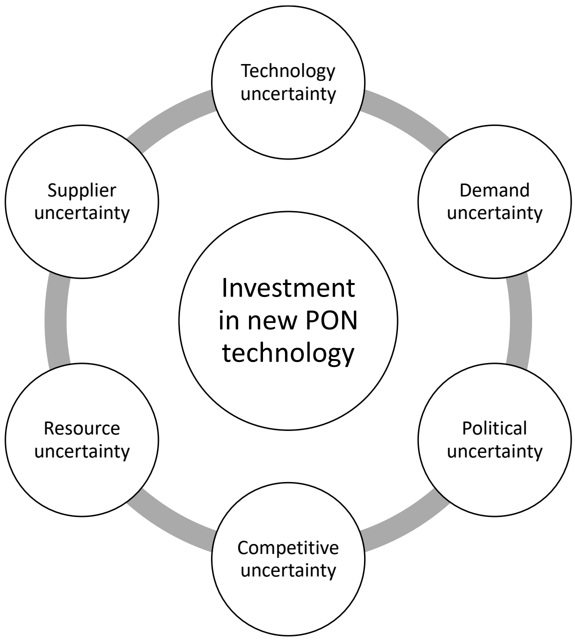

Figure 6-1 – Identification of uncertainties in investment in new PON technologies.

6.1.1 Technological uncertainties

Technological uncertainties have a major impact on the investment of PON technologies.

The unpredictable evolution of competing technologies contributes to amplifying the uncertainties and impedes the penetration of a specific technology in the PON market. The technical characteristics of the different technologies evolve thanks to learning [5], the speed of improvement, and the arrival on the main market [6]. All this constrain the possibilities of each of the new technologies to replace the older technologies.

The emergence of a new PON technology, such as XGS-PON, NG-PON2, 25GS-PON, or 50G-PON has an impact on the proliferation of GPON due to several factors. From a CO point of view, a telecom operator has to decide if:

- continue investing in GPON or delay its investment to gain an advantage using the new PON technology;
- the actual CO have the physical capacity to put more new OLTs or substitute the old ones;
- the actual CO have the physical capacity to accommodate CEX;
- the actual bandwidth capacity is enough for the actual and future users, or will end users need more bandwidth;
- will support over actual technology more types of services, or it will require more bandwidth and functionalities, as an example, support of mobile backhaul;
- new PON technology has the same power consumption and temperature working range as actual;
- new PON technology is profitable, new adopters, generally pay more for the newer technology;

From a client point of view, a telecom operator has to decide if:

- continue investing in GPON or delay its investment to gain an advantage using the new PON technology;
- maintain the same type of terminals or invest in new ones: single-family units, fiber gateways, and mobile backhauls;
- want several technologies over the same terminal, as Wi-Fi (numbers of antennas, type of Wi-Fi), IoT, number of ports, type of ports (1GbE, 2.5GbE, 10GbE), RF;
- Terminal speed: XG-PON1, XGS-PON or NG-PON2;
- The new PON terminal is “low cost”, new PON terminals have a higher cost due to the support of new higher speed optics.

Not only speed is enough for a new PON technology to penetrate and diffuse in the market but also, functionalities, capacity to support multiple technologies over it, density, power consumption, thermal working range, price, manufacturing capacity, and manufacturing delivery capacity for the target market.

6.1.2 Uncertainties about the evolution of PON infrastructure and demand

The establishment of a PON infrastructure requires very high initial investments, characterized by a long recovery time. However, without a PON infrastructure, manufacturers will not offer PON technology, telecom operators will not be capable of delivering new types of services, bandwidth demand will not be driven by the supply of new PON technologies; and without sufficient demand the infrastructure will not be profitable.

The type of implemented PON architecture can limit the implementation of a new PON technology. Several characteristics have to be taken into account regarding infrastructures, if the operator owns the fiber or if it is rented fiber, type of CO, location, and capacity, splitting ratio and consequently optical power budget, the existence of flexible fiber points between OLT port and first splitter.

Regarding COs, where the OLTs are located, they can be on a building, temperature controlled with no space limitation, or they can be located in a street cabinet or a pole. Depending on the location, several uncertainties may arise, this is: if OLTs shelf has the physical capacity to accommodate new boards; if their current backplane and data capabilities support the new boards for new PON technology; if the PON technology has the same density as currently installed technology, this is 1:1 capacity; if it is necessary to install coexistence elements to coexist both technologies; and if temperature support of new PON technology is the same as at least the legacy. Has also to be taken into account the extra power consumption, CO fiber organization, and uplink capacity

If the current OLT shelf is not capable of supporting new PON technologies, it is necessary to verify if current street cabinets or pole cabinets have space and capacity to install the new shelf and the impacts on services disruptions.

Higher splitting ratios require optics working in higher transmitting optical power and receiving in lower optical power, to accommodate the bigger PON budgets, this, of course, imposes limitations to new PON technologies, because require higher speed optics to work on their physical limits. Also, an actual infrastructure with no optical budget margin is always limited to coexist with a new PON technology since it will require changes on actual equipment to accommodate extra losses due to the integration and coexistence of future PON technologies.

The existence of a flexible fiber point between the OLT port and the first splitter is extremely important when thinking about a new PON technology. This flexible point allows the infrastructure to accommodate coexistence elements, filters for legacy PONs, or even be used as the physical port for new OLT.

Infrastructure investments are guided by demand forecasts. Forecasts help delay investment in the first infrastructures since investors are afraid of ending up with stranded assets very quickly.

Investing in new technology is guided by the investor's perception of future demand[7]. In the case of the PON market, this is new PON technology it is still difficult to predict the date and pace of market penetration and to envisage what will be the level of long-term stabilization of demand.

The diffusion of technology is complex and often dominated by particular historical circumstances that affect the path of technological change [8]. The presence of increasing adoption returns makes the result of competition between technologies uncertain: the increase in the scale of production (economies of scale) and the increase in cumulative production (learning savings) generally reduce average costs. Furthermore, once a new technology is adopted and implemented, the uncertainties weighing on its quality are reduced [3]: the benefit that the consumer derives from the good or service increases with the number of consumers using the same technology (club effects)[9].

But there is an obstacle to the development of these positive externalities induced by the progressive diffusion of alternative technologies to current GPON technology: it is the technical and institutional barring of the GPON sector even if alternative technologies are more technology data-efficient, the barriers to exit ("sunk costs") remain high for the currently dominant technology(Because there is a large amount of GPON equipment's in place – a sunk cost- operators are strongly motivated to reuse it if they can.). A current example is happening with multi-pon line cards. The service provider decided to move to a new PON line card, supporting XGS-PON and GPON in the same physical port, but instead of using new combo transceivers due to the amount and cost of GPON transceivers that exist in the network, they will populate the new multi-pon line card with "legacy" GPON transceivers.

Uncertainty about the behavior of demand is more central in the case of major technical changes. The evolution of demand in the medium and long term is challenging to anticipate since it is conditioned by several variables which are directly (like the evolution of preferences or needs) or indirectly (for example, the evolution of macro variables - Economic such as demography or economic growth) related to innovation. According to Rogers [2], adoption depends specifically on factors such as the relative advantage of innovation, compatibility with conventional technologies, complexity, experimentation, and finally observability.

On new PON technologies, which are trying to meet the need for higher bandwidth and reliability to support the services of tomorrow in the medium and long term the uncertainty about demand is superior.

6.1.3 Political uncertainty

An uncertain evolution of the legal and regulatory framework also increases the risks of investment. This political uncertainty can come from inconsistency or lack of standards, or hesitant behavior by political authorities.

Changing political directions further increases the uncertainty weighing on investment [4].

The transition to new PON technologies will not be possible without a stable framework and a clear vision on the part of the public authorities, a factor necessary to overcome the enormous technological and logistical challenges that still oppose this transition. For example, if the negotiation of a tax credit lasts too long, it will be in the best interests of firms to wait, as investment costs are likely to decrease in the future [10]. Public intervention is fundamental, allowing firms to appropriate the benefits of their innovations and encouraging them to innovate.

The European Commission aims to strengthen the competitiveness of Europe’s economy with an explicit focus on digital communications technologies. In light of this, the European Commission's strategy puts forward multiple policy measures and financial instruments that encourage private and public investments in fast and ultra-fast networks [11].

The effects of regulation and de-regulation have been subject of debate and study by FTTH councils around the world [12], [13], deregulation of wholesale broadband access where competition is sufficiently strong appears to have a positive effect on investment, as suggested by the example of Portugal. Regulatory policies that vigorously endorse infrastructure sharing and re-use could also benefit expressively to lower deployment costs. The policy focus is on empowering broadband via FTTH, disregarding the domestic bandwidth demand and solutions that make use of present broadband networks [14].

In a very changing technical context, the government may support bad technology with high costs and little benefit, on the other hand, the diffusion of new technologies can be blocked by the reinforcement mechanisms (infrastructures, complementary goods, etc.) of the dominant technology and therefore specific support for new technologies becomes necessary to overcome the technological bottleneck. Investments should then incorporate the value of creating technological diversity, taking into account the effects of irreversibility and the technical “lock-out” which, in the long term, may limit efficiency [15].

Standardization plays a major role in new PON technologies, the IEEE 802.3 Group, ITU-T SG15 question 2, and FSAN define all standards for PON technologies, however, the standardization process is long and complex. The IEEE 802.3 (Ethernet) standard development procedure is motivated on making the simplest and most cost-effective data link possible, on ITU-T SG15 Q2 and FSAN they ensure that everything that is needed is covered in an integrated standard system, which makes IEEE and ITU complementary [16].

The standardization process creates uncertainties on the evolution of new PON technologies:

“*Because these standards are the product of consensus, it is often the case that the only way to achieve that nearly unanimous state is to choose the “all of the above” answer”. For example, each operator has their own unique set of requirements. To get the support of as many operators as possible, the proposed system must support the superset of requirements. On the technical side, typically multiple solutions to a certain technical issue are proposed by the system and device vendors. In most cases, one solution is considerably better than the others and it is selected. However, sometimes there are two solutions that are so equally matched that it is difficult to choose a winner.* “[16]

Investing in a new PON technology has a very high risk before standardization because a given technology may not reach consensus in standardization and be discarded.

6.1.4 Competitive uncertainty

In a competitive framework, the effectiveness of the action of companies is conditional, it depends on the strategies of competitor companies. During a fast technological transformation, new entrants have an advantage over existing companies because they may not support the costs of developing the technology. Companies thus hesitate between engaging early in the new technology by making risky investments, or, on the contrary, supporting the opportunity cost of late entry into the market [9].

The following sub-sections are analyzed the competitive environment of a company and its influence on the definition of innovation strategies. We conclude with a discussion of the advantages and disadvantages associated with a “first-mover” strategy.

Porter´s five forces model is an important tool for understanding the main competitive forces at industry, and “*his genius reside in distilling the complex microeconomic literature into five explanatory or causal variable to explain superior and inferior performance”* [17].

6.1.4.1 Competitive environment analysis using Porter's five forces model

Porter's five competitive forces model [18] is a basic tool for analyzing the market environment, the use of which is used to better understand the nature of competition. Understanding competitive forces as much is fundamental for the success of companies as for the introduction of innovative projects. This analysis allows to prioritize the most important competitive elements in the sector and, from this, to build a competitive advantage.

According to Porter [18], the chosen strategy must allow the company to isolate itself from competitive forces and, if possible, act on the environment in its favor. The five determinants of project performance are the negotiating power of clients; the threat of new entrants; competition from alternative products or services; supplier bargaining power; competition between established companies, see Figure 6-2.

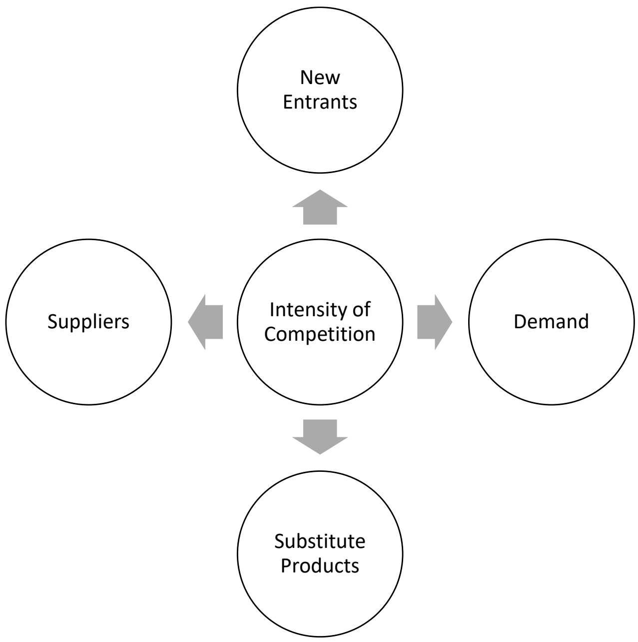

Figure 6-2- Porter's competitive strengths [18].

- **Clients' bargaining power** has a direct effect on quantities, prices, and conditions of sale, and therefore on the profitability of the project. It especially depends on the relative quantity of demand compared to supply. A single buyer facing a multitude of suppliers will have a lot of power to fix the terms of the negotiation. The market power of demand also depends on other factors such as the availability of substitute products. As an example, a broadband service provider bargaining power with equipment PON manufactures, as largest the service provider with bigger FTTH/B network as large its ability to negotiate and have access to equipment at a lower cost.
- **The risk of new entrants** is another important competitive force. The entry of new competitors attracted by market profits reduces profitability. The degree of the risk depends on the characteristics of the sector and the barriers to entry (capital intensity and economies of scale, conversion costs, learning curve). As an example:" *Efforts to reverse unbundled access included the global standards for the PON that were to replace copper local loops, developed at ITU-T Study Group15. These simply omitted unbundled access because of the absence of new entrants, governments, and regulators to argue for its inclusion. The incumbent operators and their vendors wanted a closed version of PON, which improved the economics of network investment because it excluded service-based competitors"*[19].
- **Competition from alternative products** or services widens consumers' alternatives by making them more sensitive to price increases. High conversion costs and a low willingness of consumers to change make this competitive force less important, and vice versa. Competition amongst PON manufacturers is constrained, in terms of the numbers of rivals and the nature of the technologies, by the need for licenses and use of common standards, the obligations to interconnect and interoperate. Using common, usually global, technology platforms and business models, innovations are often easily replicated, and competition limited. Differences in PON products are difficult for service providers to understand and offer a limited basis for competition.
- **The bargaining power of suppliers** to impose their conditions has an effect comparable to the bargaining power of customers. Here, the costs of switching suppliers are a key variable, they depend in particular on the existence of alternative suppliers. The high competition among supplying firms in the PON industry, the low product differentiation, the high number of substitutes, and service providers' high level of product knowledge are factors that contribute to a reduction of suppliers' bargaining power in the PON broadband industry [20].
- Finally, **the degree of competition** in the sector is simultaneously the result of the other four market forces. Stronger competition generally means less profit. The position of the sector about the life cycle of the product is another important factor for the strength of competition (growing or stagnating sector; phase of product innovation or process improvements; the number of companies high or reduced). "*The telecom industry is a very dynamic industry due to the vast changes in*

technology and the forces impacting the industry. Technological innovations, standardization, and regulatory mandates are some of the forces that can affect the competitive landscape in the telecom industry."[21]

The five competitive forces are not disconnected but rather linked together. Thus, the environment favorable to the introduction of new technology is made up of a large number of buyers with little bargaining power; the absence of substitutes; the abundance of external sources of raw materials, intermediate goods, labor, and services; and finally weak competition between established companies (for example the innovator succeeds in having the monopoly of a profitable market whose profits reward the risks taken initially).

PON technologies cannot be assessed from the comparison with the ideal environment just described. First, technological substitution for new PON technologies must face the resistance of established technologies, in particular the GPON. Second, a technological transition for a new PON technology has never occurred in the past and therefore the behavior of demand remains very uncertain.

On the supply side, many companies are active in the production of new PON technologies around the world. However, a large-scale transition to a new PON technology poses the question of the availability of resources.

6.1.4.2 Uncertainty about available resources and supplier behavior

The development of radical innovations, such as new PON technologies, is likely to come up against a lack of financial, human, and raw materials. These problems must arise more prominently during the pre-commercial phase when it is difficult to provide all the resources necessary to carry out the project.

The financial needs necessary for the technological and infrastructure development of new PON technologies are enormous, and the companies involved will be all the more difficult to access external financing as the profitability of the sector is still uncertain. This is more important during the pre-commercial phase during which significant expenses must be incurred immediately for income that will be generated in the future [22]. At this level of innovation, one of the following situations is possible: the company has a financial position enabling it to finance projects particularly from equity without taking into account the risk associated with each of the investments; the firm is obliged to call on external financing, thus remaining dependent on its availability and reimbursement conditions which may compromise the profitability of the project; Finally, the firm is not able to finance the development of innovation either by equity or by external financing, and therefore the financing depends exclusively on public subsidies. The latter situation can be very unstable because government priorities can change from year to year and threaten the continuity of projects (see political uncertainty).

The financial problem is particularly felt at the level of new PON technologies. Generally, new inventions for future PON applications come from medium-small companies. The objective of these manufacturers is to make technology competitive as quickly as possible to enter the market, reduce losses and rely more on the revenues generated by the market to finance development expenses. Until then, R&D spending is dependent on public funding and specific demonstration projects (several examples of R&D projects public funding can be found in [23]).

Radical innovations such as new PON technologies also require new human skills which sometimes do not yet exist and therefore need to be trained. The lack of human resources is normally bigger in the case of disruptive technologies than in incremental innovations due to the critical character of skills associated with radical technical change.

Innovation can still be constrained by the limited availability of raw materials: thus, for example, a new PON technology that requires the use of certain types of lasers with very specific performance can considerably increase production costs and raise questions about the competitive nature of large-scale production.

Innovation may also be constrained by the uncertain behavior of suppliers concerning the availability, quality, and cost of the supply [24]. In the context of new PON technologies, the choices of the players have interconnected: laser manufactures, vendor equipment manufacturers, suppliers to operators.

These uncertainties can, however, be reduced by vertical integration [24]: this is how equipment manufacturers set up partnerships with lasers manufacturers producing new lasers for the development of new PON technologies.

The competitive forces model presents a relatively static image of the market. This constitutes a changing environment where the dynamic aspect is very important. The introduction of innovations changes the market environment for the innovator.

The next point analyzes the factors to consider when defining a technology strategy, especially when companies are reluctant to enter a new market.

6.1.4.3 Advantages and disadvantages associated with a first to enter strategy

Innovation is a means for the company to position itself on the market. Technological change has a significant impact on its competitive capacity. Technological change affects the company's wealth, growth, and development potential [18].

The latter implements a strategy to obtain (or maintain) a competitive advantage which allows it to isolate itself from the impulses of the evolution of competitive forces. Strategy is the art of building sustainable defensible competitive advantages [18]. Porter identifies three generic or basic strategies: dominance by costs; differentiation; or concentration in a market segment by price advantage or differentiation, Table 6-1.

The technological choice must reinforce the basic strategy of the company [18]. Technological decisions have a different nature depending on whether this strategy is dominance by costs, differentiation, or focus on a specific market.

The investment in PON technologies can then be motivated by a search for lower costs, taking advantage of the better efficiency of PON technologies. Companies can also enhance the characteristics of these innovations to improve the quality of their offer (efficiency, reliability), in general, or on a particular market. Finally, investment in new PON technologies may initially target a specific market segment only, like Business-to-business (B2B) or mobile backhaul.

	Cost Dominance	Differentiation	Cost-based focus	Concentration based on differentiation
Technological progress on products	Development of products targeting cost reduction	Improvement of the characteristics of the product in terms of perceived quality, their distribution, and reinforcement of the costs of change	Product design to meet the needs of selected segments	Product development for the satisfaction of a particular segment better than competitors

Table 6-1 - Product Innovation and competitive business strategy [18].

An important aspect concerns the introduction of major innovations likely to give the pioneering firm a technological edge. Innovation opens up opportunities for the firm, and also exposes it to dangers.

The innovator strategy in the market has advantages for the firm in terms of image; faster progress on the learning curve; setting norms and standards [9]. These advantages must, however, be balanced by the disadvantages of such a strategy, in particular, because of the uncertainty about costs and the evolution of demand. Furthermore, in the case of major innovations where the initial uncertainty is very high and it disperses with the increase in production. It all depends on the pioneers who open the market. Understandably, these do not enter the market without having sufficient profit prospects to repay capital and risk.

Competitors' behavior must also be taken into account when defining the innovation calendar. Especially when it comes to radical technological change, firms hesitate between making irreversible decisions too quickly about new technologies, and the opportunity cost of adopting innovation too late [9]. The decision will then depend on the relative weight of the advantages of the newcomer, in particular, in terms of information on the market potential and economies of scale and learning.

However, the existence of externalities is likely to delay the entry of companies into the market. In addition, spillovers are more important in the case of radical innovations [25]. The innovator fails to capture all of the social benefits of investing in R&D, infrastructure, or the commercialization of the new technology, which reduces incentives for innovation [5]. Spillovers can take different forms: knowledge (the technology developed by innovators will be available free of charge to other companies); regulation (innovators bear the cost of creating codes and standards for new technologies); skills (followers can use the skills formed without having contributed to the training effort); or complementary goods (no need to reproduce the network of services that has been created by pioneer companies). Uncertainties on revenue should be discounted in the financial analysis of investment which delays the implementation of projects.

6.2 The investment decision in an uncertain environment: the case of a new PON technology

The uncertainties hanging over the future of PON are numerous. We are going to discuss the importance of a techno-economic model, starting from the theory of real options, which helps to better understand the uncertainties specific to new PON technologies.

When investments are marked by great uncertainty about the future, it is difficult to analyze their viability with precision. In this context, companies such as telecom operators use simple methods to assess the information available.

In a very uncertain context, companies prefer projects that allow the initial investment to be quickly recovered. When investors are faced with the choice between several comparable and mutually exclusive projects, they will take the one with the shortest payback period. This criterion hardly favors investments whose benefits are long-term.

Investment in new PON technology is very capital intensive and requires a long recovery period. In addition, the infrastructure must be oversized in the first years to guarantee their use to the first adopters. This means that the infrastructure will probably be underused during the transition period, penalizing profitability.

6.3 The theory of real options and the evaluation of the profitability of the investment on a new PON technology

Real option (RO) theory provides a powerful instrument to evaluate investment opportunities when the cash flows are ambiguous [26]. The theory of real options starts from the observation that a company can start a project which, despite a negative net present value in the present, opens the possibility of making profitable additional investments or contributes to creating new markets with high potential for profitability in the future [27].

The telecommunications industry uses real options analysis as a decision instrument for taking key strategic decisions and prioritizing investments because it captures the value of decision-making flexibility in practical cases. [26] [28].

An excellent explanation of real options is given by Johnathan Mun in [29]: "*Real options is a systematic approach and integrated solution using financial theory, economic analysis, management science, decisions sciences, statistics and econometric modelling in applying options theory in valuing real physical assets as opposed to financial assets, in a dynamic and uncertain business environment where decisions are flexible in the context of strategic capital investment decision-making, valuing investment opportunities and project capital expenditures.*"

However, not all investments have an option value. For this, two conditions must be fulfilled: (1) the initial investment must constitute a necessary stage for the final investment to benefit from the learning and information gains on market potential; (2) it must strengthen the company's competitive advantage, and also generate surpluses from a certain point which can compensate for the losses suffered during the early stages [27].

While a standard techno-economic analysis results in a net present value (NPV) analysis, the real options analysis methodology extends the techno-economic methodology with three extra steps. The real options analysis thus consists of four steps:

- NPV analysis;
- Identifying the uncertain input parameters of the project influencing the result;
- identifying the options;
- Calculate the option's value.

In the standard business case analysis, this is NPV, modeling the adoption of the offered services is an imperative aspect.

As discussed, the second step of the RO analysis methodology requires identifying the uncertainties present in the case. As always in long-term investments, like PON technologies projects, all input parameters are uncertain, especially in the long run. One major uncertainty is the users' adoption. Users' adoption is typically the most uncertain factor in economic analysis. Before the introduction of a new product or service, it is very hard to estimate how many consumers will adopt it and it is a factor with a high impact on the final economic calculation. Research into the adoption of new services and products has indicated that consumer adoption generally can be modeled using a bell curve, with the Rogers' bell curve as the most well-known for technology adoption [2]. These models have been translated to mathematical S-curve penetration models, like the Gompertz curves, extensively study in this work due to their importance on the decision-making process.

6.3.1 The effect of different sources of uncertainty on the option value

In the case of irreversible decisions, uncertainty contributes to increasing the value of the option to wait and thus delaying investment. According to the option theory approach, the decision investment involves two costs: the investment cost; and the opportunity cost of not leaving the investment decision for later, when all the conditions are more favorable. Dixit and Pindyck [10] show how an investment decision is very sensitive to the unpredictability of the project value. However, different types of uncertainty do not have the same effect on the opportunity cost of the investment.

Several sources of uncertainty can affect the value of the option to wait, the ones that reduce the value of the option to wait (i.e. accelerate investment) and the ones that increase the value of the option to wait.

Among the uncertainties likely to accelerate investment, we consider:

- **Technical (or cost) uncertainty**: these are particularly important in the case of long-term investments (often carried out in several stages). There are at least two types of cost uncertainties that have a contradictory effect on the value of the option to wait. The first is technical and relates to the difficulty of completing the project or estimating its total cost. In this case, information on the costs and the value of the project will be revealed only after the first investments have been made. Therefore, technical uncertainty makes the investment more attractive because of the value of the shadow information beyond its direct contribution to the realization of the project. A particular case concerns the effect of learning generated by an increase in cumulative production (Arrow, 1962a). Current production can be seen as an investment in reducing future costs. The second uncertainty concerns the volatility of prices of entrants having an opposite effect to that of technical uncertainty. The cost of the main productive factors (labor, land, capital) can vary unpredictably by influencing the cost of investment. These changes are independent of the company's investment decision since they are an external source of uncertainty; so there is no incentive to accelerate investments and they prefer to wait for more information;

- changes in interest rates can also have two opposite effects. On the one hand, they increase the likelihood of a fall in interest rates which discount future cash flows. On the other hand, the volatility of interest rates encourages the agent to wait for more information rather than invest immediately.

Other uncertainties contribute to delaying investments such as those concerning:

- **the behavior of the request**. Fluctuations in demand can also be reflected in price changes. In most markets, the degree of price uncertainty increases with the project time horizon. This uncertainty affects the value of the investment in two ways. On the one hand, the net present value will be lower - reflecting for example the use of a higher discount rate. On the other hand, the opportunity cost of the investment increases since there is a possibility that prices will increase in the future;

- **competition**. In the case of favorable development, other companies enter the market, which increases competition. This limits margins and compromises profit growth. The wait allows the company to review its position and better understand if the business opportunity is just transient;

- **policies**. Uncertainties about the development of support instruments (taxation, subsidies) or regulations can delay investments. For example, if an investment tax credit or the possibility of public financing is considered for too long, companies will prefer to wait until public support is adopted;

- **irreversibility**. An investment can be considered irreversible in cases where it is poorly recoverable or transferable (sunk or stranded costs). Investing in a project involving sunk costs entails a significant opportunity cost which is the possibility of investing later. The opportunity cost increases with the perception of the risk of the project.

In the case of PON technologies, the complexity of innovation widens the spectrum of uncertainty.

When a project is subject to uncertainty, especially technological, and when it can be carried out in stages, all the information relating to costs and technological potential is not revealed at the time of the first investment execution phase. The implementation of this first phase, therefore, has an informative value that reduces the costs of the entire project [10]. This is particularly the case for technologies with high potential economies of scale, learning gains, like PON: we know that increasing cumulative production will reduce costs in the future.

If a project is not initially profitable, it can be broken down into a series of stages, each of which constitutes an option to be widened. The investor can stop, resume or abandon the investment at any time if the targeted minimum performances are not reached, which allows him to avoid heavy losses. The principle is that the value of the information obtained from the first investments justifies its realization.

The first investment step then corresponds to a real option whose value is equivalent to that of a financial purchase option (option call option). The option holder invests to have the right (not the obligation) to continue investing after receiving more information about the technology and the market [10].

6.4 Bi-S curves modeling uncertainties - GPON market

In previously studied models, the rate of growth, this is, new adopters, presents a lower fit to data compared to the cumulative. As discussed, is important to model the uncertainties to be taken the right decisions, as so, modeling the uncertainties has to be part of the techno-economic methodology.

The different BI-S growth models presented in section 4.1.3 were fitted to the vendor units data for ONT/ONU – 2.5G GPON and OLT- 2.5G GPON for Global level, EMEA, and NA from OMDIA market share 2Q20 [30] (Appendix B- GPON Market Share) to analyze the variations in market behavior due to uncertainties and to define the best parametrization. As presented before, the new adopters on the annual market in the traditional growth models present a lower fit to data compared to the cumulative. By visual analysis of the global vendor units for ONT/ONU 2.5G GPON is possible to identify the two major market uncertainties, Figure 6-3, marked with arrows, in 2015 a higher annual equipment adoption is observed, and in 2019 a decline in equipment annual adoption is notorious.

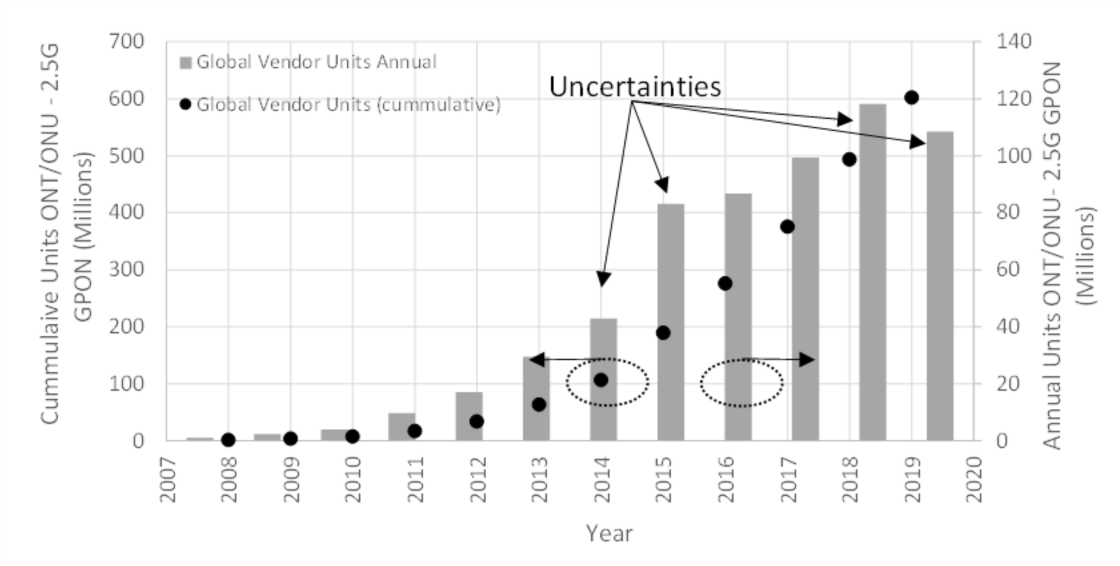

Figure 6-3- Global vendor units for ONT/ONU – 2.5G GPON.

As regards the EMEA market, three major market disturbances are identified, Figure 6-4, marked with arrows. Between 2010 and 2012 is observed a market adoption fluctuation, in the 2016 year a decrease in adoption is observed and in the 2019 year a large number of equipment adoption is noted when compared to previous years.

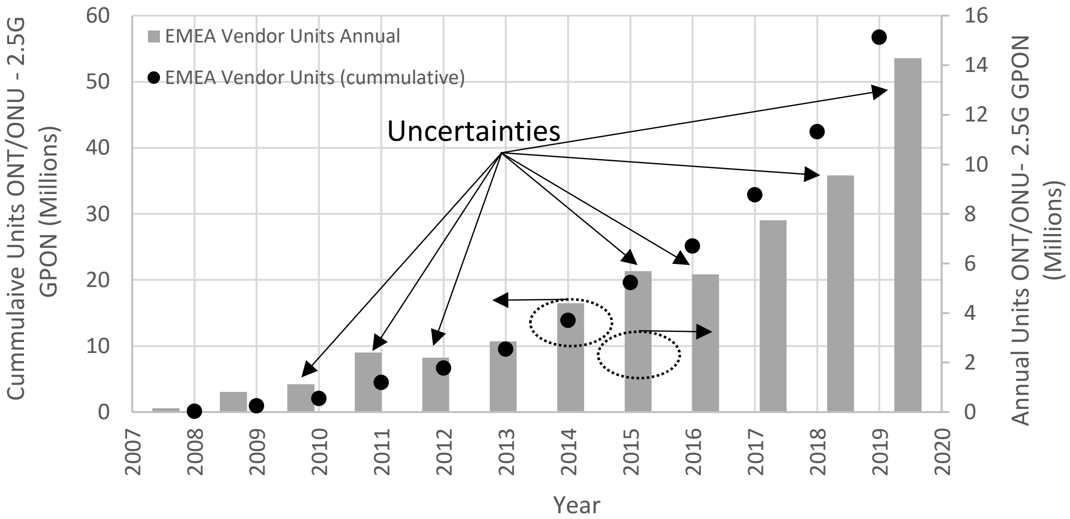

Figure 6-4- EMEA vendor units for ONT/ONU – 2.5G GPON.

In NA, the annual market adoption fluctuations were mainly observed at the beginning of the diffusion of GPON, between the 2008 and 2011 years, Figure 6-5, marked with arrows.

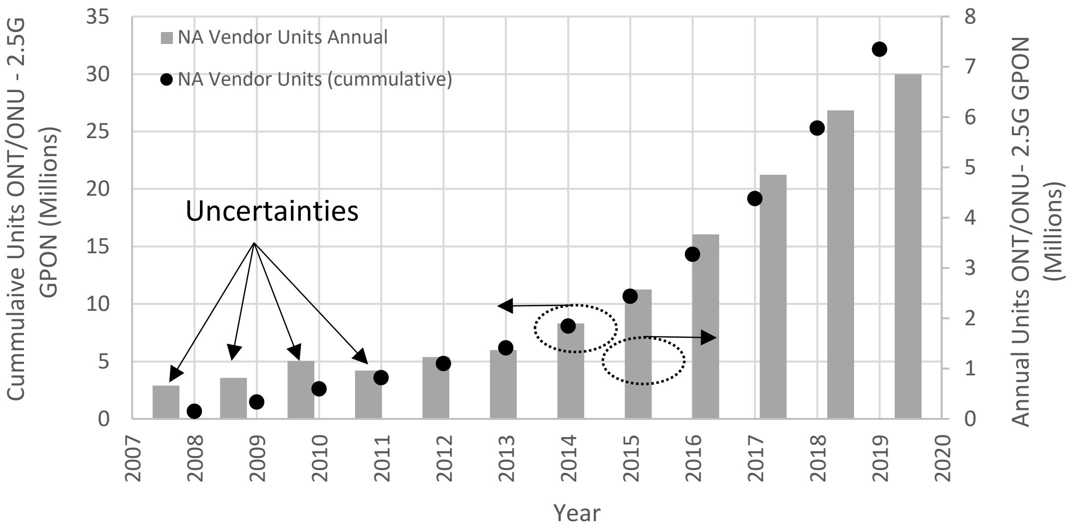

Figure 6-5 - NA vendor units for ONT/ONU – 2.5G GPON.

These accelerations and decelerations in GPON equipment adoptions, are possible to be mapped in specific events happening in the FTTx world, the main influence on take-up rate is how long an FTTH/B service provider has been in operation and how the equipment adoption follows the service availability and the infrastructure (not deployed simultaneously in every country). Public policies (the government can play the role of an “enabler” or a “rule-maker” in broadband development [31]), incumbent operators investment in FTTH (as an example, in EMEA in 2017, incumbents operators represent 43% of the total number of homes passed vs 21% in 2011 [32]), the reluctance of some countries investing in FTTH/B technologies are also behind the equipment annual adoption.

At Global level, specifically in the Asian market, China plays a major role in equipment adoption and acceleration and deceleration of the market, one thing to be notice is that: in 2013, the State Council officially announced the Broadband China Plan, in which quantified goals, a technology roadmap, development timetable, key tasks and specific projects were set, aiming to build a ubiquitous, fast and advanced national broadband network before 2020; One week after the release of this plan the State Council released another policy guideline entitled "Several Opinions of the State Council on Promoting Information Consumption to Expand Domestic Demand" where the Chinese government aimed to boost public and household spending on the information products and services and in 2015, the State Council issued the third directive policy on broadband development, entitled "*Guiding Opinions of the General Office of the State Council on Accelerating the Construction of High-speed Broadband Networks, Boosting Internet Speed and Lowering Internet Charges*" [31].

A historical view of the FTTH market, Appendix B - PON and FTTH a historical view, is provided to map the uncertainties and market variations observed in the different curves.

To estimate the initiate parameters, we are going to use the results previously obtained by the Gompertz and Logistic curve to the GPON ONU/ONT 2.5G GPON. That is, this Bi-Gompertz and the Bi-Logistic model require an a priori or external knowledge of the system to derive estimates reasonably and efficiently. In Table 6-2 is possible to compare the results of the different Bi-S curves model to GPON ONT/ONU vendor units for the different analyzed regions. The parameters defined for the NLS regressions can be found in Appendix C - Uncertainties related to investment in PON technologies, Bi-Logistic, and Bi-Gompertz to model GPON terminals . The results of the NLS regression suggest the general suitability and sufficiency of all the growth models towards explaining the adoption and the market fluctuations of the GPON technology across the three studied regions. This is evident from the high values of their adjusted *r square* – the metric used to evaluate the model fitness criteria. The *r square* in the cells highlighted in dark grey presents the best model fit to the data.

	Market Potential Volume (millions)	**Cumulative market *r square***	**Annual Market *r square***
Global vendor units for ONT/ONU – 2.5G GPON			
Bi- Logistic	802	0,999	0,978
Bi-Gompertz	1504	1,000	0,986
EMEA vendor units for ONT/ONU – 2.5G GPON			
Bi- Logistic	145	0,999	0,987
Bi-Gompertz	196	0,998	0,963
NA vendor units for ONT/ONU – 2.5G GPON			
Bi- Logistic	148	0,999	0,989
Bi-Gompertz	172	1,000	0,998

Table 6-2 – Summary of modeling of different Bi-S curves to vendor units for ONT/ONU – 2.5G GPON.

In terms of the model best fit to explain the adoption dynamics of GPON, the following could be observed after taking into account the *r square* and the feasible market potential estimates. For the global and NA market, the best fit to data is obtained by using the Bi-Gompertz. For EMEA, Bi-Logistic presents the best fit for data.

For the analyzed markets, the Bi-Gompertz reveals an improvement of the fit compared to the fit of the simple S curves tested in section 5.2. As so, the modeling using Bi-Gompertz can fit complex growth with multiple processes.

The values of the estimated constants by the fitting of the Bi-Gompertz function were applied to the temporal derivative of the market size. As regards the annual modeling using cumulative constrains is demonstrated an improvement of the fit compared to the fit of the simple S curves tested in section 5.2.

The fit of the Bi-Gompertz model to the Global and NA vendor units for ONT/ONU – 2.5G GPON can be observed in Figure 6-6 and Figure 6-7 respectively. In the same figures are represented the annual market fits using the constants obtained by the fit of the Bi-Gompertz and a model fit using the same constraints of the cumulative market.

The fit of the Bi-Gompertz to the Global vendor units can be observed in Figure 6-6. A potential market forecast of around 1,5 billion units for GPON ONU/ONT globally was determined. The first curve has its inflection point at end of the year 2012 and the second curve in the middle of the year 2018. The maximum growth rate was 21,9% for the first curve and 21,2 % for the second Gompertz. The time interval to grow from 10% to 90%, this is, Δt, for the first curve is 14 years and 14,5 years for the second one.

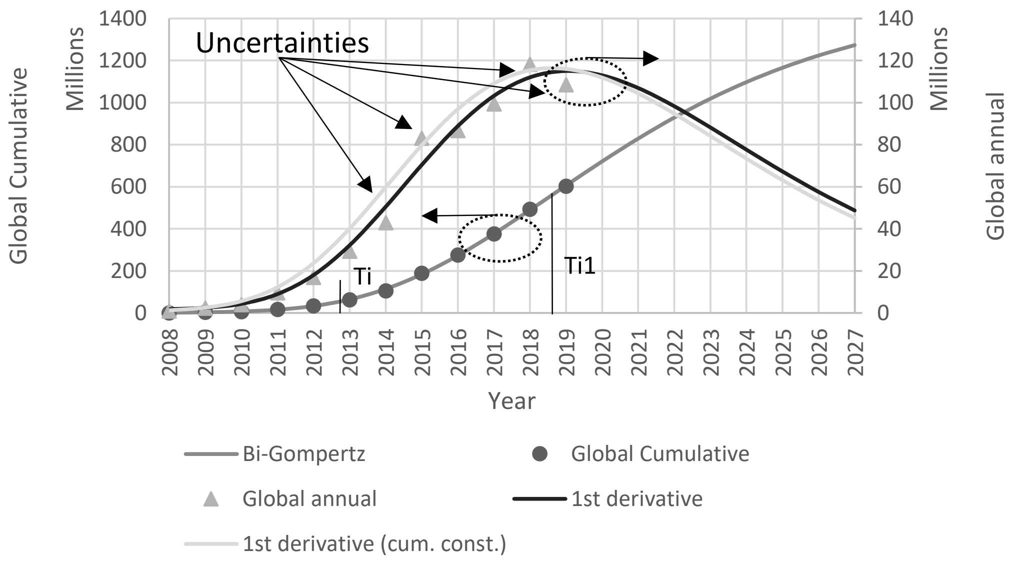

Figure 6-6 – Bi- Gompertz fit to the global vendor units for ONT/ONU – 2.5G GPON.

As what regards the NA market, a potential market forecast of 172 million units was determined by using Bi-Gompertz. The first curve has its inflection point in the middle of the year 2009 and the second curve in the year 2023. The maximum growth rate was 40,6% for the first curve and 14,8% for the second Gompertz. The time interval to grow from 10% to 90%, this is, Δt, for the first curve is 7,6 years and 20,8 years for the second one.

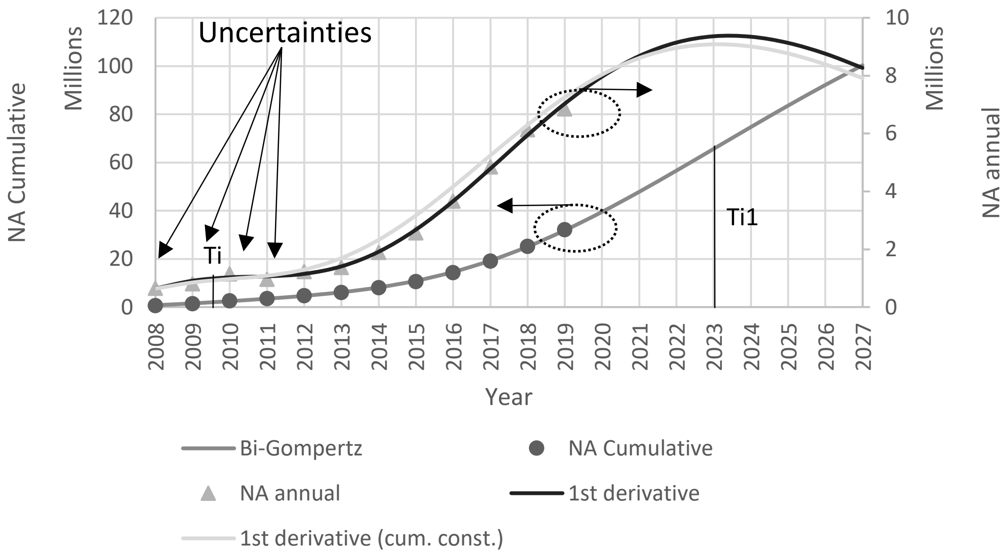

Figure 6-7- Bi- Gompertz fit to the NA vendor units for ONT/ONU – 2.5G GPON.

Regarding the model fit of the Bi-Logistic to the EMEA vendor units for ONT/ONU – 2.5G GPON, it can be observed in Figure 6-8. A potential market forecast of 145 million units was determined. The data set is the sum of two identical logistic growth pulses with the midpoints separated by 8 years and two overlapping S-shaped curves are visible. The first curve has its inflection point in the middle of the year 2012 and the second curve in the middle of the year 2020. The time interval to grow from 10% to 90%, this is, Δt, for the first curve is 5,6 years and 9,6 years for the second one.

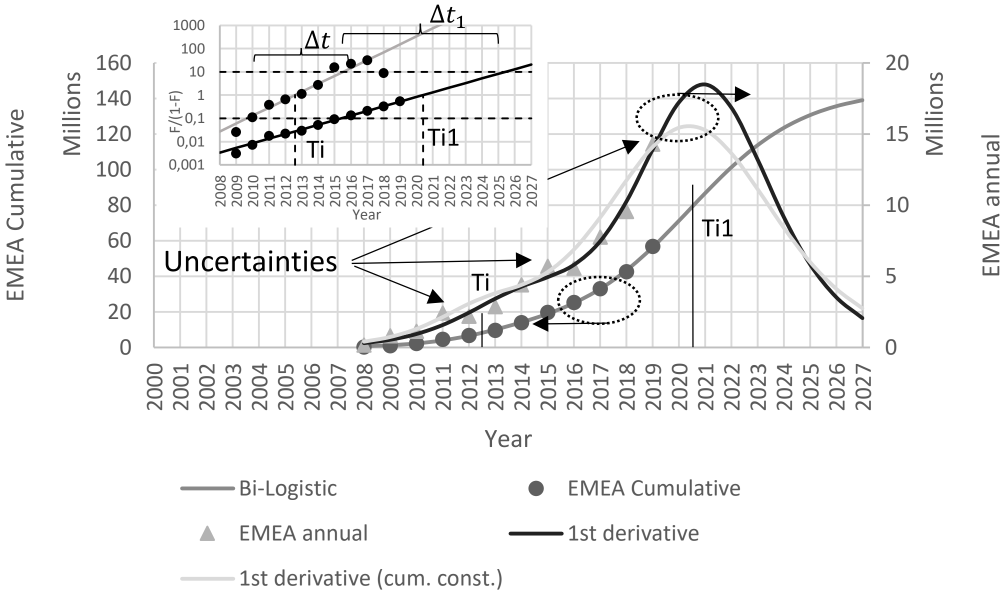

Figure 6-8- Bi- Logistic fit to the EMEA vendor units for ONT/ONU – 2.5G GPON. The inset shows the component growth curves linearized with the Fisher-Pry transform.

The two data sets, $W_{0i}(t)$ and $W_{1i}(t)$ are plotted as a linear function of time by utilizing the Fisher-Pry transform, as shown in the inset, left side top of Figure 6-8, with the circle designating $W_{0i}(t)$ and squares designating $W_{1i}(t)$. As is possible to see the first and second curves are parallel diverging growth curves, the longer pulse in the second curve emanates from the success of developing the technology, which exhibits prolongation of the second curve.

The same constraints used for the cumulative modeling were applied to the temporal derivative of the market size to analyze uncertainties. As happened to the cumulative market, the Bi-Logistic derivative presents a better fit than the traditional Logistic derivative.

It is important to notice that the EMEA market is, from the markets under analysis, the one that presents large variations of the annual market over time due to uncertainties. Under visual analysis is possible to identify 3 major variations. This specific market will be analyzed later using a multi-Logistic model.

To evaluate the forecasting accuracies of each of the Bi-S models, and as done on the modeling of the simple S growth curves, we segregate a portion of the know data points from the historical data and keep them aside as the “hold-out” data. We then forecast the GPON adoption figures, over the same period as the hold-out data, using the NLS determined coefficients of the growth models. Finally, the MAPE values are evaluated for the corresponding periods, by comparing the forecasted values with the real GPON adoption values. The MAPE indictor thus obtained, helps in establishing the forecasting capabilities, both the long and short-term of the models, in a rigorous manner.

Table 6-3 presents the results of the MAPE calculations for the different Bi-Gompertz and Bi-Logistic models that fit the vendor units for ONT/ONU -2.5G GPON. We have chosen 3 scenarios with varying hold-out periods consisting of 4 (MAPE4), 6 (MAPE 6), and 12 (MAPE12) years, respectively.

Regarding the forecasting performance of the models, we can observe from the table that for the cumulative and annual Global and NA markets the Bi-Gompertz model present the best performance.

As regards the EMEA cumulative and annual market, the Bi-logistic model-based forecast presents the best performance for short-term and mid-term adoption and Bi-Gompertz in the long-term adoption.

ONT/ONU	**Cumulative Market**			**Annual Market**		
	MAPE4 (%)	**MAPE6 (%)**	**MAPE12 (%)**	**MAPE4 (%)**	**MAPE6 (%)**	**MAPE12 (%)**
Global vendor units for ONT/ONU – 2.5G GPON						
Bi-Gompertz	0,72	2,22	9,79	7,71	12,37	21,57
Bi-Logistic	1,26	2,97	40,63	14,07	14,52	40,58
EMEA vendor units for ONT/ONU – 2.5G GPON						
Bi-Gompertz	2,08	3,05	23,84	2,08	3,05	23,84
Bi-Logistic	0,95	1,46	35,91	0,95	1,46	35,91
NA vendor units for ONT/ONU – 2.5G GPON						
Bi-Gompertz	1,09	1,33	3,78	7,53	12,64	11,81
Bi-Logistic	0,99	1,47	10,52	11,29	14,84	20,26

Table 6-3- MAPE (%) for different hold-out periods for the Bi-Gompertz and Bi-Logistic growth models fit the vendor units for ONT/ONU – 2.5G GPON.

The Bi-Gompertz and Bi-Logistic model-based forecasts are consistent across the three regions for both the cumulative and annual markets presenting a good forecast model for both short-term and mid-term adoption. As what regards the model best fit to explain the pattern adoption dynamics of GPON taking into account the market fluctuations and uncertainties, Table 6-2, and the best model forecasting performance for both short term and mid-term adoption, Table 6-3, we point out Bi-Gompertz for the Global and NA market and Logistic model for EMEA.

As presented before, in section 5.3, the traditional growth model for new adoptions of GPON OLT ports on the annual market presented low to fit data, mainly in EMEA and NA. Figure 6-9 are identified the annual market fluctuations due to uncertainties (marked with arrows – black arrows - Global market, grey arrows - EMEA, light grey arrows - NA) for the three analyzed markets. As it is possible to see, in the Global market a fast adoption is observed between the years 2010 and 2011 followed by a “stagnation”, after 2016 the market started to decline. In the EMEA market, between the years 2010 and 2015, the OLT GPON port adoption is floating. As what regards the NA market, it presents a low adoption between the year 2009 and 2013 followed by a fast adoption and a decline after the year 2016.

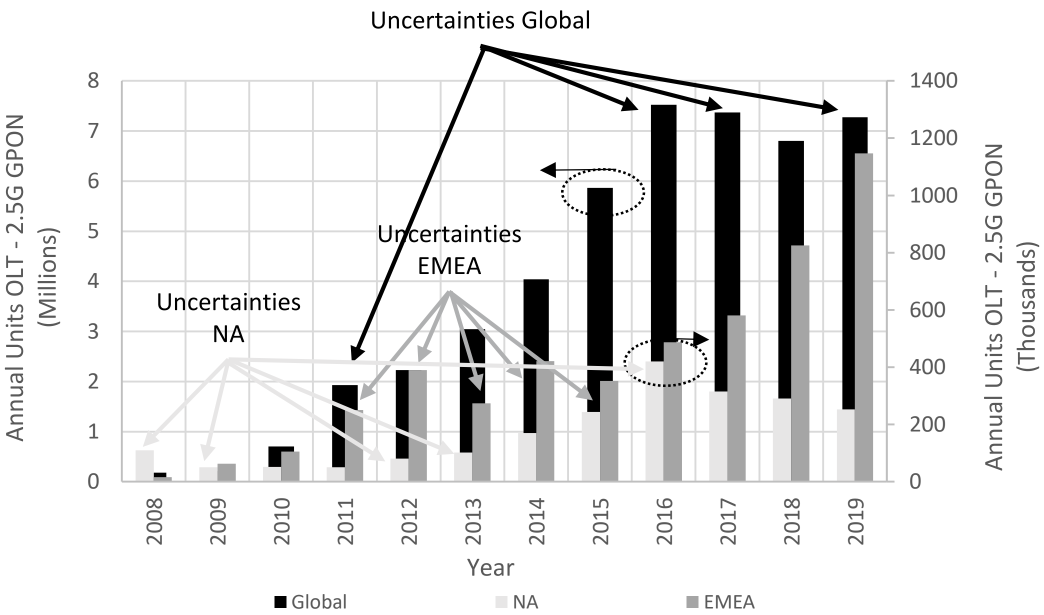

Figure 6-9 –Global, EMEA, and NA annual vendor units of OLT ports – 2.5G GPON and identification of market uncertainties (marked with arrows – black arrows - Global market, grey arrows - EMEA, light grey arrows - NA).

To estimate the initiate parameters, we are going to use the results previously obtained by the Gompertz and Logistic curve to OLT 2.5G GPON. That is, the Bi-Gompertz and the Bi-Logistic models require an a priori or external knowledge of the system to derive estimates reasonably and efficiently. The parameters defined for the NLS regressions can be found in Appendix C -Uncertainties related to investment in PON technologies, Bi-Logistic to model GPON OLT, and Bi-Gompertz to model GPON OLT. In Table 6-4 is possible to compare the results of the different Bi-S curves model to OLT GPON vendor units for the different analyzed regions. The results of the NLS regression suggest the general suitability and sufficiency of all the Bi-S growth models towards explaining the adoption and the market fluctuations of the OLT GPON ports across the three studied regions. This is evident from the high values of their adjusted *r square* – the metric used to evaluate the model fitness criteria. The *r square* in the cells highlighted in dark grey presents the best model fit to the data.

Table 6-4 compares the results of the different Bi-S curves model to GPON OLT vendor units for the different analyzed regions. This analysis can be further explored in Appendix C - Bi-Logistic to model GPON OLT and Bi-Gompertz to model GPON OLT .

As happened for the ONT/ONU markets, the fitting of the Bi-S functions presented an improvement of the fit compared to the fit of the simple S curves tested in section 5.3. As regards the EMEA market, and because the Bi-Gompertz model presents the best improvement in the data fit, *r square*, the results are further explored here.

	Market Potential Volume (million)	**Cumulative market *r square***	**Annual Market *r square***
Global vendor units for ONT/ONU – 2.5G GPON			
Bi- Logistic	59	1,000	0,975
Bi-Gompertz	94	1,000	0,983
EMEA vendor units for ONT/ONU – 2.5G GPON			
Bi- Logistic	7,8	0,999	0,975
Bi-Gompertz	12	0,999	0,979
NA vendor units for ONT/ONU – 2.5G GPON			
Bi- Logistic	2,3	0,999	0,930
Bi-Gompertz	2,6	0,999	0,932

Table 6-4 – Summary of modeling of different Bi-S curves to vendor units for OLT – 2.5G GPON.

The fit of the Bi-Gompertz model to the EMEA vendor units for OLT– 2.5G GPON can be observed in Figure 6-10. In the same figure is represented the annual market fits using the constants obtained by the fit of the Bi-Gompertz and a model fit using the same constraints of the cumulative market.

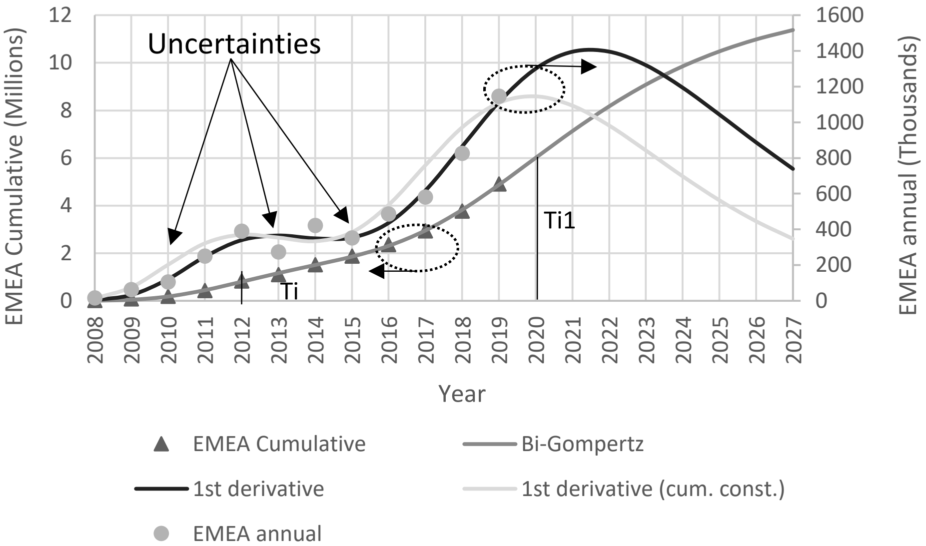

Figure 6-10 - Bi- Gompertz fit to the EMEA vendor units for ONT/ONU – 2.5G GPON.

A potential market forecast of 12 million units was determined by using Bi-Gompertz. The first curve has its inflection point in 2012 and the second curve in the year 2020. The maximum growth rate was 44,6% for the first curve and 29,2% for the second Gompertz.

The time interval to grow from 10% to 90%, this is, Δt, for the first curve is 6,9 years and 10,5 years for the second one. The *r square* of 0,979 in the annual market reports an improvement on the fit of the market, but it stills is not ideal.

To evaluate the forecasting accuracies of each of the Bi-S models, and as done before, we evaluate the MAPE values for the corresponding periods, by comparing the forecasted values with the real GPON adoption values. Table 6-5 presents the results of the MAPE calculations for the different Bi-Gompertz and Bi-Logistic models that fit the vendor units for OLT -2.5G GPON. We have chosen 3 scenarios with varying hold-out periods consisting of 4 (MAPE4), 6 (MAPE 6), and 12 (MAPE12) years, respectively.

OLT	Cumulative Market			Annual Market		
	MAPE4 (%)	MAPE6 (%)	MAPE12 (%)	MAPE4 (%)	MAPE6 (%)	MAPE12 (%)
Global vendor units for ONT/ONU – 2.5G GPON						
Bi-Gompertz	1,03	1,73	8,04	5,56	6,01	16,51
Bi-Logistic	1,18	1,46	21,95	9,07	10,96	28,54
EMEA vendor units for ONT/ONU – 2.5G GPON						
Bi-Gompertz	1,26	1,16	11,44	15,53	15,34	23,82
Bi-Logistic	1,58	1,47	14,10	18,67	17,66	27,98
NA vendor units for ONT/ONU – 2.5G GPON						
Bi-Gompertz	0,93	1,51	2,36	11,88	20,11	21,86
Bi-Logistic	1,61	1,75	1,19	13,12	11,56	15,09

Table 6-5 - MAPE (%) for different hold-out periods for the Bi-Gompertz and Bi-Logistic growth models fit the vendor units for OLT – 2.5G GPON.

As what regards the forecasting performance of the models, we can observe from the table, that for the cumulative and annual Global and EMEA market the Bi-Gompertz model present the best performance. As regards the NA cumulative and annual market, the Bi-logistic model-based forecast presents the best performance for long-term adoption and Bi-Gompertz in the short and mid-term adoption.

The Bi-Gompertz and Bi-Logistic model-based forecasts are consistent across the three regions for both the cumulative and annual markets presenting a good forecast model for both short-term and mid-term adoption. As what regards the model best fit to explain the pattern adoption dynamics of OLT GPON taking into account the market fluctuations and uncertainties, Table 6-4, and the best model forecasting performance for both short term and mid-term adoption, Table 6-5, we point out Bi-Gompertz for the three markets.

6.5 Multi-Gompertz and Multi-Logistic to Model EMEA GPON ONT/ONU

As discussed in the previous section, the GPON ONU/ONT 2.5G GPON EMEA market was the market that presents more oscillations, Figure 6-4. To optimize the model fit a Multi-Gompertz and Multi-Logistic functions are proposed and model to the GPON ONU/ONT 2.5G GPON EMEA market data. The parameters defined for the NLS regressions can be found in Appendix C -Uncertainties related to investment in PON technologies, Multi-Gompertz and Multi-Logistic to model EMEA GPON terminals.

The results of the NLS regression presents high values of their adjusted *r square*, Table 6-6, suggesting general suitability and sufficiency of the multi-S growth models towards explaining the adoption and the market fluctuations of the OLT GPON ports, however, when we compare these results with the modeling of the Bi-S curves, Table 6-2, only an improvement is obtained by the use of the Multi-Gompertz for both cumulative and annual market.

	Market Potential Volume (million)	**Cumulative market *r square***	**Annual Market *r square***
EMEA vendor units for ONT/ONU – 2.5G GPON			
Multi-Logistic	101	0,999	0,986
Multi-Gompertz	109	1,000	0,993

Table 6-6 - Summary of modeling of Multi-Logistic and Multi-Gompertz to the vendor units for ONT/ONU – 2.5G GPON.

The fit of the Multi-Gompertz and Multi-Logistic model to EMEA vendor units for ONT/ONU – 2.5G GPON can be observed in Figure 6-11 and Figure 6-12 respectively.

The Multi-Gompertz presents a potential market forecast of 109 million. The first curve has its inflection point in the middle of the year 2009, the second curve in the year 2014, and the third curve in the year 2019. The maximum growth rate was 85,9% for the first curve, 48,1% for the second Gompertz, and 43,7% for the third. The time interval to grow from 10% to 90%, this is, Δt, for the first curve is 3,5 years, 6,4 years and 7 years for the second and third curves respectively.

The data set is the sum of three identical logistic growth pulses with the midpoints separated by 5 years and is possible to notice that the second and third growth curve only starts to grow when the previous one reaches half of the market, we have then a superposed pattern of growing, this overlapping causes the first adoption process to co-evolve with the second one and consecutively the second one with the third one.

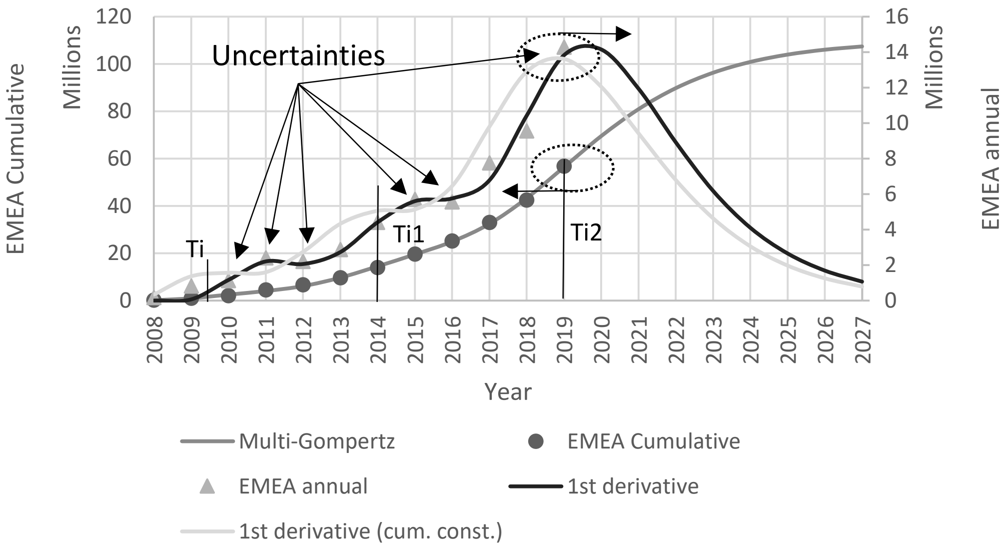

Figure 6-11 – Multi-Gompertz fit to the EMEA vendor units for ONT/ONU – 2.5G GPON.

As regards the model fit of the Multi-Logistic to the EMEA vendor units for ONT/ONU – 2.5G GPON, it can be observed in Figure 6-12. A potential market forecast of 101 million units was determined. The data set is the sum of three diverging logistic growth pulses with the midpoints separated by 5 years. The first curve has its inflection point in the middle of 2010, the second curve in the middle of the year 2015, and the third one in the middle of 2019. The time interval to grow from 10% to 90%, this is, Δt, for the first curve is 3,5 years, 5,8 years, and 4,6 years for the second and third curves respectively.

The three data sets, $W_{0i}(t)$, $W_{1i}(t)$, $W_{2i}(t)$ are plotted as a linear function of time by utilizing the Fisher-Pry transform, as shown in the inset, left side top of Figure 6-12, with the circle designating $W_{0i}(t)$, squares designating $W_{1i}(t)$ and triangles designating $W_{1i}(t)$. As is possible to see the first and second curves are parallel diverging growth curves, the longer pulse in the second curve emanates from the success of developing the technology, which exhibits prolongation of the second curve. The faster and shorter pulse in the third curve overtaking the second reaches culmination faster, meaning the market saturation and decline.

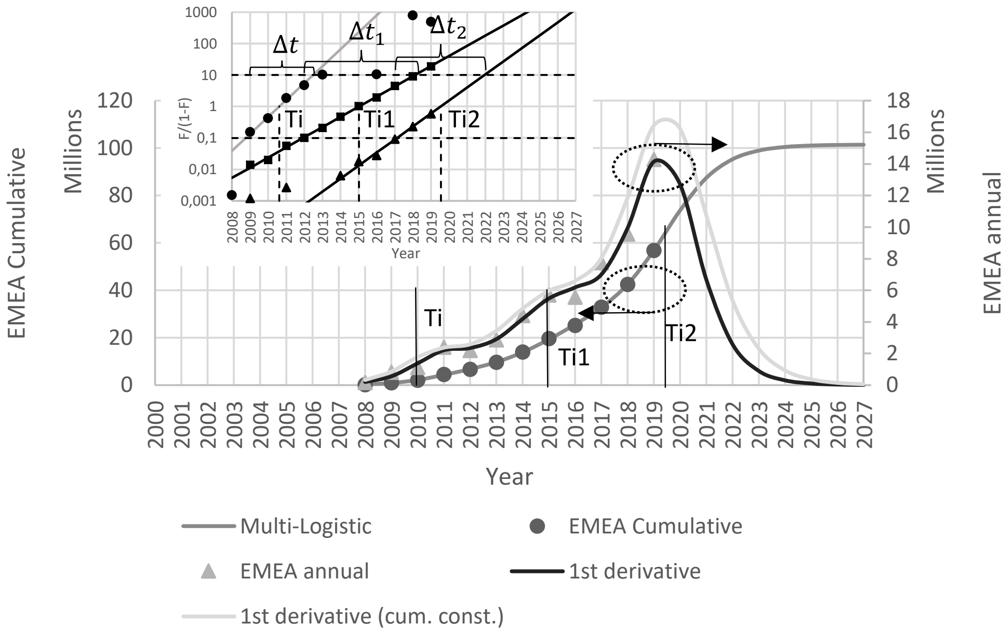

Figure 6-12 - Multi-Logistic fit to the EMEA vendor units for ONT/ONU – 2.5G GPON. The inset shows the component growth curves linearized with the Fisher-Pry transform.

To evaluate the forecasting accuracies of each of the Multi-S models, and as done before, we evaluate the MAPE values for the corresponding periods, by comparing the forecasted values with the real GPON adoption values. Table 6-7 presents the results of the MAPE calculations for the Multi-Gompertz and Multi-Logistic models that fit the vendor units for ONT/ONU -2.5G GPON. We have chosen 3 scenarios with varying hold-out periods consisting of 4 (MAPE4), 6 (MAPE 6), and 12 (MAPE12) years, respectively.

ONT/ONU	Cumulative Market			Annual Market		
	MAPE4 (%)	MAPE6 (%)	MAPE12 (%)	MAPE4 (%)	MAPE6 (%)	MAPE12 (%)
EMEA vendor units for ONT/ONU – 2.5G GPON						
Multi-Gompertz	1,25	1,56	7,0	7,07	5,04	20,32
Multi-Logistic	0,55	0,74	11,53	6,45	5,72	11,26

Table 6-7 - MAPE (%) for different hold-out periods for the Multi-Gompertz and Multi-Logistic growth models fit the EMEA vendor units for ONT/ONU – 2.5G GPON.

As regards the forecasting performance of the models, we can observe from the table, that for the cumulative and annual market the Multi-Logistic model presents the best performance, nonetheless, the results are similar between both models.

As regards the model best fit, the multi-Gompertz explains the pattern adoption dynamics of ONT/ONU GPON taking into account the market fluctuations and uncertainties, Table 6-6, and the best model forecasting performance for both short term and mid-term adoption, Table 6-7.

6.6 Conclusions

This chapter has analyzed the uncertainties related to the PON development: technological, the evolution of infrastructure and demand, political and competitiveness. Was also approached the investment decision in an uncertain environment and the Real option (RO) theory instrument as a tool to evaluate investment opportunities.

The uncertainties in GPON diffusion and rate of growth were identified and Bi-S growth curves models using an NLS regression were modeled to data. The estimated models' parameters were compared, and the best fit models were determined. An evaluation of the forecasting capabilities of each type of Bi-S growth model was also performed by using MAPE.

A Multi-Gompertz and Multi-Logistic growth model was proposed and analyzed for the ONT/ONU 2.5G GPON diffusion in EMEA.

As regards the model best fit to explain the pattern adoption market fluctuations, uncertainties, and dynamics of GPON, as well as the best model forecasting performance for both short term and mid-term adoption, we point out Bi-Gompertz for the Global and NA market and Logistic model for EMEA.

Bi-Gompertz was the model that best fit to explain the pattern adoption dynamics of OLT GPON and the one that presents the best model forecasting performance for both short-term and mid-term adoption.

Regarding the modeling of the EMEA market using the multi-S curves, the multi-Gompertz was the model that presents the best fit and forecasting performance.

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Chapter 7: Forecast of NG-PON technologies

The previous models address the diffusion process according to a binary perspective building on the assumption that by its progression, a single innovation in the market replaces old technology. However, diffusion can also be the result of competition between several old and new technologies. In this case, the competitive scenario is a non-binary diffusion pattern of competition and technological multi-substitution. As such it is relevant to consider different situations of technological competition.

In this chapter different forecast scenarios, based on the path dependence of current GPON and FTTH networks are proposed for Next-Generation PONs based on the Bi-Logistic, Bi-Gompertz, and Logistic Substitution Model. It is also analyzed the ONT/ONU and OLT forecast units with the FTTH/B penetration.

7.1 Forecasting Next Generation Markets

The technology changes the inherently stable economic system environment, where careful and conservative planning can assure business longevity, to ones where chaotic change can rapidly fall even the most solid.

Most decisions that technical managers make comprise specific markets, demand behavior, availability and quality of suppliers, regulation, policy, and legal constraints as well as the competitive environment, but not only, the changes at social dimension, as well as users practices and societal behavior also play an important role.

The next-generation PON market is not only driven by the demand from end consumers for more bandwidth or applications driven. The market itself is influenced by technological advances in optical technologies and the constant launch of high-speed electronics that allows it. The behavior of technology developers, as well as the behavior of organizations in providing more and more technology to sell it, causes final consumers to despair. The political actors themselves, as well as the standardization bodies, cause instability in the market. The constant development of new standards with higher speed technologies, makes the market want them, even if it does not need them currently, but to meet possible future requirements. Technology developers end up creating problems with the need for greater bandwidth to sustain their markets, without the need for them.

We can see the PON market as a “technological system”[1], Lundvall in volume on *The Globalizing Learning Economy*,“*...it is useful to think in terms of ‘technological systems’ as a special version of innovation systems. A technological system is a combination of interrelated sectors and firms, a set of institutions and regulations characterizing the rules of behavior and the knowledge infrastructure connected to it. Most innovation policies […] are well suited when it comes to supporting existing technological systems, but much less when it comes to stimulating the creation of new ones*.”[2]. Science and technology are likely to be the major source for the broad majority of technological innovations and demand was the greatest companion to drive innovation in the right economic and institutional directions [3]. Indeed, a prerequisite for a discovery to become widely accepted is that there be adequate demand for the benefits that the new technology produces.

Forecasting and managing technologies require an understanding of how the market will pull them to success. Achieving this understanding can be at least as hard as predicting the breakthroughs that will enable new technologies, this is, analyzing what comes before diffusion and use of technology, this is “technology activation”, is equally important [4].

Technology activation is the system of factors, which are external to the user's domain and not directly under its control, that enable the efficient supply and diffusion of technology-based innovation. In the lack of these requirements, technology innovation would not result in a noticeable market offer, and subsequent dissemination of the technology by users would not be a viable option. The term activation is proposed by Ghezzi [4] and is used specifically to highlight that technology is not ready for diffusion per se, although its inherent properties and quality. The external multidimensional context plays the main role in setting the proper conditions to activate innovation diffusion.

The idea of “market activation” is a resultant from that of technology activation. An “activated market” is a market area in which specific antecedents and requirements that enable diffusion have been met and barriers or uncertain blocks to technology commercialization have been overcome, thus achieving a supply-side technology activation [4]. This is observed on the PON market, where the NG-PON does not inherit the GPON barriers benefiting from an “activated market” where fiber is already spread, the policies are already defined and the supply chain is well defined.

Innovations are unlikely to be pushed into markets by their elegance, originality, or inherent performance. They are accepted and grow because there is a real need for their capabilities and a competitive environment that is receptive to their acceptance and growth. Understanding the future paths of innovation requires understanding the markets and the forces within them that will affect those paths.

While many technologies directly affect the choices available to the ultimate consumer, many others reside in the supply chain that develops, delivers, and services products.

To forecast the size and growth of a market for new technology, it is important to *know who the customer is going to be.*

As used in previous chapters, approaches that have proven to be useful in forecasting technologies include both extrapolative and simulation models. Two that can be particularly useful and intensively discussed in this work are the Fisher-Pry and Gompertz models. With limited data, one can use them to extrapolate a forecast of the growth of technology that has the S-shape, which was described earlier as the pattern of technology adoption and diffusion.

First, it is important to note to which stage of technology growth these models apply. Martino [5] described the stages of technology growth in seven stages:

1. Scientific findings: determination of opportunity or need;
2. Demonstration of laboratory feasibility;
3. Operating a full-scale prototype or field trial;
4. Commercial introduction or operational use;
5. Widespread adoption;
6. Proliferation and diffusion to other uses;
7. Effect on societal behavior and/or significant involvement in the economy.

The diffusion models are useful for Stages 4 through 7.

The Fisher-Pry and Gompertz models focus on different processes. Fisher-Pry curves accurately depict the common diffusion situation in which the accumulation of sales facilitates an increasing growth rate of purchases as customers become familiar with the product. The Gompertz model is better for situations in which the technology's advantages are established early and penetration is characterized by robust early growth followed by a period in which the rest of the market waits for the existing technology to wear out before purchasing the new.

7.1.1 Technological competition in the presence of network externalities

In our study of the general Lotka-Volterra model [6][7] to the description of growth and structural changes processes in the PON telecom sector we have to consider three aspects of interaction:

- The interaction of a species (equipment) with its (liming) environment (telecom market) in the form of a growth process;
- The interaction (competition) between two species (two different PON equipment's technologies) inside a particular environment (telecom market) in the form of substitution models.

The interaction (competition) between more than just two species (different PON equipment's technologies) in the form of a multiple substitution model.

The Lotka-Volterra equations model both the emerging and declining competitors, allowing an intuitive understanding of the factors driving substitution [6]. From the Lotka-Volterra competition equations and as very special cases, is possible to obtain the different substitution models: Gompertz, Fisher-Pry, Sharif-Khabir and Bass and multiple substitution model as the one presented by Marchetti and Nakicenovic [6], [8]–[10].

In the classic paper of Fisher and Pry [11], it is proposed a substitution model of technological change based upon a simple set of assumptions, "*technological advances can be considered as competitive substitution of one method of satisfying the need for another*" and it is suggested, that the model could be applied for "…*forecasting technological opportunities, recognizing the onset of technologically based catastrophes, investigating the similarities and differences in innovative change in various economic sectors, investigating the rate of technical change in different countries and different cultures, and investigating the limiting features to technological change*."

The Fisher and Pry model expresses the fractional rate of fractional substitution of the old technology by the new in terms of what is left to substitute, this is, the rate of the fractional substitution $F_1(t)$ is proportional to the remaining substitution $1 - F_1(t)$ *(7-1)*. The model suggests a logistic substitution trajectory:

$$\frac{F_1(t)}{1 - F_1(t)} = e^{a+Kt} \qquad (7\text{-}2)$$

a and K are constants and t is the independent variable, usually time. The equation is equivalent to the re-writing of the logistic function with a linear right-hand side presented in section 4.1.1, this is, the Fisher-Pry transform, where the three-parameter Logistic growth curve is reduced to a two-parameter, as $A = 1$, logistic substitution curve with $t = 0$ at $F = 0{,}5$.

The share of the two technologies $F_1(t)$ (for technology 1) and $1 - F_1(t)$ *(7-3)* (for technology 2) in the total market is given by [7]:

$$F_1(t) = \frac{N_1}{N_1 + N_2} \qquad (7\text{-}4)$$

At first, this mathematical transform reduces the number of parameters defining logistic growth and allows the comparison of growth processes with very different absolute values [12]. In this model, the life cycle of competitive technologies is subdivided into three periods: growth, saturation, and decline, where the growth and decline stages are logistic growth processes.

Most of the sources for logistic substitution models refer to the publications of C. Marchetti, and N. Nakicenovic [13], because it deals with the drawback of the Fisher-Pry model than only deals with two competitors, whereas in reality, more than two technologies may compete on the market [7].

In the Marchetti, and N. Nakicenovic [13], the logistic substitution model describes the competitors' niche market (e.g. fraction of market share). The life cycle of competitive technologies is subdivided into three periods: growth, saturation, and decline, where the growth and decline stages are logistic growth processes as Fisher-Pry model, however, two additional assumptions are made: "*(1) When more than two technologies compete in a market, one technology is in its (non-logistic) saturation phase defined as residual after the logistic growth/decline trajectories of the other technologies are calculated. (2) The technology that enters the saturation phase (due to the growth of newer competitors) is the oldest of the growing technologies"*[7].

Yet, two additional suppositions can be acknowledged, that there are n competing technologies chronologically ordered in the sequence of market appearance and that technology in saturation phase follows a non-logistic path that links the period of growth to its subsequent period of decline [12].

The market share of growing/declining technologies are:

$$y_i(t) = ln\frac{F_i(t)}{1 - F_i(t)} = a_i + k_i t \qquad (7\text{-}5)$$

and the model share of the saturating technology is given by:

$$F_j(t) = 1 - \sum_{i \neq j} F_i \qquad (7\text{-}6)$$

Models of adoption behavior in the presence of network effects show that the technology that is most efficient or the most appreciated by agents at the outset is not necessarily retained by the market, in particular, due to the choice of the first consumers.

- Technological competition and path dependence

In the path dependency model [14][15], different technological alternatives compete in the market. This model of technological competition is based on the idea that technology becomes attractive at the moment it is adopted, and not because it was the best, to begin with. The existence of increasing returns to adoption (learning by doing, learning by using, increasing returns to information, or strong technological interrelationships) works in favor of the adopted technology. These benefits grow stronger as it spreads. Technology will gradually prevail against the competition and the possibility of challenging its dominance is more difficult. The market then becomes locked onto a technology. The result is therefore affected by the succession of historical events, which makes it impossible to predict in advance which technology will prevail. It is not possible to predetermine the market shares of each technology because different sequences of events produce different results - the process is non-ergodic, mathematical language, or path-dependent. Thus, the choices of the first consumers for inefficient technology may block the development of other technologies later.

This model, however, has a series of limitations, most notably it applies to competition between contemporary technological options. This is a serious handicap for the study of long-term technological substitution between old and new technology. The following model allows a better analysis of the competition between non-contemporary technologies entering the market at different points in time.

- Sequential decisions and excess inertia

Now we consider the cases of a struggle between old and new technology. Both are released to the market at different points in time and the structure of adoption depends on the sequence of decisions between the two periods.

Katz and Shapiro [16] analyzed the case when the two technologies are compatible either through the use of converters or through technological standardization. In this way, the agent benefits from the installed base, which is made up of all consumers who have purchased either technology in the past. Each agent then acquires the technology that allows them to have the greatest satisfaction. The authors show that under these conditions the best available technology triumphs.

7.2 The NG-PON opportunity

NG-PON technologies are starting to be deployed to support nonresidential customers and applications, providing additional sources of revenues over the same FTTH network. Is expected that NG-PON equipment will be used in enterprises, smart city, campus, and xHaul transport applications with the increasing availability of 10G-PON optics and equipment and the future 25GS-PON and 50G-PON. As older generations of PON technologies, such as GPON were used for nonresidential applications, where limited bandwidth was a constraint, with NG-PON this can be overtaken. Residential was not the focus for the NG-PON technology, but the longer-term effects of the pandemic on society, such as changes to individuals' working habits, reduced international travel, and the rebalancing of business activity towards digital products and channels are posing opportunities for the 10G-PON.

The pandemic has highlighted the importance of home broadband, and operators should work with governments to deliver the necessary new infrastructure. The enterprise market has been permanently altered, and operators need to re-position their product portfolios to support changed working practices and business priorities.

Residential

Unprecedented demand generated by the pandemic, more people working and learning from home as well as increased virtual social communications, advanced video gaming, smart home applications, and e-health are pushing the current residential PON technology to its limits, offering opportunities to the NG-PON bandwidth.

The importance of reliable broadband for households in this new world cannot be overstated, and this will be reflected in public policy.

Enterprises

10G-PON enables service providers (SPs) to offer symmetrical bandwidth services, such as 1 Gbit/s and higher, versus the older PON technologies generations. Higher symmetrical bandwidth expands the market opportunity for 10G-PON deployments, spreading from residential and small and home offices (SOHOs) to bigger small and medium-sized enterprises (SMEs).

Several SPs are building, expanding, and/or upgrading their FTTH PON networks to NG-PON to support new SME customers, a new customer segment. PON enables efficient use of fiber to support clusters of SMEs, such as those in central business districts.

SPs use typically point-to-point fiber to support business customers and sometimes happen fiber unavailability due to customer growth along with increased bandwidth demand from existing customers. Other SPs want to move SMEs onto less expensive infrastructure, such as PON.

One reason for using PON is simply fiber efficiency; PON can support multiple SMEs on the same fiber strand, thereby saving fiber usage and minimizing footprint in the CO.

A major challenge to the reuse of PON for SME services is organizational, where different departments are responsible for supporting residential versus SME customers.

The use of PON for SMEs is leading to new product innovation. Several vendors are adding to the PON equipment capabilities of switching and routing as well as wireless.

The importance of reliable broadband for SMEs in this new world cannot be overstated, and this will be reflected in public policy.

Smart Cities

SPs are supporting municipalities as these local governments roll out smart city services. While we often associate smart cities with wireless connectivity, several smart city applications require significant symmetrical bandwidth, such as public safety video surveillance. Concurrently, municipalities are deploying smart city plans that include cloud-based platforms to support interactions with residents and businesses. 10G-PON is being deployed to support municipalities as they use the cloud to support more e-services.

xHaul

PON has been used to support small cell backhaul for many years, but older generations of PON had bandwidth constraints. 10G-PON can support the higher bandwidth wireless backhaul requirements expected from dense 5G small cell deployments. PON’s point-to-multipoint topology enables fiber asset efficiency versus point-to-point solutions. This efficiency becomes vital when planning to implement significant volumes of small cells. Alongside, is needed less space in COs when is used PON versus a point-to-point fiber.

PON is just one of many solutions for wireless backhaul. It is not expected the use of PON to become the dominant solution, but it has several advantages and should be evaluated alongside alternatives as new PON generations with increasing bandwidths are coming.

The use of 25GS-PON to support 5G wireless mid-haul and backhaul as well as future 50G-PON to support 5G fronthaul is gaining mindshare.

In evaluating PON for xHaul applications, there are several different business models and strategies that should be considered:

- For SPs that offer both wireless and wireline services, the use or reuse of existing FTTH PON networks can save time and money. FTTH PON equipment can be reused to support wireless backhaul by adding and/or upgrading to 10G-PON in the CO and the future 25GS-PON and 50GPON.
- SPs without existing FTTH PON can adopt unified access network planning, deploying PON for both residential customers and wireless backhaul.
- Several integrated and wireline-only only SPs wholesale their PON services to support wireless backhaul traffic for other operators. This model enables SPs to achieve a faster return on investment due to multiple revenue streams.

Passive optical LANs

Campuses, such as airports, manufacturing facilities, financial institutions, universities, and hotels/resorts often operate internal communications networks. Traditionally, these LANs consist of switches and routers where devices are connected using copper-based cables, such as Cat5 or Cat6. The adoption of passive optical LANs would require replacement of electrical cabling with optical-fiber cabling, but the replacement can be done fragmentary, such as focusing on a particular building or facility, or can be campus-wide.

Typically, the business reasons for moving to passive optical LAN are due to bandwidth demand among campus-based network users, along with increased cloud-based usage. Cloud-based services, including software-as-a-service, infrastructure-as-a-service, and platform-as-a-service, are being adopted by enterprises throughout the world. These cloud-based services require more bandwidth and symmetrical bandwidth for campus users.

There are many advantages to a passive optical LAN compared to a traditional copper-based LAN. Passive optical LAN advantages include:

- Bandwidth and ease of bandwidth upgrades—support for up to 10G per end-user when 10G-PON is deployed. In addition, with passive optical LAN, IT departments can decide which users or facilities need higher bandwidth rates.
- Potential Capex and OpEx savings, including power and space—an optical LAN uses less cabling, fewer racks and switches, and less power than a traditional LAN.
- Passive optical LAN can support large campuses with a reach of 20 kilometers and beyond.
- Reliability, redundancy, security, management. The underlying ODN can be designed to provide redundancy if determined necessary. PON infrastructure is considered highly secure. It is resistant to interfering, and it meets the security requirements of governmental defense agencies. Passive optical LAN solutions include end-to-end element and provisioning management tools.

7.2.1 Forecasting XG(S)-PON ONU/ONT Markets with Bi-Gompertz and Bi-Logistic

As for the ONU and OLT GPON market share, for the XG(S)-PON market shares our study will also focus on the global analysis, NA, and EMEA. The regional definitions can be found in Appendix B - Regional Definitions and the vendor units for ONT/ONU and OLT – XG(S)-PON for Global level, EMEA, and NA from OMDIA market share 2Q20 for PON [17] in Appendix D- XG(S)-PON market share.

To forecast the Global XG-PON1 and XGS-PON ONU vendor units a Bi-Gompertz and Bi-Logistic models will be used. As we have already some market numbers from the year 2015 to 2019 a W_0 form of the Gompertz curve was used, Norton´s model, to have the first function of the Bi-Gompertz.

The forecast of the XG(S)-PON ONT/ONU using the Bi-Logistic will be done in the same approach as for the Bi-Gompertz. With the available data from the market, from 2015 to 2019, a logistic curve will be fitted by using an NLS regression in SPSS, and this will be the first component of the Bi-Logistic model.

The parameters defined for the NLS regression of the first curves of the Bi-model forecast can be found in Appendix D - Forecasting XG(S)-PON terminals with Bi-Gompertz and Bi-Logistic. The values of the constants obtained by the fit of Norton´s and Logistic model (presented in the same appendix) will be used as the first component of the Bi-Gompertz and Bi-Logistic, respectively, for the analyzed markets. By using the historical behavior of market diffusion of GPON and assuming that the future XG(S)-PON ONT/ONU markets will have similarities. Different forecasts scenarios, for the second component of the Bi-Gompertz and Bi-Logistic, were defined and are presented in Table 7-1 for the Global Market.

<table>
<tr><th>Forecast Scenario</th><th>Market Potential</th><th>K_G (growth rate coefficient of the second component)</th><th>T_i (time at the inflection of the second component)</th></tr>
<tr><td>FS1</td><td rowspan="3">At least the total ONT/ONU 2.5G GPON cumulative market in 2019, is, 602190415</td><td>Same as found for GPON market: by applying Bi-Gompertz, 0,212; by applying Bi-Logistic, 0,620.</td><td>Taken into account the market till 2019 and the: 1st component of Gompertz 14,647 years; 1st component of Logistic 16,324 years.</td></tr>
<tr><td>FS2</td><td rowspan="3">10% higher than found for GPON market, due to already installed FTTH/network, this is 0,312 for Bi-Gompertz.
Double than found for GPON market, this is, 0,124 for Bi-Logistic.</td><td>Taken into account the market till 2019 and the: 1st component of Gompertz, 11,647 years; 1st component of Logistic, 11,1 years.</td></tr>
<tr><td>FS3</td><td rowspan="2">Same as found for GPON market by applying: Bi-Gompertz, 10,647 years; Bi-Logistic, 9,324 years.</td></tr>
<tr><td>FS4</td><td>At least 50% of the total ONT/ONU 2.5G GPON cumulative market in 2019, this is, 301095208</td></tr>
</table>

Table 7-1 – Forecast scenarios for the Bi-Gompertz and Bi-Logistic XG(S)-PON ONT/ONU for the global market.

The EMEA and NA markets forecasts are presented in Appendix D - Forecasting XG(S)-PON terminals with Bi-Gompertz and Bi-Logistic.

The forecast of the Global vendor units for ONT/ONU – XG(S)-PON using Bi-Gompertz can be observed on the left side of Figure 7-1 using the constant obtained by the fit of Norton´s re-parametrization and the values for the constants defined on the forecast scenarios, Table 7-1.

The fit of the Bi-Logistic to the Global vendor units for ONT/ONU – XG(S)-PON can be observed on the right side of Figure 7-1 using the constant obtained by the fit of Logistic Function and the values for the constants defined on the forecast scenarios.

On the same plots is possible to observe and compare the wireline broadband access equipment forecast from Ovum, March 2019 (pre-pandemic)[18] (squares) and the forecast from OMDIA 2019-2025, July 2020 [19] (triangles).

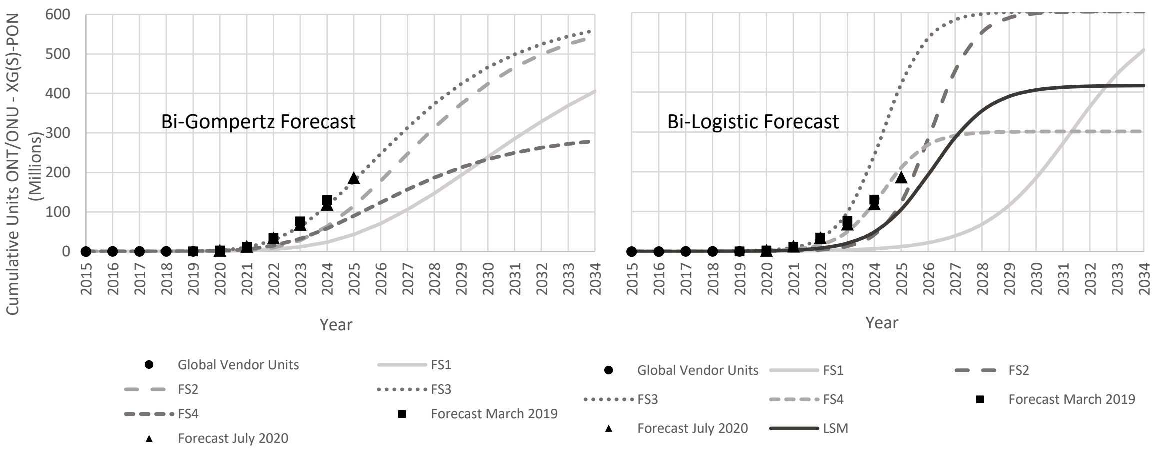

Figure 7-1 - Forecast for the Global Vendor Units ONT/ONU – XG(S)-PON using Bi-Gompertz (left), Bi-Logistic (right), and LSM (right side).

The values of the estimated constants by the fitting of the Bi-Gompertz and Bi-Logistic functions were applied to the temporal derivative of the market size. Figure 7-2, presents the derivative fit for the Global market using the constants of the Bi-Gompertz (left side) and Bi-Logistic (right side), respectively. As for the cumulative market, on the same graphics is possible to observe and compare the wireline broadband access equipment forecast from Ovum, March 2019 (pre-pandemic)[18] (squares) and the forecast from OMDIA 2019-2025, July 2020 [19] (triangles).

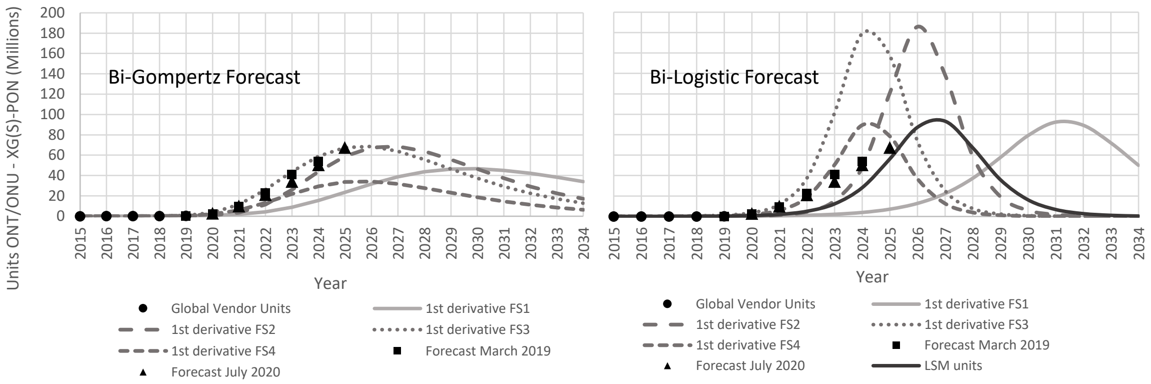

Figure 7-2- Bi-Gompertz (left side), Bi-Logistic (right side), and LSM (right side) derivative fit forecast to the global vendor units ONT/ONU – XG(S)-PON.

The simple logistic substitution model (LSM), this is, the Fisher and Pry model, was also applied using GPON data for each region as the old technology to forecast the XG(S)-PON ONT/ONU market. The LSM market fraction is possible to observe in Figure 7-3, the inset presents the LSM Fischer-Pry transform. The inflection time occurs in the year 2026 and the length of time interval to the XGS-PON market growth from 10% to 90% of the total market is 4,71 years.

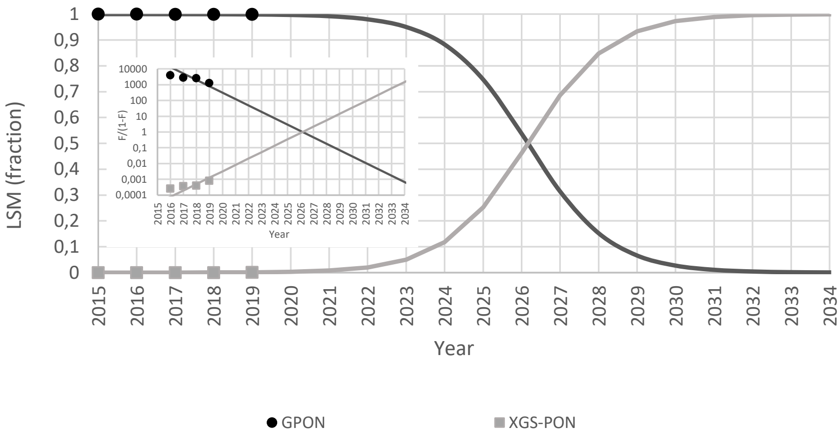

Figure 7-3 – Market share forecasts using the LSM for the Global vendor units for ONT/ONU – XG(S)-PON. In the inset, the LSM Fisher-Pry transform.

The forecast scenarios presented in Table 7-1, Figure 7-1, and Figure 7-2, were defined based on the assumptions that the 10Gbit/s market is widely expanding beyond 2021. The use of XGS-PON to support the new residential bandwidth needs, enterprises requirements, and 5G wireless will start to gain market share beyond 2022 and will benefit from the already installed infrastructure. Considering that GPON was mainly used for residential applications and due to the widespread of this technology worldwide and with the 10Gbit/s market starting to spread, a market potential on the 2nd phase equal to GPON market in 2019 with the same growth rate and 50% of GPON market in 2019 with a higher rate growth can be considered a good market approach.

The XG(S)-PON still competes with the GPON market on the first phase, having a clear disadvantage against the 2,5 Gb/s optics price. The delay and squeeze of the 5G investment plans by several operators is benefiting the GPON technology. The second phase of the

XG(S)-PON will happen in the first phase of the upcoming 25GS-PON, and the 25GS-PON will suffer on the first phase of the high-cost optics. Nevertheless, as the optics cost starts to decrease and taking into account the widespread of fiber of cell sites and the support of mobile services, and the need for higher bandwidth the market potential on the second phase can be considered a good market forecast approach.

As regards the forecast results of each of the models, in the Bi-logistic model, the initial sales of XGS-PON were challenging despite its potential and the size of the potential market. As applications grow, so does the overall knowledge of the technology and its benefits and, as it is possible to see, a fast market adoption in the second phase is achieved causing the market to reach saturation sooner than on the Bi-Gompertz. The Bi-Gompertz model presents quite different dynamics, for penetrations greater than 50% the rate of penetration depends primarily on the fraction of the market remaining, in our forecast at a lower growth rate, causing the market adoption to be slower and reach saturation later. Thus, the Bi-Gompertz model is appropriate for forecasting market penetration for XG(S)-PON technologies for which initial sales were low (2015- 2019). This dynamic is found with XG(S)-PON offer in the first phase because no clear-cut benefits were found by SPs over GPON (GPON was sufficient for the SPs service offers).In the second phase, as new service requirements appear, GPON technology is replaced by a newer technology that performs the same tasks with essentially the same financial and/or functional efficiency. Purchases simply replace equipment that has worn out or has been destroyed. These conclusions are directly related to the use in the forecast of the historical behavior of market diffusion of GPON.

Since the dynamics of the two models are different it is reasonable to expect significant differences in the forecasts they produce. The Bi-Logistic model forecasts a more rapid penetration than does the Bi-Gompertz. The goodness of fit cannot be used as a criterion to determine which model to use; instead, the dynamics of the model must be matched to the dynamics of the process being forecast.

Regarding the LSM, this model is based on substitution of the old technology, GPON, by the one, XGS-PON, which does not necessarily happen on the PON telecom market, since both technologies can coexist in the same network, and as presented before, the number of homes passed with FTTH/B versus the number of subscribers have enough margin to accommodate the new XGS-PON terminals without a direct substitution.

The forecast provided by Ovum, March 2019 (pre-pandemic)[18] and the forecast from OMDIA 2019-2025, July 2020 [19] provide us an interesting view, where is observed a forecast adoption decrease in the evaluation done during the Covid-19 pandemic. This view is in line of thought that the pandemic not only brings opportunities but also major drawbacks for the NG-PON market, as the economic outlook from International Monetary Fund [20] for the next years is poor, with unemployment expected to rise, the causing consequences to the broadband market cannot be underestimated:

- Users will be increasingly price-sensitive, leading to higher churn and increasing pressure on average revenue per user (ARPU);
- Customers will be less willing to tie themselves into longer-term contracts for fixed and mobile services, given the ongoing uncertainty;

- Corporate insolvencies such as hospitality and tourism and site closures in certain areas such as business districts will cause further reductions in telco revenue in the B2B segment;
- Users facing increased job insecurity will be warier of committing to expensive new devices purchases such as mobile handsets and may be postponed until the outlook is clearer –this will reduce the demand for 5G.

Another line of thought is that the pandemic caused a permanent shift in working patterns, secondary effects will include individuals relocating away from major cities to take advantage of the lower cost of living in more rural areas. This decentralization will have implications for enterprise telecoms services, with a renewed emphasis on cloud services and universal communications at the expense of services supporting dedicated office spaces.

The forecast provided by our study to the ONT/ONU XG(S)-PON, mainly the one using Bi-Gompertz takes into account these market uncertainties, a higher and faster adoption can be observed in the FS3 of Bi-Gompertz and a more conservative like the FS4.

The forecast conclusion is that GPON will remain in the market and XGS-PON will address specific cases and demands on the PON networks.

7.2.2 Forecasting the XG(S)-PON OLT market with Bi-Gompertz and Bi-Logistic

The methodology used to forecast the OLT XGS-PON market is similar to the one presented in the ONT/ONU XGS-PON market, as so, here only will be presented the results of the forecast scenarios for the Global market. The forecast results for the EMEA and NA markets can be found in Appendix D - Forecasting XG(S)-PON OLT with Bi-Gompertz and Bi-Logistic.

The different forecasts scenarios, for the second component of the Bi-Gompertz and Bi-Logistic, were defined and are presented in Table 7-2, by using the historical behavior of market diffusion of GPON and assuming that the future XG(S)-PON OLT markets will have similarities.

<table>
<tr><th>Forecast Scenario</th><th>Market Potential</th><th>K_G (growth rate coefficient of the second component)</th><th>T_i (time at the inflection of the second component)</th></tr>
<tr><td>FS1</td><td rowspan="3">At least the total OLT 2.5G GPON cumulative market in 2019, this is 47173059.</td><td>Same as found for GPON market by applying: Bi-Gompertz, 0,224; Bi-Logistic, 0,586.</td><td rowspan="2">Same as found for GPON OLT market by applying: Bi-Gompertz 9,795 years; Bi-Logistic, 9,012 years;</td></tr>
<tr><td>FS2</td><td>10% higher than found for GPON market, due to already installed FTTH/network: Bi-Gompertz,0,324; Bi-Logistic, 0,686;</td></tr>
<tr><td>FS3</td><td rowspan="2">20% higher than found for GPON market, due to already installed FTTH/network: Bi-Gompertz, 0,424; Bi-Logistic, 0,786.</td><td rowspan="2">Earlier inflection: Bi-Gompertz, 7,9 years; Bi-Logistic, 8,5 years;</td></tr>
<tr><td>FS4</td><td>At least 50% of the total OLT 2.5G GPON cumulative market in 2019, this is 23586529.</td></tr>
</table>

Table 7-2 – Forecast scenarios for the Bi-Gompertz and Bi-Logistic XG(S)-PON OLT for the global market

The forecast of the Bi-Gompertz (left side) and Bi-Logistic (right side) to the Global vendor units for OLT – XG(S)-PON can be observed in Figure 7-4, using the constants obtained by the fit of Gompertz and Logistic functions, respectively, and the values for the constants defined on the forecast scenarios, Table 7-2. On the plots is possible to observe and compare the wireline broadband access equipment forecast from Ovum, March 2019 (pre-pandemic)[18] (squares) and the forecast from OMDIA 2019-2025, July 2020 [19] (triangles).

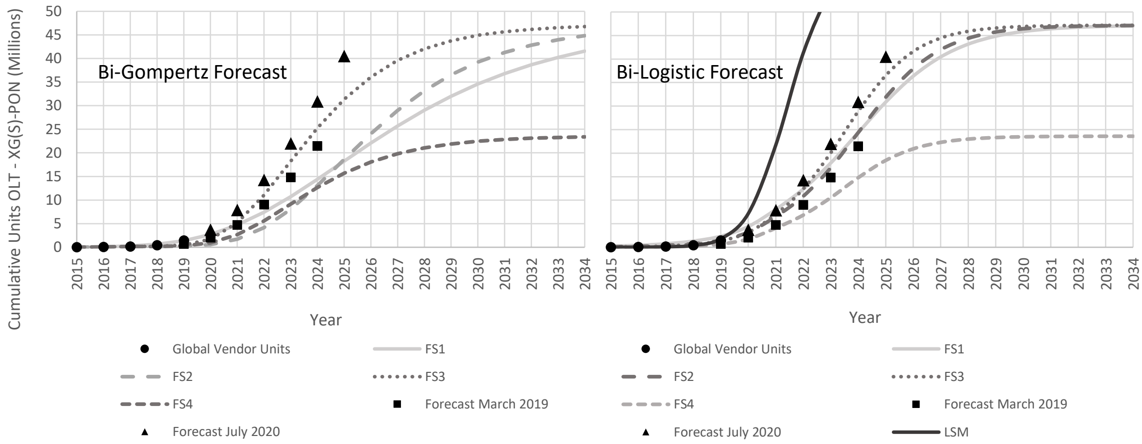

Figure 7-4 - Forecast for the Global Vendor Units OLT – XG(S)-PON using Bi-Gompertz (left side), Bi-Logistic (right side), and LSM (right side).

The values of the estimated constants by the fitting of the Bi-Gompertz and Bi-Logistic were applied to the temporal derivative of the market size. Figure 7-5, presents the derivative fit for the Global market using the constants of the Bi-Gompertz, left side, and Bi-Logistic, right side. As for the cumulative market, on the same plots is possible to observe and compare the wireline broadband access equipment forecast from Ovum, March 2019 (pre-pandemic)[18] (squares) and the forecast from OMDIA 2019-2025, July 2020 [19] (triangles).

The simple logistic substitution model (LSM), this is, the Fisher and Pry model, was also applied using GPON OLT market data for each region as the old technology, Figure 7-4 for the cumulative market (left side – LSM) and Figure 7-5 annual market forecast adoption (left side – LSM). The LSM for the global market presents an inflection time in the 2021 year and the length of time interval to the XGS-PON market growth from 10% to 90% of the total market is 3,1 years.

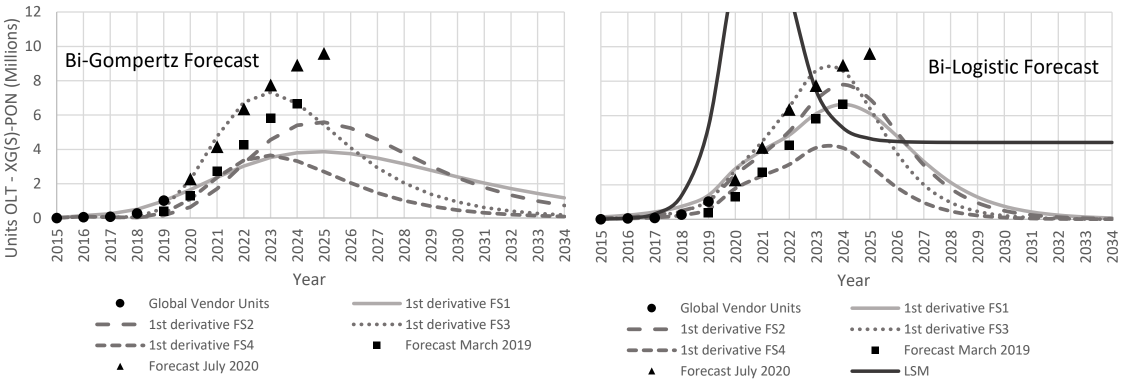

Figure 7-5 - Bi-Gompertz (left side), Bi-Logistic (right side), and LSM (right side) derivative fit forecast to the global vendor units OLT – XG(S)-PON.

The forecast scenarios presented in Table 7-2, Figure 7-4, and Figure 7-5, were defined based on the assumptions that the 10Gbit/s market is widely expanding beyond 2021 and that the SPs will continue to invest and expand their PON network. As stated before, pandemic changed the way of life and work, causing a permanent shift in working patterns and consequently a higher dependency on connectivity. Covid-19 increased data consumption [21], highlighted the need for better and higher bandwidth, and placed an unprecedented demand on communication networks, pushing them to the limits [22] what caused SPs to rethink the network investment, as so, in our forecast scenarios a market potential on the 2nd phase equal to GPON market in 2019 with same growth rate and 50% of GPON market in 2019 with a higher rate growth can be considered a good market approach.

As regards the forecast results of each of the models and contrary to the XGS-PON ONT forecasts, the Bi-Logistic presents a more conservative approach, but in line with the forecast of XGS-PON ONT/ONU using Bi-Gompertz. A delay is observed between the OLT XGS-PON port adoption and the XGS-PON ONT/ONU adoption characterized by the infield implementation of equipment, service offering, and consequently the starting of adoption by the end-users.

Another interesting point is that even using the historical behavior of market diffusion of GPON, and taking into account that the Bi-Gompertz model presented the best fit to explain the pattern adoption dynamics of OLT GPON and the best model forecasting performance, in this forecast, the Bi-Logistic for XGS-PON OLT forecast is more aligned with the wireline broadband access equipment forecast from Ovum, March 2019 (pre-pandemic)[18] (squares) and the forecast from OMDIA 2019-2025, July 2020 [19] (triangles).

Nevertheless, since the dynamics of the two presented models are different, it is reasonable to expect significant differences in the forecasts they produce. The Bi-Logistic model has observed a slower and longer adoption when compared to the Bi-Gompertz. The dynamics of the Bi-Logistic model can be assumed as a good forecast model to match the dynamics of the XGS-PON OLT future market.

7.2.3 Forecasting the NG-PON2 market with Bi-Gompertz and Bi-Logistic

The NG-PON2 technology, standardized in ITU-T G.989 at the end of 2014 [23] had its first field trial in Verizon at the end of 2015 [24] and have been used in several field trials and demonstrations successfully, as an example the 4.5G demonstration at Web Summit [25], however, despite all the advantages that it has, compared to the preceding technologies and even with XGS-PON and 25GS-PON, it never gained sufficient traction with the SPs, mainly due to the higher cost of the optics for client terminals [26].

The NG-PON2 is mainly pointed out to be used by Verizon, targeting both residential customers and 5G mobile support [27]. For this reason and taking into account the market research, the forecast will only be done for the NA region.

For the NG-PON2 ONU market, Bi-Gompertz and Bi-Logistic functions will be used to forecast the market. For the first component of both functions, the constants obtained by the fit of the Bi-Gompertz and Bi-Logistic functions to the ONT/ONU 2.5G GPON NA market will be used, with the upper asymptote for the first component being defined as the total cumulative units in sold till 2019, this is 103304 units. For the second component of both forecast functions, different forecast scenarios will be proposed based on the following market assumptions, Table 7-3, and the historical behavior of market diffusion of GPON and assuming that the future NG-PON2 ONT/ONU NA market will have similarities.

Forecast Scenario	Market Potential	K_G (growth rate coefficient of the second component)	T_i (time at the inflection of the second component)
FS1	30% of the total ONT/ONU 2.5G GPON NA cumulative market in 2019, this is, 9651602	10% higher than found for GPON market, due to already installed FTTH/network. Bi-Gompertz 0,248, Bi-Logistic, 0,458.	Taken into account the market till 2019 and the: first component of Gompertz, 8,126 years; Bi-Logistic, 8,918 years.
FS2	50% of the total ONT/ONU 2.5G GPON NA cumulative market in 2019, this is, 16086004	Same as found for GPON market by applying: Bi-Gompertz, 0,148; Bi-Logistic, 0,358.	Taken into account the market till 2019 and the: first component of Gompertz, 13,126 years; Bi-Logistic, 12,918 years.
FS3			Same as found for GPON market by applying: Bi-Gompertz, 15,126 years; Bi-Logistic, 14,918 years.

Table 7-3 - Forecast scenarios for NG-PON2 ONT/ONU, NA market.

The fit of the Bi-Gompertz and Bi-Logistic to the NA vendor units for ONT/ONU – NG-PON2 can be observed in Figure 7-6 left side and right side, respectively. The simple logistic substitution model (LSM), this is, the Fisher and Pry model, was also applied using 30% of GPON data for NA region as the old technology, Figure 7-6 right side - LSM. On the same graphics is possible to observe and compare the wireline broadband access equipment forecast from Ovum, March 2019 (pre-pandemic)[18] (squares) and the forecast from OMDIA 2019-2025, July 2020 [19] (triangles).

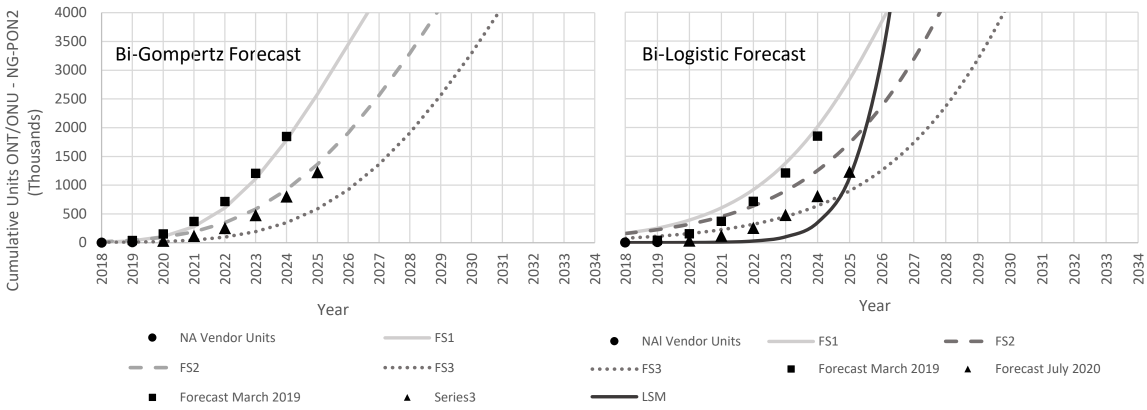

Figure 7-6 - Forecast for the NA Vendor Units ONT/ONU – NG-PON2 using Bi-Gompertz (left side), Bi-Logistic (right side), and LSM (right side).

The LSM market fraction is possible to observe in Figure 7-7. The inflection time occurs in the third quarter of 2024 year and the length of time interval to the NG-PON2 market growth from 10% to 90% of the total market is 3,735 years.

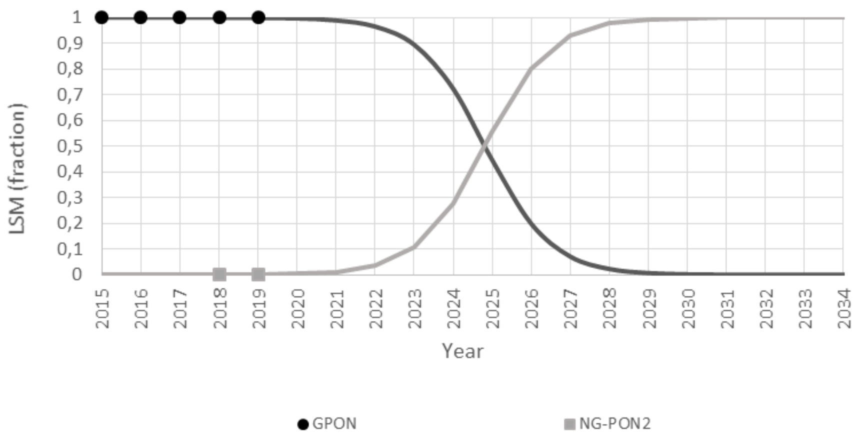

Figure 7-7 - LSM for the NA vendor units for ONT/ONU – NG-PON2.

Figure 7-8 presents the derivative fit for the NA market respectively using the constants of the Bi-Gompertz (left side) and Bi-Logistic (right side) respectively. As for the cumulative market, on the same graphics is possible to observe and compare the wireline broadband access equipment forecast from Ovum, March 2019 (pre-pandemic)[18] (squares) and the forecast from OMDIA 2019-2025, July 2020 [19] (triangles).

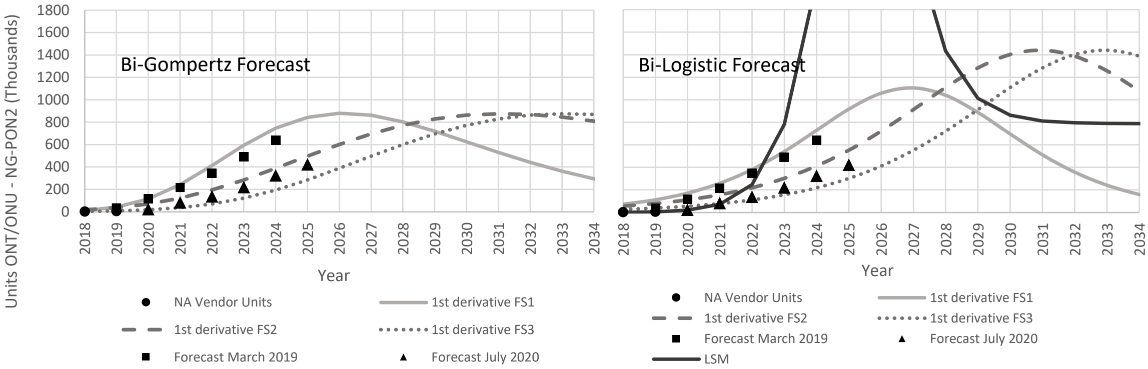

Figure 7-8 - Bi-Gompertz, Bi-Logistic, and LSM derivative fit forecast to the NA vendor units ONT/ONU – NG-PON2.

The forecast scenarios presented in Table 7-3, Figure 7-6, and Figure 7-8 were defined based on the assumptions that the NG-PON2 market is widely expanding beyond 2021, taking into account the most recent news from Verizon and they continue investing in this technology [26]–[30]. The use of NG-PON2 to support the new residential bandwidth needs, enterprises requirements, and 5G wireless will start to gain market share beyond 2022 and will benefit from the already installed FTTH/B infrastructure. Taking into account that GPON was mainly used for residential applications and due to the widespread of this technology in the NA market, the market potential of NG-PON2 on the 2nd phase of the forecast functions of 30% of GPON market in 2019 with higher growth rate and 50% of GPON market in 2019 with the same rate growth can be considered a good market approach.

The NG-PON2 has a clear disadvantage against the XGS-PON optics price and is not benefiting from worldwide implementation. Nevertheless, the Verizon investment in NG-PON2 will cause the optics cost to start to decrease, and taking into account the widespread of fiber of cell sites and the support of mobile services, and the need for higher bandwidth the market potential on the second phase can be considered a good market forecast approach.

As regards the forecast results of each of the models, in the Bi-logistic model, slower market adoption is observed compared to the Bi-Gompertz model and consequently, the market saturation happens later. The Bi-Gompertz model presents a faster adoption, and the market reaches its inflection point earlier.

Since the dynamics of the two models are different it is reasonable to expect significant differences in the forecasts they produce. Regarding the LSM, this model is based on substitution of the old technology, GPON, by the one, NG-PON2, which does not necessarily happen on the PON telecom market, since both technologies can coexist in the same network and Verizon intends to expand their 5G network using NG-PON2. The model presents a very aggressive adoption beyond 2022, a phenomenon unlikely to happen.

The forecast provided by Ovum, March 2019 (pre-pandemic)[18] and the forecast from OMDIA 2019-2025, July 2020 [19] provide us an interesting view for NG-PON2 ONT/ONU market, where is observed a forecast adoption decrease in the evaluation done during the Covid19 pandemic. These results may be a conservative approach for considering the contraction of Verizon investment on the network due to the uncertainty. We can observe that our forecast models have considered both situations, the contraction investment on the network (FS3) and the expansion of the network (FS1).

For the NG-PON2 OLT market, we are going to use the same methodology as used for the ONT/ONU forecasts. A Bi-Gompertz and Bi-Logistic functions will be used to forecast the NG-PON2 OLT market. For the first component of both functions, the constants obtained by the fit of the Bi-Gompertz and Bi-Logistic functions to the OLT 2.5G GPON NA market will be used, with the upper asymptote for the first component being defined as 20% of the total units. For the second component of both functions, different forecast scenarios will be proposed based on the following market assumptions, Table 7-4, and the historical behavior of market diffusion of GPON OLT and assuming that the future NG-PON2 OLT NA market will have similarities.

Forecast Scenario	Market Potential	K_G (growth rate coefficient of the second component)	T_i (time at the inflection of the second component)
FS1	30% of the total OLT 2.5G GPON cumulative market in 2019, this is, 641348.	Same as found for GPON OLT market by applying: Bi-Gompertz, 0,442; Bi-Logistic, 0,711;	Same as found for GPON OLT market by applying: Bi-Gompertz, 8,024 years; Bi-Logistic, 8,092 years.
FS2		10% higher than found for GPON market, due to already installed FTTH/network: Bi-Gompertz, 0,542; Bi-Logistic, 0,811;	
FS3	20% of the total OLT 2.5G GPON cumulative market in 2019, this is, 427565.	20% higher than found for GPON market, due to already installed FTTH/network: Bi-Gompertz, 0,424; Bi-Logistic, 0,911;	Earlier inflection: Bi-Gompertz, 7,024 years; Bi-Logistic, 6,092 years.

Table 7-4 - Forecast scenarios for NG-PON2 OLT, NA market.

The fit of the Bi-Gompertz and Bi-Logistic to the NA vendor units for ONT/ONU – NG-PON2 can be observed in Figure 7-9 (left side- Bi-Gompertz, right side- Bi-Logistic).

The simple logistic substitution model (LSM), this is, the Fisher and Pry model, was also applied using 30% of GPON OLT data for NA region as the old technology, Figure 7-9 (right side – LSM).

On the same graphics is possible to observe and compare the wireline broadband access equipment forecast from Ovum, March 2019 (pre-pandemic)[18] (squares) and the forecast from OMDIA 2019-2025, July 2020 [19] (triangles).

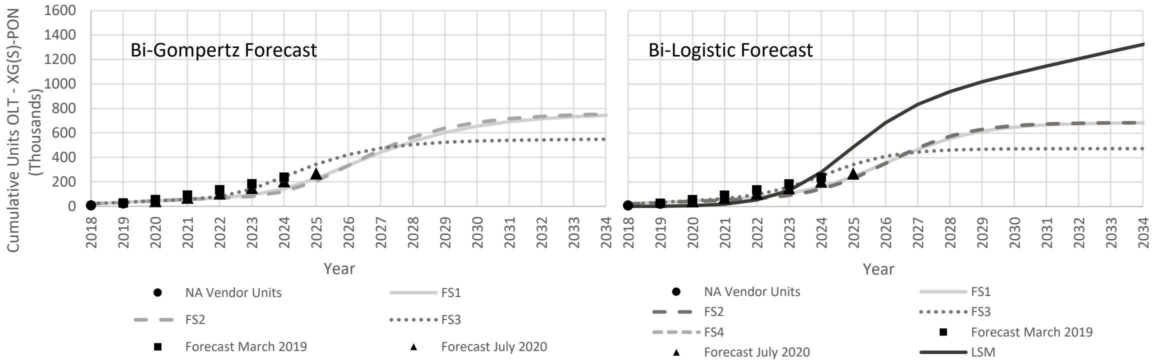

Figure 7-9- Forecast for the NA Units OLT – NG-PON2 using Bi-Gompertz (left side), Bi-Logistic (right side), and LSM (right side).

In LSM Figure 7-9 (right side – LSM) the inflection time occurs in the second quarter of the 2022 year and the length of time interval to the NG-PON2 market growth from 10% to 90% of the total market is 4,7 years.

Figure 7-10 presents the derivative fit for the OLT NA market respectively using the constants of the Bi-Gompertz (left side) and Bi-Logistic (right side), respectively. As for the cumulative market, on the same graphics is possible to observe and compare the wireline broadband access equipment forecast from Ovum, March 2019 (pre-pandemic)[18] (squares) and the forecast from OMDIA 2019-2025, July 2020 [19] (triangles).

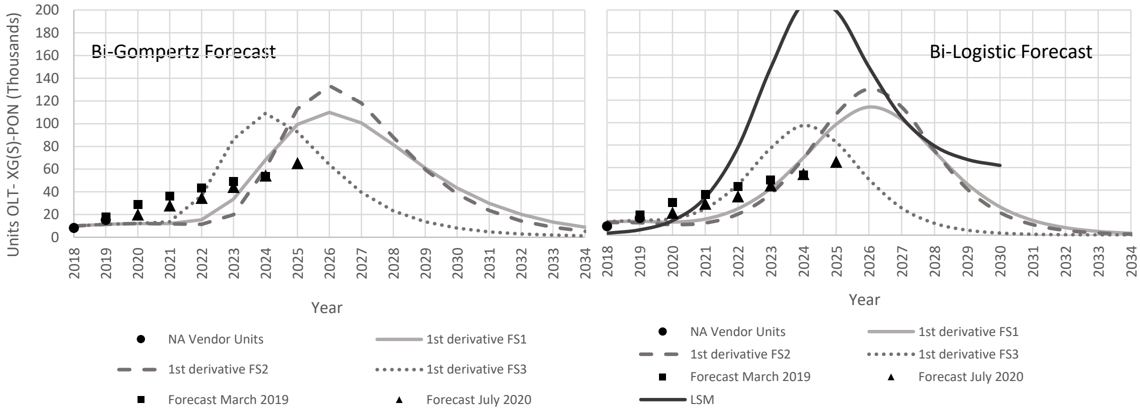

Figure 7-10 - Bi-Gompertz (left side), Bi-Logistic (right side), and LSM (right side) derivative fit forecast to the NA vendor units OLT – NG-PON2.

As regards the forecast results of each of the models and considering the NG-PON2 ONT forecasts, the Bi-Logistic model presents a forecast in line with the forecast of the terminals. A delay is observed between the OLT NG-PON2 port adoption and the NG-PON2 ONT/ONU adoption characterized by the infield implementation of equipment, service offering, and consequently the starting of adoption by the end-users.

The wireline broadband access equipment forecast from Ovum, March 2019 (pre-pandemic)[18] (squares) and the forecast from OMDIA 2019-2025, July 2020 [19] (triangles), presents a linear growth of the OLT NG-PON2 ports when compared to our forecast models, both Bi-Logistic and Bi-Gompertz forecast models are more conservative in the first years of implementation and presenting a fast growth beyond 2022 aligned with the latest news, "*Verizon is expanding 5G Ultra Wideband mobility... 100 million mobility customers in the first quarter of 2022*.[31]"

7.3 The NG-PON market and FTTH forecast

To verify the consistency of the forecast models presented in previous sections, a comparison with past and future FTTH/B subscribers is performed for the EMEA and NA.

Figure 7-11 presents the FTTH/B subscribers and the different modeling and forecast scenarios for PON technologies for the EMEA market. This figure is based on the numbers presented in the FTTH Council Europe report from September 2019 [32], FTTH Council Middle East and North Africa (MENA) report in September 2019 [33] (blue columns), FTTH forecast for Europe, 2020-2026 [34] (green columns) and the total fixed broadband subscription and forecast from OMDIA [35] (orange columns). As is possible to see the GPON market will remain strong and the main technology on the FTTH/B preference, it is also possible to notice, that the contribution of XGS-PON for the total FTTH/B subscription market is residual, of course starting to occupy its space from 2015 but more strongly beyond 2023.

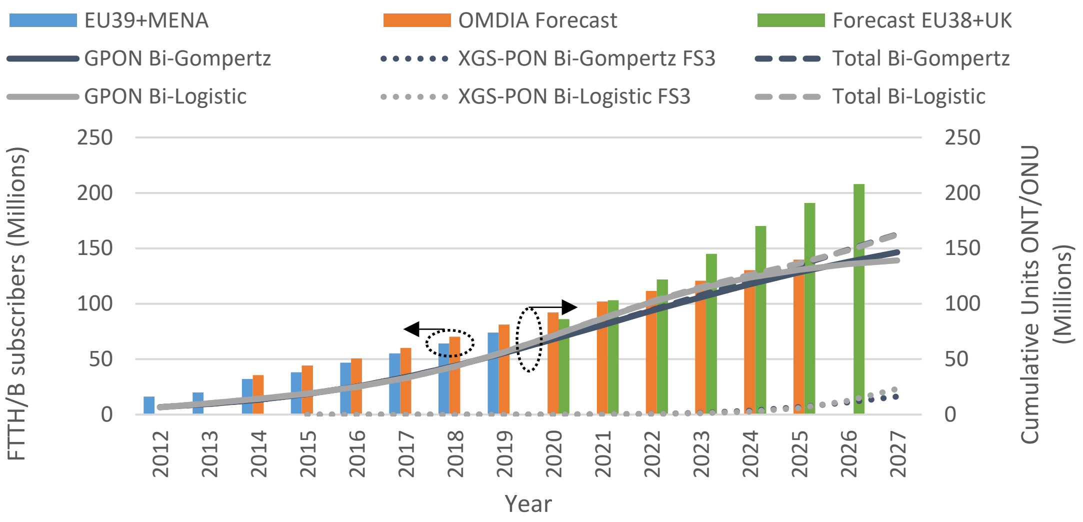

Figure 7-11 - FTTH/B subscribers EMEA market, cumulative units ONT/ONU and the fit of Bi-Gompertz and Bi-Logistic (2.5G GPON), Bi-Gompertz and Bi-Logistic forecast scenario 3 (XG(S)-PON) and total market (Bi-Gompertz and Bi-Logistic).

The observed discrepancy between the studied growth models and the presented forecasts could be due to:

- the data used to model the EMEA market includes reported vendor results and OMDIA estimates [17];
- the data used to fit the growth models include the major PON equipment vendors, but it is noticed that other smaller vendors, with a significant presence in EMEA, are not included;
- the forecasts of NG-PON were based on the historical behavior of market diffusion of GPON, and the GPON model fit only include the major GPON equipment vendors data;
- the data from FTTH council include operator data FTTH/B subscription, this means different data sourcing (vendors vs operators);
- reconditioned equipment is not taken into account in our model.

Regarding FTTH/B Homes passed, Figure 7-12, the market will maintain its "*fiberalization*", as well as the tendency of percentage market adoption of such technology by the population. The technology adoption is increasing as new homes are passed, generating also opportunities for new technologies.

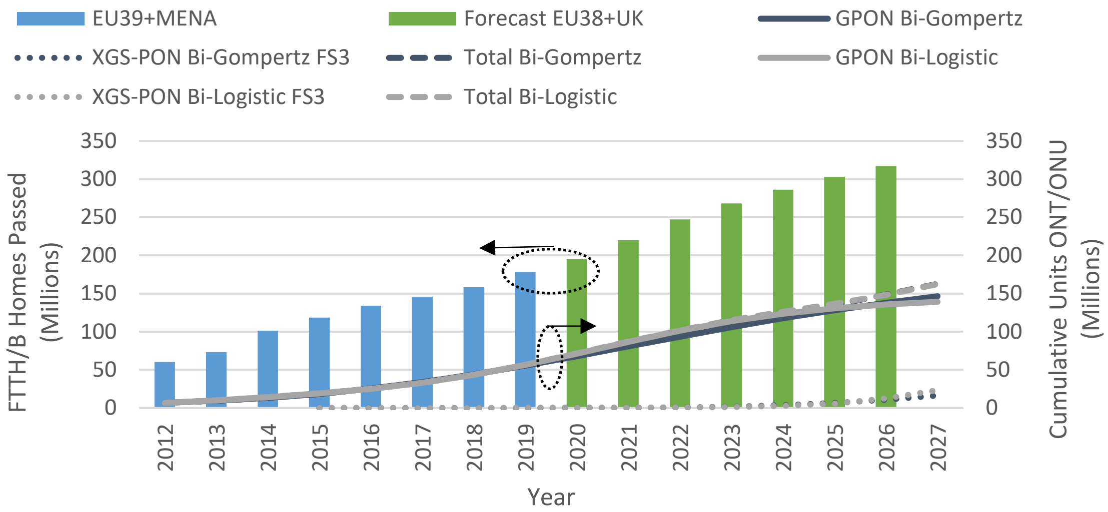

Figure 7-12 - FTTH/B homes passed EMEA market, cumulative units ONT/ONU and the fit of Bi-Gompertz and Bi-Logistic (2.5G GPON), Bi-Gompertz and Bi-Logistic forecast scenario 3 (XG(S)-PON) and total market (Bi-Gompertz and Bi-Logistic).

Figure 7-13 presents the FTTH/B subscribers and the different modeling and forecast scenarios for PON technologies for the NA market. This figure is based on the available data for the United States of America from the Fiber Broadband Association [36] (blue columns) and total fixed broadband subscription and forecast from OMDIA [35] (orange columns). As is possible to see the GPON market will remain strong and the main technology on the FTTH/B preference, it is also possible to notice, that the contribution of XGS-PON and NG-PON2 for the total FTTH/B subscription market is residual. The XGS-PON is starting to occupy its space beyond 2021 strongly than NG-PON2. Is possible to notice that the quantity of equipment sold to the NA market is always superior to the total quantity of network subscribers.

The observed discrepancy between the growth models and the presented forecasts could be due to:

- the data used to model the NA market includes reported vendor results and OMDIA estimates [17];
- the data used to fit the growth models only include the major PON equipment vendors;
- the forecasts of NG-PON were based on the historical behavior of market diffusion of GPON, and the GPON model fit only include the major GPON equipment vendors data;
- the data from Fiber Broadband Association include operator data FTTH/B subscription, this means different data sourcing (vendors vs operators);
- the data from Fiber Broadband Association include major operators data FTTH/B subscription and smaller regional/local operators are not taken into account;
- reconditioned equipment is not taken into account on our model;
- warranty and operational equipment substitution after some specific period of operation in the field not included on the forecast;

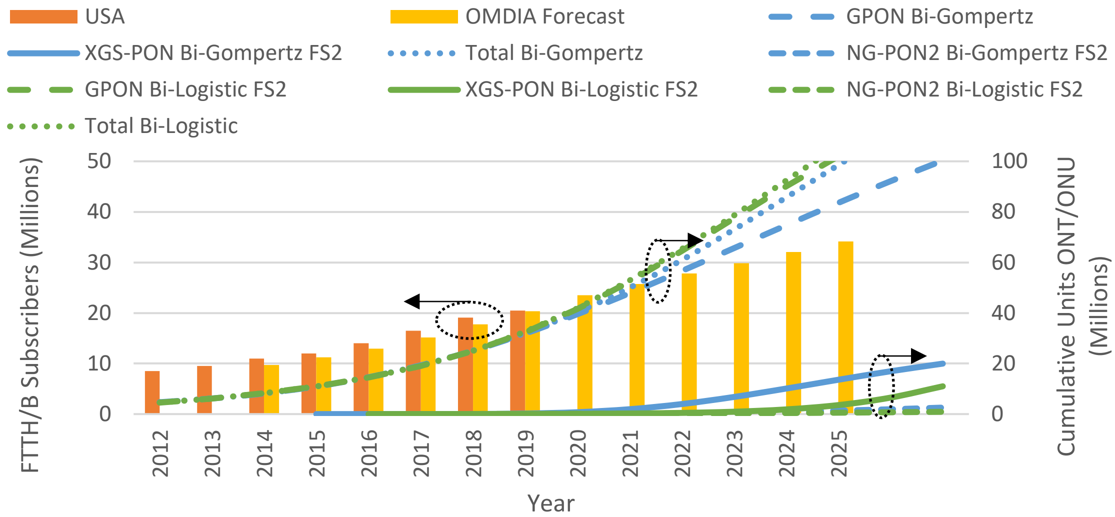

Figure 7-13- FTTH/B subscribers NA market, cumulative units ONT/ONU and the fit of Bi-Gompertz and Bi-Logistic (2.5G GPON), Bi-Gompertz and Bi-Logistic forecast scenario 2 (XG(S)-PON and NG-PON2), and total market (Bi-Gompertz and Bi-Logistic).

In Figure 7-14 is possible to observe the current USA FTTH/B homes passed. The tendency is to continue the expansion of the FTTH/B networks to address more and different markets served by GPON mainly on residential customers and using XG(S)-PON and NG-PON2 in X-Haul and business connections.

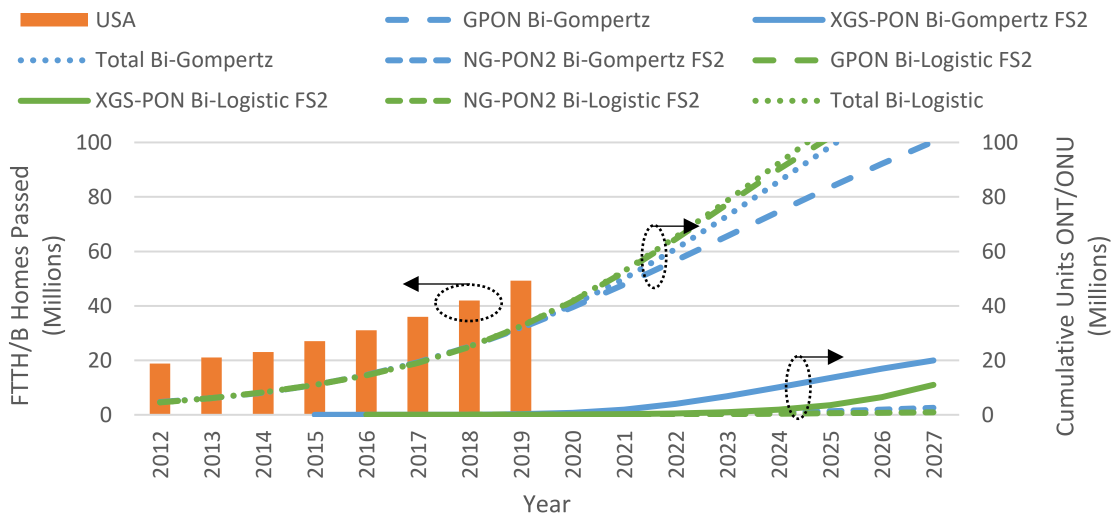

Figure 7-14- FTTH/B homes passed NA market, cumulative units ONT/ONU and the fit of Bi-Gompertz and Bi-Logistic (2.5G GPON), Bi-Gompertz and Bi-Logistic forecast scenario 2 (XG(S)-PON and NG-PON2), and total market (Bi-Gompertz and Bi-Logistic).

7.4 Outlook beyond 10G PON: 25GS-PON and 50G-PON[7]

At the end of 2019, ITU-T released the ITU-T G.9804.1 defining the requirements for the Higher Speed Passive Optical Networks (HSPON) [37]. The specifications of the physical medium dependent (PMD) layer for 50G single-channel PON systems, G.hsp-50Gpmd [38] are still under study. Nonetheless, it is already generating splitting opinions on the PON industry, where the downstream bandwidth is not gathering consensus and a division is emerging between those in favor of 25G instead of 50G [39], [40]. The basic architectures of higher-speed PON (HSP) systems can be split between Time Division Multiple Access (TDM/TDMA) based and point-to-point (PtP) based. In a 50G TDM PON, the OLT is a special case of a higher speed multi-channel PON system with just one channel in each direction [37]. A new PON-based 5G Mobile FrontHaul (PON-MFH) was included as in the services categories supported by higher speed PON scenarios [37].

In October 2020 was signed a 25G symmetric PON multi-source agreement (25GS-PON MSA) to promote and accelerate the development of 25GS-PON. The MSA Group defined the 25GS-PON specification needed to address the gap between 10G XGS-PON and 50G PON in the ITU-T. The MSA was created as the ITU-T SG15/Q2 group did not reach a consensus to standardize 25GS-PON, which is seen as a key technology by many of the world's top operators and vendors [40]. The 25GS-PON MSA Group specification for 25GS-PON includes optical specifications based on the IEEE 802.3ca 25G EPON standard, along with a Transmission Convergence (TC) layer that is an extension of XGS-PON [40]. A 25G TDM PON ONU shall be able to support the maximum service rate of approximately 25 Gbit/s in downstream and symmetric nominal line rate of 25 Gbit/s upstream. It will also be possible to support asymmetric 10 Gbit/s in the upstream direction.

The 25GS-PON can benefit from the already optical technology employed in data centers which leverage the most cost-effective solution, high capacity, fastest time-to-market, and simplest evolution path when compared to the 50G-PON. These requirements will demand a massive technology leap with a considerable lag to mature.

By using the historical behavior of market diffusion of GPON and assuming that the future 25GS-PON and 50G-PON ONT/ONU markets will have similarities. Different forecast scenarios were defined and are presented in Table 7-5.

The expected time frame of 25GS-PON start deployment would be around the year 2022, as some companies already presented commercial solutions, and for 50G-PON 2025 [41].

As a summary, the GPON data modeled to a Bi-logistic presented *r square* of 0,999. The model allowed to identify two phases of the market: the first logistic curve presenting a market penetration of 37 million units, a characteristic duration (time to grow from 10% to 90%) of 5,8 years, a growth of 0,748, and an inflection point in the middle of 2012 (4.6 years); and a second component of the function that presented a market penetration of 765 million units, with a characteristic duration of 7 years, a growth of 0,62 and an inflection time at the end of the first quarter of 2017 (9,3 years). The total GPON market is forecast to be 802 million units.

[7] This section of the thesis is based on the following conference article: "Cláudio Rodrigues, Francisco Rodrigues, Cátia Pinho, Nuno Bento, Marlene Amorim, António Teixeira, " 25G and 50G Optical Access Network Deployment Forecasts using Bi-Logistic curves", Proceedings Optical Fiber Communication Conference (OFC) 2021, 6–11 June 2021, Washington, DC, United States"[42]

Forecast Scenario		1^{st} curve			2^{nd} curve		
		Market potential	**Characteristic duration**	**Inflection time**	**Market potential**	**Characteristic duration**	**Inflection time**
50G-PON	**FS1**	10% of the total GPON	Same as found for GPON market		20% of the total GPON	Same as found for GPON market	
	FS2		20% higher growth, 4,63 years	Same as GPON market		20% higher growth, 5,35 years	Same as GPON market
25GS-PON	**FS3**	5% of total GPON	Same as found for GPON		10% of the total GPON	Same as found for GPON	
	FS4		20% higher growth, 4,63 years	Reaches inflection time one year earlier.		20% higher growth, 5,35 years	Reaches inflection time one year earlier.

Table 7-5 - Forecast scenarios for the Bi-Logistic 25GS-PON and 50G-PON ONT/ONU for the global market.

The forecast scenarios presented in Table 7-5 were defined based on the assumptions that the 10Gbit/s market is widely expanding beyond 2021. The forecast of the Bi-Logistic for the 25GS-PON and 50G-PON can be observed in Figure 7-15. The use of 25GS-PON to support 5G wireless will start to gain market share beyond 2022, but the competition with the 50G-PON beyond 2025 will result in a market splitting and consequently a decrease in market share for the 25GS-PON. Taking into account that GPON was mainly used for residential applications and due to the widespread of this technology worldwide and with the upcoming 10Gbit/s market starting to spread, the market potential of 5% for 25GS-PON and 10% for 50G-PON in the first phase can be considered a good market approach.

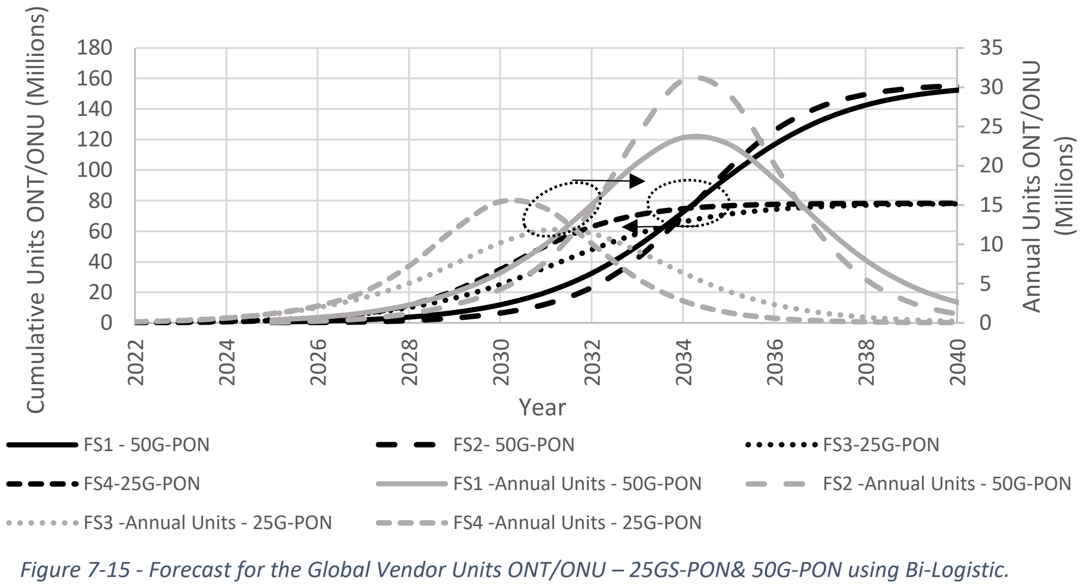

Figure 7-15 - Forecast for the Global Vendor Units ONT/ONU – 25GS-PON& 50G-PON using Bi-Logistic.

The 25GS-PON will still compete with the 10 Gbit/s market on the first phase, having a clear disadvantage against the 10 Gbit/s optics price. The delay and squeeze of the 5G investment plans by several operators will benefit the 50G-PON technology. The 25GS-PON can be considered as a middle step towards a higher-speed PON since it leverages existing technologies. The second phase of the 25GS-PON happens in the first phase of 50G-PON, and the 50G-PON will suffer on the first phase of the high-cost optics. Nevertheless, as the optics cost starts to decrease and taking into account the widespread of fiber of cell sites and the support of PON-MFH by this standard, a 20% of market potential on the second phase should be considered.

25GS-PON and 50G-PON technologies do not have residential customers as a target, resulting in diminished market potential, because such technologies are aimed to the X-Haul connections and Enterprises. As they will benefit from the already installed FTTH/B infrastructures the growth was defined to happen faster and consequently resulting in time inflection.

The final market forecast for the 50G-PON market is bigger than the 25GS-PON because the 25GS-PON will compete with the 10 Gbit/s market, as well as the inherent support of the 50G-PON of PON-MFH. The 25GS-PON will benefit from the already 25G Ethernet optical technology allowing a faster and earlier time to market, but with smaller market potential, mainly on EMEA and NA.

7.5 Conclusions

This chapter presented different forecast scenarios for Next-Generation PONs, based on the path dependence of current GPON and FTTH networks. The forecast was based on the Bi-Logistic, Bi-Gompertz, and Logistic Substitution Model. It was also analyzed the ONT/ONU and OLT forecast units with the FTTH/B penetration.

Since the dynamics of the Bi-Logistic and Bi-Gompertz models are different, significant differences in the forecasts were produced. Was tried to match the dynamics of the proposed models with the dynamics of the process being forecast, NG-PONs, to improve the robustness of the models.

Regarding the LSM, this model is based on substitution of the old technology, GPON, by the new one, NG-PON, which does not necessarily happen on the PON telecom market, since both technologies can coexist in the same network,

Using the same methodology a forecast for the upcoming 25GS-PON and 50G-PON was provided.

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Chapter 8: Conclusions and Future Work

8.1 Conclusions

The objective of this thesis was to develop a strategy for the deployment of next-generation optical networks and to understand what are the enabling factors as well as the obstacles.

The research work began by reviewing, in chapter 2, the current PON technologies. GPON, XG(S)-PON, and NG-PON2 were characterized from a technical point of view and their limitations and possible implementations were presented. The power consumption of NG-PON2 was discussed and its advantage over other PON technology was demonstrated. The feasibility of optical access networks to carry radio access network traffic for the existing and future mobile generations was described and topics related to the evolution of radio access interfaces, their transmission through ODNs, and PON technology feasibility were discussed. PON technologies beyond 10 Gbit/s were presented and the optical technology for 25GS-PON and 50G-PON was analyzed, the pros and cons of each were discussed and a possible path forward for the technology was presented.

Chapter 3 examines the characteristics of technological breakthroughs and how they apply to PON technologies. The theory of innovation cycles, the role of innovation, and the typology of technical change were analyzed as well as the main drivers of technological change. The most important phases of the telecom technology innovation process were explored, research and development, the transition phase between the laboratory and the market, technological learning, and dissemination.

The methodological framework for our analysis is provided in chapter 4. Starting from the Lotka-Volterra equation, several models originating from biology that deals with processes of growth or decline of innovation and its interaction with the technological, economic, and social environment in which it is embedded were described and analyzed. These models are at the base of our PON diffusion study, analysis of uncertainties, and forecast of NG-PON technologies, the three-parameter Logistic model, the traditional Gompertz (mortality law), and its parametrizations and re-parametrizations are discussed as a useful tool for systematization and organization of empirical data to describe the long-term development pattern of PON development.

In chapter 5, and based on the methodological framework proposed in chapter 4 we studied the historical development of FTTH/B infrastructure and the market share of PON equipments. The data from GPON ONT/ONU and OLT ports in EMEA, North America, and globally was modeled to the different studied growth curves by using an NLS regression, the estimated model parameters were compared, and the best fit models were determined. Was performed an evaluation and comparison of the estimated models with FTTH/B penetration of the forecasting capabilities of each type of growth model. For the Global GPON ONT/ONU, the Gompertz model presented the best fit to explain the pattern adoption and also the best model forecasting performance for both short-term and mid-term adoption. As regards the EMEA and NA markets the Logistic model presented the best fit and the best model forecast. Relatively to the GPON OLT markets, the Logistic model presents the best fit to explain the pattern adoption dynamics and the best model forecasting performance for both short-term and mid-term adoption. The GPON OLT market has a different market behavior than the terminals market and is highly dependent on the desire and/or necessity of the SPs to invest and expand their business. Of course, being the terminal market dependent on the OLT market and FTTH/B penetration, it is, however, also dependent on the economic wellbeing and the good financial status of the end-users.

Chapter 6 further extends the analysis of the pattern of PON market behavior. Telcos and Telecom investment and expansion of their business are highly influenced by uncertainties of all kinds, namely, technological, infrastructural, political, and competitive. Here, the uncertainties in GPON diffusion were identified and different multiple S growth curves were modeled to the data where a comparison of the estimated parameters was realized and an evaluation of the forecasting capability was done. As regards the model best fit to explain the pattern adoption, market fluctuations, uncertainties, and dynamics of GPON ONT/ONU & OLT, as well as the best model forecasting performance for both short term and mid-term adoption, we point out Bi-Gompertz for the Global and NA market. Regarding the modeling of the EMEA market, the multi-Gompertz was the model that presents the best fit and forecasting performance. The Bi S curves and the proposed Multi-Logistic and Multi-Gompertz were able to map the uncertainties on the diffusion of the GPON market and also provide good models to perform the forecast of the GPON market.

Forecasts for the diffusion of NG-PON technologies are presented in chapter 7. The 10 Gbit/s PON market, despite starting in 2015 with XG-PON and NG-PON2 is only today gaining traction, mainly with XGS-PON, so different forecast scenarios based on the Bi-Logistic and Bi-Gompertz models were proposed considering the historical diffusion behavior of the GPON market. The use of classic models, as the Fisher-Pry substitution model and the multi-substitution models, proved to be inadequate for the 10G-PON forecasting. The forecast scenarios presented for XGS-PON OLT and ONT/ONU were defined based on the assumptions that XGS-PON diffusion will grow to support the new residential bandwidth needs, enterprises requirements, and 5G wireless, the models provided us with interesting insight along the lines that the pandemic not only brings opportunities but also major drawbacks for the NG-PON market. As for NG-PON2, the forecast was only performed to the NA market, due to the know intentions of Verizon's investment in this technology and having as a clear disadvantage against the XGS-PON the optics price, and is not benefiting from worldwide implementation. However, Verizon´s investment in NG-PON2 will cause the cost of the optics to begin to decline, and given the widespread of fiber for cell sites for the support of mobile services, and the need for higher bandwidth, the proposed forecast can be considered a good approach. An outlook of the 25GS-PON and 50G-PON was also provided based on the GPON data modeled to a Bi-logistic and on the future possible market due to the target of such technologies. The final market forecast for the 50G-PON market is bigger than the 25GS-PON because the 25GS-PON will compete with the 10 Gbit/s market, as well as the inherent support of the 50G-PON of PON-MFH. The 25GS-PON will benefit from the already 25G Ethernet optical technology allowing a faster and earlier time to market, but with smaller market potential, mainly on EMEA and NA.

The work presented in this thesis reinforces what could be achieved by co-operation between the SPs (customer) and the PON equipment manufacturers (suppliers) by giving the supplier access to the customer's real demand data. Customer–supplier relationships in which close long-term co-operation simultaneously increase the value produced by the demand chain and decreases the overall cost of the chain. Good forecasts models can be produced with the right data accessed, but the test of the validity of forecasting only really comes with the passage of time.

The PON investment must take into account the different market signs, as the technological adoptions by the end-users, other telecom technologies, the mobile market, the Wi-Fi market as well as when and where. The uncertainties are always surrounding the PON markets and the different solutions. The appearance of new PON technologies that splits markets and the capacity and price of GPON as well as the continuing investment in expanding the FTTH/B, makes GPON a "*forever technology*", for at least the residential market.

8.2 Future Work

"*Forecasting has been done since people first started making long-term investments. … The most fundamental forecast is that things will happen in the future in pretty much the same way they have happened in the past. While this is referred to as naive forecasting, it is still prevalent and powerful.*"[1]

It was not the objective of this work to develop a new comprehensive theory of PON development, diffusion, and forecast, instead, the study aimed at combining the methodological apparatus developed within the diffusion research with the empirical research tradition of economic history applied to the telecom market. This Ph.D. thesis provided an overview of different theoretical streams within the diffusion research and studied the diffusion phenomena for the PON networks, contributing to different forecasts models. The analysis was made at a macro-economic level and the similarities and differences in the development patterns were analyzed for the different regions. The research conducted and reported in this thesis has addressed a very broad topic, the PON telecom market.

The following topics are suggested for subsequent follow-up research, which would be very valuable to Telco's and the telecom industry:

- Extend the study and data modeling to other growth models as the Generalized Richards, Von Bertalanffy, Weibull, Bass, Floyd, or Mansfield Model to expand the market behavior comprehension.
- Modify the studied diffusion models to include the equipment cost effect. As equipment cost decrease more and more potential customers are likely to adopt;
- Using different fitting methods to the data. In our study, we used the most common method in literature, the NLS based on sequential quadratic programming. A genetic algorithm based on Monte-Carlo could also be used to compare the fitting results.
- Expand the study to a microeconomic level and verify the accuracy of the modeling and forecasting.

- Forecasting using the Delphi method where the information is obtained through a questionnaire addressed to several experts in a series of forecasting rounds;
- Conduct a Real Options analysis of the NG-PON technologies. The creation of a RO framework allows telecom operators to view clearly their strategic investment.

8.3 Bibliography

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Appendix A. Optical Access Networks

A.1 Operator energy-saving achievements by using NG-PON2 functionalities

The different OLT scenarios studied depending on the type and number of OLT line cards (LCs) are presented. An OLT system is equipped with eight LCs with four NG-PON2 CTs each one, Figure A.1-1. An OLT system is equipped with four LCs with eight NG-PON2 CTs each one, Figure A.1-2.

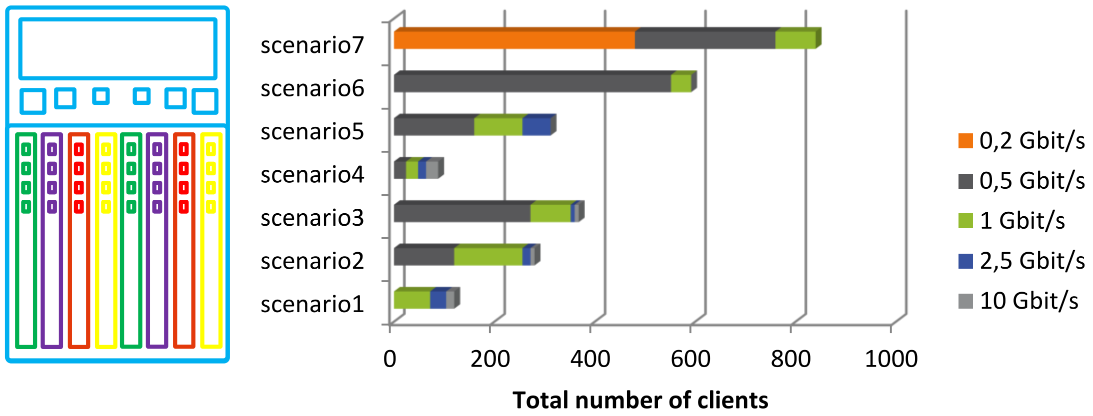


Figure A.1-1 - Total number of clients on the scenario with eight LCs with four CTs each.

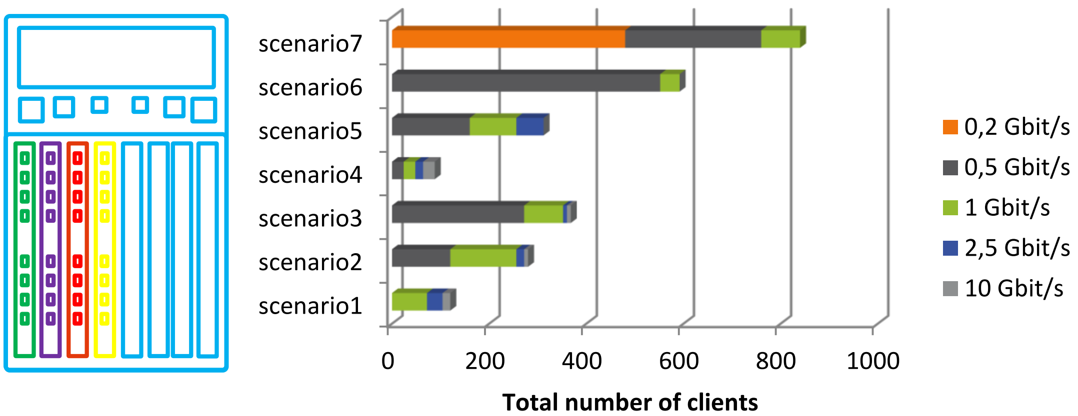


Figure A.1-2 - Total number of clients on the scenario with four LCs with eight CTs each.

Figure A.1-3 is presented the energy consumption per day for the scenario with four LCs with four CTs. Is possible to see that NG-PON2 technology with wavelength mobility presents always less power consumption when compared to XGS-PON technology (without mobility).

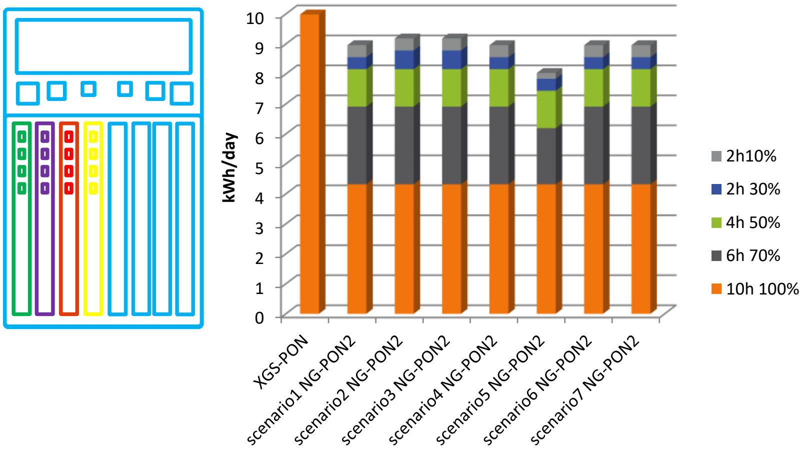


Figure A.1-3 - Energy consumption for four LCs with four CTs for the different traffic environments.

The scenario with eight LCs with four CTs, Figure A.1-4, follows the same behavior as the previously presented scenario.

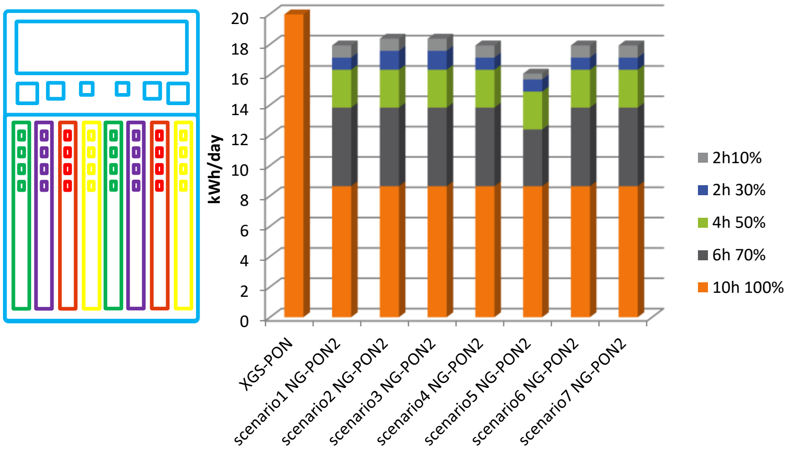


Figure A.1-4 - Energy consumption for eight LCs with four CTs for the different traffic environments.

Figure A.1-5 is presented the energy consumption per day for the scenario with four LCs with eight CTs. It presents a difference of about 10 kWh/day for the scenario without mobility versus the NG-PON2.

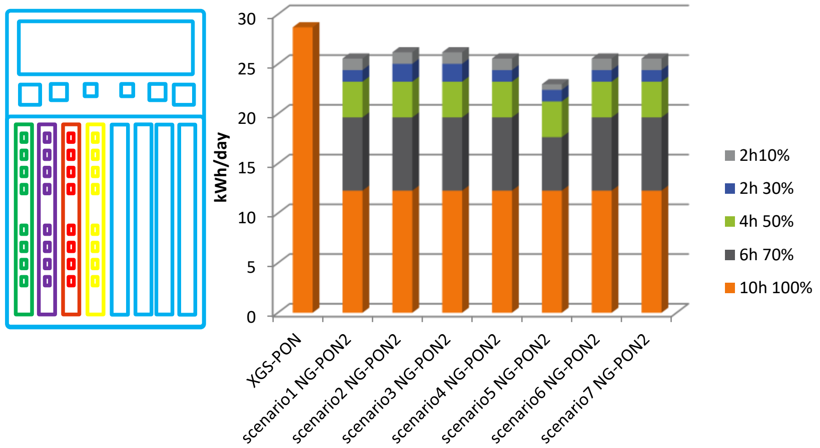


Figure A.1-5 - Energy consumption for four LCs with eight CTs for the different traffic environments.

A.2 Energy efficiency in the tunable optical head for NG-PON2 Optical Network Unit

Figure A.2-1 presents the optical head power consumption (kWh/day) for the optimized ONT PON channel distribution for an ambient temperature of 45ºC. Figure A.2-2 presents the optical head power consumption (kWh/day) for the non-optimized ONT PON organization.

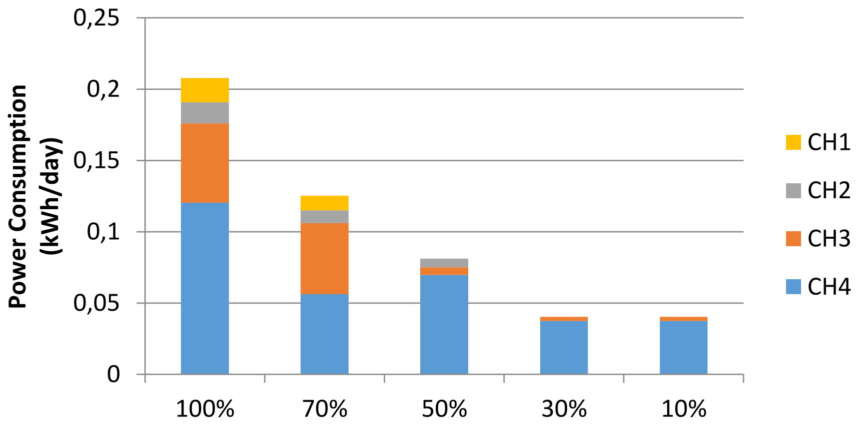


Figure A.2-1 Optical head power consumption (kWh/day) for a 45ºC ambient temperature – optimized channel distribution.

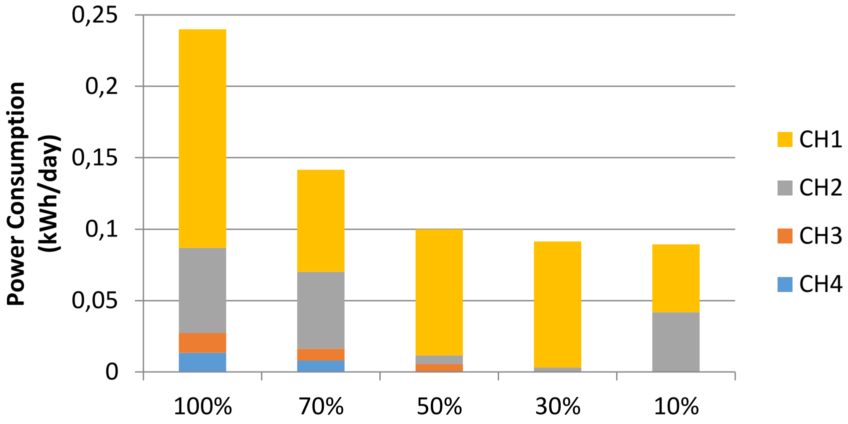


Figure A.2-2 - Optical head power consumption (kWh/day) for a 45ºC ambient temperature.

A.3 Cell site and optical access network description

Areas with plenty of dark fiber resource

If the number of fibers in the access network is not limited, a point-to-point fiber topology is recommended for transmission as shown in Figure A.3-1. This topology could improve the availability of transmission. Any failures of one branch won't affect the others. Nevertheless, a cable failure could affect several RAN links. Dark fiber is suggested in this scenario without any passive optical devices except for optical fiber splices and connectors in a point-to-point configuration.

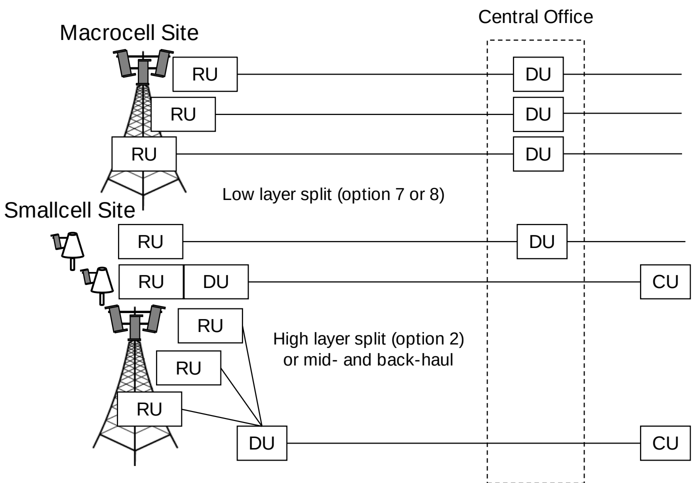


Figure A.3-1 - PtP fiber topology of fronthaul with plenty of dark fiber resources.

Areas with available but limited dark fiber resources

In this scenario, the available fiber is supposed not to support the number of fiber connections required for each RU or by chaining RUs to DU in point-to-point mode. With the densification and splitting of cell sites, the RUs will require fiber connectivity which is more and more overlapping with FTTx ODN that naturally matches the same network locations. As a consequence, to considerably, reduce the network construction costs for the fronthaul network, sharing with the FTTx ODN infrastructure must be considered. The first possibility is to reuse the maximum capacity of the ODN and PON systems deployed for residential application and extend them for mobile applications based on PON point to multipoint (PtMP) (Figure A.3-2)

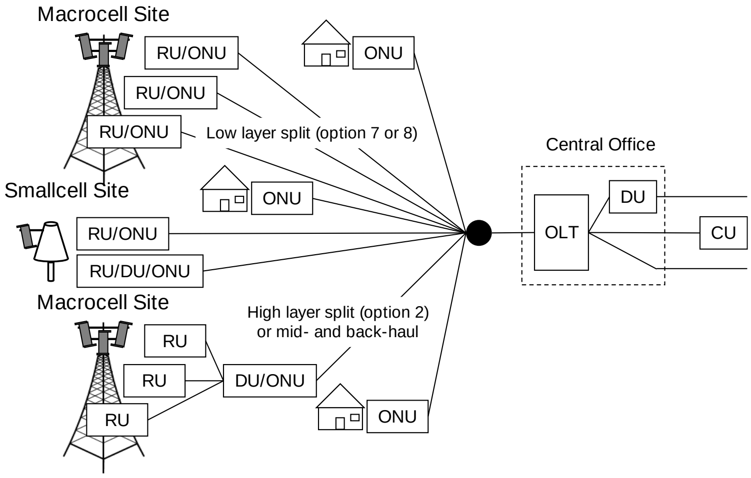


Figure A.3-2 - PtMP topology of fronthaul based on TDM.

The existing TDM and time division multiple access (TDMA) PON is capable of supporting the backhaul service but the high and continuous data rates of the low layer RAN split is a technical challenge. Another challenge comes from the fact that the aggregated mobile traffic should not degrade the fixed user services. With the evolution trend of RAN split based on high layer, the mobile fronthaul data traffic (high layer split) constraints can be relaxed and could thus provide more relevant sharing with fixed users. For low-level RAN split, the TDM-PON system could be also considered. Due to the throughput and latency requirement of this low-level RAN split, a dedicated TDM PON and ODN could be used for mobile applications (Figure A.3-3) with potential sharing cable and enclosure.

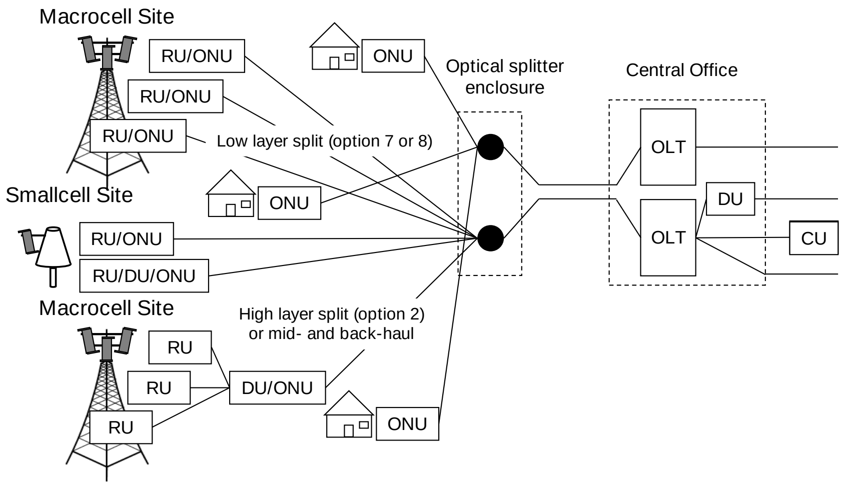


Figure A.3-3– PtMP topology of fronthaul based on TDM.

NG-PON2 (ITU-T G.989) proposes to isolate TDM channels by using wavelength channels, Figure A.3-4. NG-PON2 depicts a possible coexistence through wavelength overlay with legacy PON systems, such as G-PON, XG-PON, and XGS-PON. Network architecture, wavelength spectrum, and reference points have been defined in the G.989

series recommendations. Mobile fronthaul and backhaul are considered as potential services that must be supported by NG-PON2. NG-PON2 systems support both PtP WDM and TWDM with coexistence through legacy Passive Optical Network (PON) systems. The ODN consists of a combination of an optical power splitter and wavelength filters (CEx and WM).

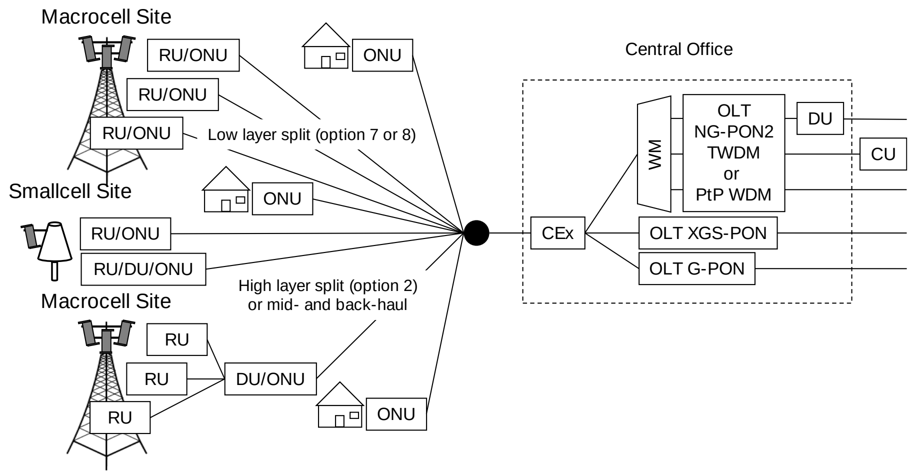


Figure A.3-4 - PtMP topology of fronthaul using wavelength overlay.

When the use of wavelength overlay with legacy PON is not required, it is possible to achieve a new ODN dedicated to the mobile application with efficient multiplexing of fronthaul and backhaul traffic over a single fiber. To use limited dark fiber resources, this specific ODN could then be constructed, for instance, with supernumerary fiber in FTTx cables. NG-PON2 describes in G.989.2 Amd. 1 Annex C a wavelength-routed (WR) ODN for PtP WDM PON (Figure A.3-5). The ODN supports passive bandpass or band stop filters to achieve the Multiplexing/DeMultiplexing of PtP WDM channels. We should notice that power splitters are not excluded from PtP WDM since they allow both coexistence and Greenfield cases even if wavelength filters are considered as the preferred option.

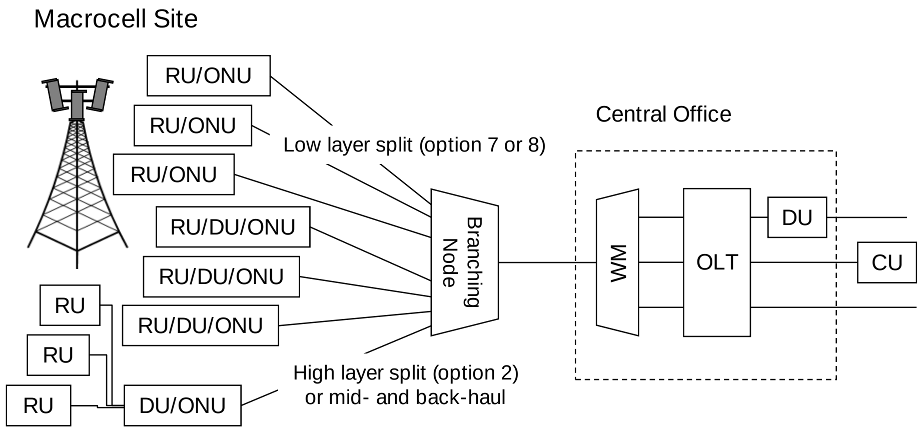


Figure A.3-5 – PtMP topology of fronthaul based on WDM.

A.4 TDM PON technologies suitability for fronthaul

Wavelength-routed (WR): the branching node is composed of a WM device such as Arrayed waveguide gratings (AWG) or a combination of thin-film filters (TFF) (Figure 2-24). The ONU's wavelength allocation is pre-determined by its physical connection to the branching node, for example by a port on the WM. Nevertheless, an exchange between the OLT and each ONU is required to allocate and stabilize the wavelength channel of the ONU transmitter. In the WR architecture, the wavelength channel allocation of the ONU receiver cannot be optionally controlled. Each drop port of the branching node must carry the channel pair (one wavelength per direction). Typically, upstream and downstream wavelengths may be the same or may differ by a multiple of the free spectral range (FSR) of the AWG.

Wavelength-selected (WS): The branching node is composed of an optical power splitter or bandpass wavelength filter (Figure A.4-1). The full or a part of the wavelength spectrum is available at the ONU so that the ONU and OLT can communicate on a large spectrum bandwidth. The ONU's wavelengths at the receiver and transmitter parts are determined during an activation process under the control of the OLT. As an example, the upstream wavelength is typically established as a fixed function of the assigned downstream wavelength.

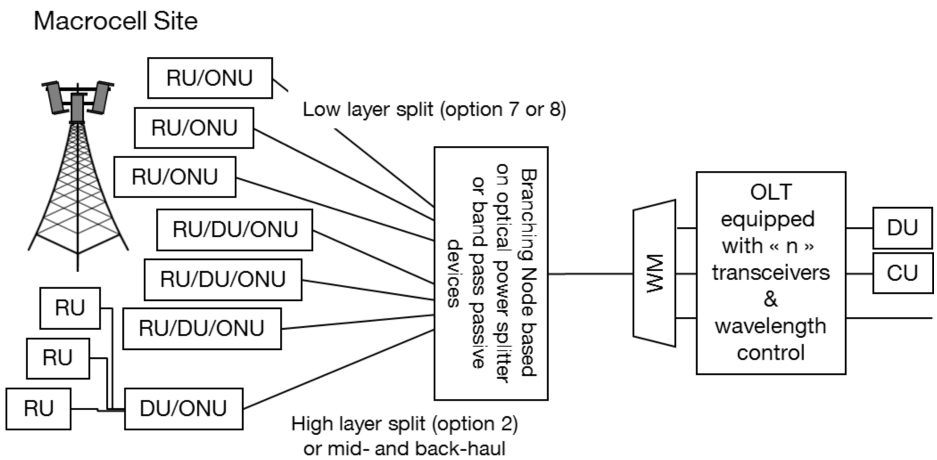


Figure A.4-1 - Wavelength selected PtP WDM-PON.

The wavelength-routed could be preferred for Greenfield ODN due to its low insertion loss. With a tunable wavelength technology at emission and reception, ONUs designed to work on power splitter-based ODN is normally reused in coexistence to residential scenarios. The provided optical budget must match the existing ODN.

Appendix B. Modeling the PON Market

B.1 PON and FTTH a historical view

A historical view of the FTTH market is provided to map the uncertainties and market variations observed in the different curves.

Year	NA Market
2008	• The market is still dominated by Verizon´s FiOS FTTH Rollout, which began to use GPON extensively [1]; • A large number of smaller Telco's, whose FTTH deployments were being supported by the Broadband Loan and Loan Guarantee Program of the US Department of Agriculture´s Rural Development Agency[1]; • GPON deployments were appearing to ramp slowly [1]; • Concerns about interoperability between ONU and OLTs [1]; • 2007-2009 recession [2], [3] ;
2009	• Single broadband provider, Verizon, represents the large majority of deployment [4]; • Regulatory Framework based on a duopoly between Telco's and cable with some potential disruption by WiMAX/LTE [4]; • In Canada, FTTH deployment has been limited almost exclusively to municipalities and some CLECs building in rural markets [4]. • 2007-2009 recession [2], [3] ;
2010 2011	• Verizon and AT&T continue strategic rollouts [5]. • In Canada selective investment in FTTH/B/N/VDSL [5]. • The National Broadband Plan "Connecting America" was adopted in March 2010 and recommended that the country adopt and track six goals for 2020, the first of which was "At least 100 million U.S. homes should have affordable access to actual download speeds of at least 100 megabits per second and actual upload speeds of at least 50 megabits per second". Thus the objectives did not include 100 % of the population and the targets specified actual upload and download speeds [6].
2012	• North America remains the region with the second-largest GPON customer base and its subscription numbers [7]; • Growth is muted in North America (the US and Canada) as operators – like AT&T in the US– attempt to squeeze more life out of their copper assets with VDSL FTTC/N rollouts[7]. • 10.9 Million FTTH/B subscribers [8];
2013	• 12.4 Million FTTH/B subscribers [9]; • OLT port consumption, representing 2 % of total world quantity; • ONT/ONUs consumption, representing 3 % of total world quantity;
2014	• OLT port consumption, representing 3 % of total world quantity; • ONT/ONUs consumption, representing 3 % of total world quantity;
2015	• OLT port consumption, representing 3 % of total world quantity; • ONT/ONUs consumption, representing 2 % of total world quantity;
2016	• Altice US announced plans to deploy FTTP [10]; • Vendors have announced numerous trials for XGS-PON and NG-PON2 and several operators have announced deployment plans.
2017	• OLT port consumption, representing 4 % of total world quantity [11]; • ONT/ONUs shipments consumption, representing 4 % of total world quantity [11]; • Disagreement in the vendor and operator community concerning the next step after 10G GPON [12];

2018	• OLT port consumption, representing 4 % of total world quantity [11]; • ONT/ONUs consumption, representing 4 % of total world quantity [11]; • NG-PON2 equipment deployments began in 2018, with Verizon, the key operator, pursuing the use of this type of next-generation GPON technology [11]; • Verizon chose NG-PON2 over XGS-PON, citing numerous reasons including the need for bandwidth beyond 10G [13]. • Verizon is striving to achieve "universal" access; where possible, the goal is to have a single access network support residential and business/enterprise customers [13]. • Operators hoping to reuse their PON ODNs (optical distribution networks) to support xHaul – mobile backhaul (MBH) and mobile fronthaul (MFH) for 5G networks [13].
2019	• Operators are evaluating numerous solutions to support 5G xHaul[14];

Year	EMEA Market
2008	• Providers of Telecommunications were not pointed toward widespread FTTH deployment [1]; • Limited greenfield deployment [1]; • Issues with the regulation of fiber access networks (how much should be opened to competing providers) [1]; • European Commission announced the launch of a public consultation on next-generation access [1]; • Business starts growing in UAE and Saudi Arabia [1]; • Concerns about interoperability between ONU and OLTs [1];
2009	• Scandinavia—already have significant deployments and were accelerating rollouts boosted in part by municipal and utility-driven projects [4]; • Still struggling in finding the right regulatory model to incentivize Telco's to invest while avoiding the development of new broadband monopolies [4]; • Some regulators favor infrastructure competition (multiple fibers owned by separate operators extending to every home) but recognize the advantage of incumbents owning telecom ducts. These regulators (Spain, Portugal, and France) aim to enforce regulated access by alternative operators to the ducts, but not to the fiber itself [4]; • the in-building connection has proved to be an issue due to inadequate housing rules in multitenant buildings [4];
2010	• Europe has not taken the leadership position in the deployment of FTTB/H. The perceived lack of a robust business case, question marks over demand, and the availability of other high-speed broadband solutions (e.g. FTTN combined with VDSL) are the major reasons [5].; • Russia's aggressive fiber rollout [5].; • FTTH growing across several countries, mainly in northern Europe and in urban areas (due to encouragement of municipal investment) [5].; • Joint-venture investments or partnerships in passive infrastructure; • Governments, regulators, and many commercial players are anxious to avoid unnecessary network duplication ensuring a viable framework, implementation, and pricing for competitor access to SMP operator networks is key [5]. • New EU regulator established [15] • Digital Agenda for Europe launched- sets out targets for fast and ultra-fast internet to maximize the social and economic potential of Information and Communication Technologies (ICT) [6].
2011	• FTTH sees a 30.6% increase in annual growth across Europe [16]; • Russia, Ukraine, Turley, France, and the Netherlands as the top 5 FTTH/B subscribers [16];
2012	• The five large Western European incumbents remain cautious with their GPON FTTH rollouts [7].

	• Growth is muted in Western Europe as operators – like BT in the UK – attempt to squeeze more life out of their copper assets with VDSL FTTC/N rollouts[7]. • Large GPON rollouts in Middle East operators, such as du and Etisalat in the UAE [7]. • 6.47 Million FTTH/B subscribers [8]; • Digital Agenda for Europe updated- by 2013, to bring basic broadband to all Europeans; by 2020, to ensure coverage of all Europeans with fast broadband (> 30 Mbps); and by 2020, to ensure take-up of 50 % or more of European households to ultra-fast broadband (> 100 Mbps) [6].
2013	• 9.4 Million FTTH/B subscribers in EU28, France, Spain, and Portugal with the biggest growth, 10.6 Million FTTH/B subscribers in Russia and 1.3 Million FTTH/B subscribers in MENA [9]. • OLT port shipments, representing 6 % of total world quantity [17]; • ONT/ONUs shipments, representing 6 % of total world quantity [17];
2014	• Historical trends confirm the move towards FTTH/B [18]; • 2014 seems to be a year of real start for FTTH/B [18]; • OLT port shipments, representing 8 % of total world quantity [17]; • ONT/ONUs shipments, representing 7 % of total world quantity [17];
2015	• OLT port shipments, representing 4 % of total world quantity [17]; • ONT/ONUs shipments, representing 5 % of total world quantity [17]; • 127 million FTTH/B Homes Passed in EU39 [18]; • Municipalities, along with utilities when appropriate, remain those that help ensure an exhaustive coverage at term [18];
2016	• 44.3 million FTTH/B subscribers and 148 million FTTH/B Homes Passed in EU39 in September 2016 [19] • Governments and local authorities are entering the game and the Digital Agenda is one of the main important objectives to achieve [19]. • European Commission identified in a Communication commonly known as the 'Gigabit Society for 2025 three strategic objectives for 2025 that complement those set out in the Digital Agenda for 2020: Connectivity of at least 1 gigabit10 for all main socio-economic drivers (such as schools, transport hubs and the main providers of public services); all urban areas and all major terrestrial transport paths to have uninterrupted 5G coverage; and all European households, rural or urban, to have access to internet connectivity offering a download speed of at least 100 Mbps, upgradable to Gigabit speed [6].
2017	• 51.6 million FTTH/B subscribers and more than 148 million FTTH/B Homes Passed in EU39 in September 2017 [19]; • OLT port consumption, representing 7 % of total world quantity [11]; • ONT/ONUs consumption, representing 6 % of total world quantity [11];
2018	• 59.6 million FTTH/B subscribers and more than 160 million FTTH/B Homes Passed in EU39 in September 2018 [20]; • Public-private initiatives are the key trend of 2018: more and more involvements from public authorities(via subsidies and an adequate policy framework) to promote fiber expansion throughout their country [20]; • OLT port consumption, representing 11 % of total world quantity [11]; • ONT/ONUs consumption, representing 6 % of total world quantity [11]; • Many operators are hoping to reuse their PON ODNs (optical distribution networks) to support xHaul – mobile backhaul (MBH) and mobile fronthaul (MFH) for 5G networks [13].
2019	• 70.4 million FTTH/B subscribers and more than 172 million FTTH/B Homes Passed in EU39 in September 2019 [21]; • During 2019, more governments launch subsidy programs to reach new FTTH areas, including rural regions [21];

	• FTTH investments delayed due to alternative technologies such as Cable [21]; • Next-gen PON ONT/ONU and OLT starts growing [22];

Year	Global Market
2008	• In Asia EPON with established presence with increasing interest by GPON as the preferred technology [1]; • Change of regulatory environment in Japan and Korea [1]; • China Telecom and Netcom already using GPON equipment massively [1]; • Concerns about interoperability between ONU and OLTs [1]; • FSAN is developing standards for 10GPON [1];
2009	• Leading FTTx developments and millions of customers (especially in Japan and South Korea) already have access to next-generation access, but the service ecosystem was not yet truly adapted to the capabilities of the new infrastructure [4]; • China's market was growing, but FTTH was only accessible to a minute proportion of the population [4]. • 10GPON standards emerging (ITU-T G.987.1 and G.987.2)
2010	• Japan, Korea, and Taiwan are still the leading countries [5]. • Strong emerging market carriers such as China Telecom [5].
2011	• World-first initiative for interoperability certification – BBF247 [16].
2012	• Asia Pacific had the largest number of GPON subscriptions at the end-2012 [7].
2013	• Asia Pacific with 93 Million FTTH/B subscribers [9].; • FTTx PON account for 43% of the market share of the broadband access equipment market [17]; • China’s major FTTx PON deployments, the AP region continues to dominate OLT port shipments (90% of total quantity) and ONU/ONTs shipments (89% of total world quantity) [17];
2014	• FTTx PON account for 54% of the market share of the broadband access equipment market [17]; • China’s major FTTx PON deployments, the AP region continues to dominate OLT port shipments (86% of total quantity) and ONU/ONTs shipments (87% of total world quantity) [17];
2015	• FTTx PON account for 65% of the market share of the broadband access equipment market [17]; • China’s major FTTx PON deployments, the AP region continues to dominate OLT port shipments (90% of total world quantity) and ONU/ONTs shipments (89% of total world quantity) [17]; • Next-Gen PON shipments have begun [17];
2016	• China's consumption of FTTx PON equipment began to decline[10]; • XG-PON1 started in some countries, supporting 1G bandwidth offerings. Deployments in China, Japan, Hong Kong, Singapore [10];
2017	• China OLT port consumption, representing 80 % of total world quantity [11]; • China ONT/ONUs consumption, representing 80 % of total world quantity [11]; • Disagreement in the vendor and operator community concerning the next step after 10G GPON [12];
2018	• China OLT port consumption, representing 73 % of total world quantity [11]; • China ONT/ONUs consumption, representing 74 % of total world quantity [11] • Many operators hoping to reuse their PON ODNs (optical distribution networks) to support xHaul – mobile backhaul (MBH) and mobile fronthaul (MFH) for 5G networks [13].

	• China Mobile is concerned about the high costs of tunable lasers needed in NG-PON2 and plans to begin massive XGS-PON deployment [13]. • The divergence in PON types puts a strain on the PON component and equipment market. It takes resources to develop components and equipment for every type of PON being deployed and considered [13].
2019	• The FTTH standards-based approach does not apply to 5G-based xHaul or transport [14]; • Operators are evaluating numerous solutions to support 5G xHaul[14]; • 25G or 50G TDM-PON would meet the bandwidth requirements for 5G fronthaul [14]; • The divergence in PON solutions for transport is putting a strain on the ecosystem, which encompasses subcomponent vendors, optical module vendors, equipment vendors, and operators [14]; • The role of fiber-based access networks is expanding with use cases for nonresidential applications and subscribers, including SMEs, campuses, smart cities, and wireless backhaul [23]. • Next-gen PON ONT/ONU and OLT starts growing [22];

B.2 Regional Definitions

North America (NA)	**Europe, Middle East, and Africa (EMEA)**		
Canada	Albania	Georgia	North Macedonia (EU39)
United States	Algeria	Germany (EU28)	Norway (EU39)
	Angola	Ghana	Oman
	Armenia	Greece (EU28)	Palestine
	Austria (EU28)	Guinea	Poland (EU28)
	Azerbaijan	Guinea-Bissau	Portugal (EU28)
	Bahrain	Hungary (EU28)	Qatar
	Belarus (EU39)	Iceland (EU39)	Reunion
	Belgium (EU28)	Iran	Romania (EU28)
	Benin	Iraq	Russia (EU39)
	Bosnia-Herzegovina	Ireland (EU28)	Rwanda
	Botswana	Israel (EU39)	Sao Tome and Principe
	Bulgaria (EU28)	Italy (EU28)	Saudi Arabia
	Burkina Faso	Jordan	Senegal
	Burundi	Kenya	Sierra Leone
	Cameroon	Kuwait	Slovakia (EU28)
	Cape Verde	Latvia (EU28)	Slovenia (EU28)
	Central African Republic	Lebanon	Somalia
	Chad	Lesotho	South Africa
	Comoros	Liberia	Spain (EU28)
	Congo	Libya	Sudan
	Cote d'Ivoire	Lithuania (EU28)	Swaziland
	Croatia (EU28)	Luxembourg (EU28)	Sweden (EU28)
	Cyprus (EU28)	Madagascar	Switzerland (EU39)
	Czech Republic (EU28)	Malawi	Syria
	Denmark (EU28)	Mali	Tanzania

	Djibouti	Malta (EU28)	Togo
	Egypt	Mauritania	Tunisia
	Equatorial Guinea	Mauritius	Turkey (EU39)
	Eritrea	Moldova	Uganda
	Estonia (EU28)	Morocco	Ukraine (EU39)
	Ethiopia	Mozambique	United Arab Emirates
	Finland (EU28)	Namibia	United Kingdom (EU28)
	France (EU28)	Netherlands (EU28)	Yemen
	Gabon	Niger	Zambia
	Gambia	Nigeria	Zimbabwe

B.3 GPON Market Share

Table B.3-1 presents the vendor units for ONT/ONU – 2.5G GPON for Global level, EMEA, and NA from OMDIA market share 2Q20 [24].

	Annual vendor units			**Cumulative vendor units**		
year	**Global**	**NA**	**EMEA**	**Global**	**NA**	**EMEA**
2008	1038399	660876	153500	1038399	660876	153500
2009	2280583	814329	808579	3318982	1475205	962079
2010	3960558	1154727	1123291	7279540	2629932	2085370
2011	9623132	959997	2400287	16902672	3589929	4485657
2012	16991906	1229058	2193270	33894578	4818987	6678927
2013	29458391	1371350	2857470	63352969	6190337	9536397
2014	42935322	1898024	4395813	106288291	8088361	13932210
2015	83127426	2573907	5691626	189415717	10662268	19623836
2016	86747071	3669237	5555882	276162788	14331505	25179718
2017	99381573	4851489	7743284	375544362	19182994	32923002
2018	118188791	6136160	9558857	493733153	25319154	42481859
2019	108457262	6852855	14280381	602190415	32172009	56762241

Table B.3-1 - Vendor Units ONT/ONU – 2.5G GPON, cumulative and annually.

Table B.3-2 presents the vendor units for OLT – 2.5G GPON for Global level, EMEA, and NA from OMDIA market share 2Q20 for PON [24].

	Annual vendor units			**Cumulative vendor units**		
year	**Global**	**NA**	**EMEA**	**Global**	**NA**	**EMEA**
2008	181560	110192	15868	181560	110192	15868
2009	210333	50638	63362	391893	160830	79230
2010	702344	51552	105224	1094237	212382	184454
2011	1929792	50476	250428	3024029	262858	434882
2012	2226470	80718	389702	5250499	343576	824584
2013	3043904	101868	273587	8294402	445444	1098171
2014	4041740	170306	421462	12336143	615750	1519633
2015	5861779	243240	351695	18197922	858990	1871328

2016	7523391	420670	486815	25721313	1279660	2358143
2017	7370914	314796	580644	33092227	1594456	2938787
2018	6803640	290794	825815	39895867	1885250	3764602
2019	7277193	252579	1146685	47173060	2137829	4911287

Table B.3-2 - Vendor Units OLT – 2.5G GPON, cumulative and annually.

B.4 Gompertz to model GPON terminals

Traditional cumulative Gompertz is modeled to Global GPON ONU vendor units, EMEA and NA. The starting values of the constants were defined, $K_g = 0{,}01$, $T_i = 0{,}01$ and $A = 99999$ and several constraints were defined to fit the data to the different curves, Table B.4-1.

Parameter	**Constraints**		
Region	**Global**	**EMEA**	**NA**
K_g	>=0,1; <=0,4	>=0,2; <=1	>=0,1; <=1
T_i	>=10;<=11	>=8 ; <=12	
A	>= 1404380830	>=56762240; <=156762240	>=32172009 ; <=132172009

Table B.4-1 - Constraints Traditional Cumulative Gompertz - Vendor Units ONT/ONU – 2.5G GPON.

The result of the constrained nonlinear regression analysis for the Global level is presented in Table B.4-2. For EMEA and NA the run stopped after 999 interactions because it reached the limit of the number of iterations, the second run used the starting values from the previous analysis and also reached the limit of iterations. No improvement was observed after the 3rd run.

The same constraints used for the cumulative modeling were applied to the temporal derivative of the market size to analyze the arrival of new adopters. The results of the constrained nonlinear regression analysis are presented in Table B.4-2. In the NA modeling the run stopped after 999 interactions because it reached the limit of the number of iterations, the second run used the starting values from the previous analysis and also reached the limit of iterations. No improvement was observed after the 3rd run.

The values of the estimated constants by the fitting of the traditional Gompertz function, Table B.4-2, were applied to the temporal derivative of the market size.

Parameter	**Region**	**Cumulative market**	**Annual market using cumulative constants**	**Annual market using cumulative market constraints**
A	**Global**	1504689769,630		1404380830,000
	EMEA	101700835,949		156762240,000
	NA	71340230,868		83857370,073
K_g	**Global**	,207		,219
	EMEA	,218		,200
	NA	,178		,208
T_i	**Global**	10,558		10,776
	EMEA	9,209		12,000

	NA	10,239		11,913
R SQUARE	**Global**	1,000	0,965	0,986
	EMEA	0,985	0,680	0,877
	NA	0,980	0,746	0,917

Table B.4-2- Parameter estimates for traditional cumulative Gompertz.

B.5 Zwietering modification to model GPON terminals

The Zwietering modification of the Gompertz function is model to the Global GPON ONU vendor units, EMEA and NA. The starting values of the constants were defined, $K_Z = 99999$, $T_i = 0$ and $A = 99999$ .The constraints defined for the nonlinear regression can be found in Table B.5-1. These constrain were defined by approach since SPSS was not capable of obtaining any approximation fitting when the variables are unconstrained.

These constraints are defined based on the assumptions that the absolute growth happens between the first units shipped and the last ones and its inflection time is between 2013 and 2020. The final market forecast has to be bigger than the cumulative quantity by 2020.

Parameter	**Constraints**		
Region	**Global**	**EMEA**	**NA**
$\boldsymbol{K_g}$	>= 80000000	>=153500; <=56762240	>=660876; <=32172009
$\boldsymbol{T_{lag}}$	>=5	>=1;<=12	>=1; <=12
$\boldsymbol{A}$	>= 800000000	>=56762240; <=156762240	>=32172009; <=132172009

Table B.5-1 -– Constraints Zwietering modification of Gompertz - Vendor Units ONT/ONU – 2.5G GPON.

The result of the constrained nonlinear regression analysis is presented in Table B.5-2. The run for NA and EMEA stopped after 999 interactions because it reached the limit of the number of iterations, the second run used the starting values from previous analysis and also reached the limit of iterations. No improvement was observed after the 2nd run.

The same constraints used for the cumulative modeling were applied to the temporal derivative of the market size to analyze the arrival of new adopters. The results of the constrained nonlinear regression analysis are presented in Table B.5-2 (column: Estimates for the annual market (1st derivative)).

For the EMEA modeling the first run stopped after 999 interactions because it reached the limit of the number of iterations, the second run used the starting values from the previous analysis and obtained the best fit after 502 iterations. For NA modeling the first run stopped after 999 interactions because it reached the limit of the number of iterations, the second run used the starting values from previous analysis and obtained the best fit after 67 iterations.

The values of the estimated constants by the fitting of the Zwietering function were applied to the temporal derivative of the market size.

Parameter	Region	Cumulative market	Annual market using cumulative constants	Annual market using cumulative market constraints
A	Global	855685866,966		800000000,000
K_g		99444296,095		80000000,000
T_{lag}		5,000		5,000
A	EMEA	110253226,298		133135362,804
K_g		7672586,459		10633871,840
T_{lag}		4,407		6,808
A	NA	69822413,252		114451612,750
K_g		4299380,815		7071798,524
T_{lag}		4,281		7,422
R SQUARE	Global	0,994	0,832	0,809
	EMEA	0,984	0,689	0,855
	NA	0,978	0,955	0,938

Table B.5-2 - Parameter estimates for Zwietering modification of Gompertz.

B.6 Zweifel and Lasker to model GPON terminals

The Zweifel and Lasker re-parametrization of the Gompertz function is modeled to the Global GPON ONU vendor units, EMEA and NA. The starting values of the constants were defined, $W_0 = 0$, $K_g = 0{,}01$ and $m = 0$. The starting point, W_0 was defined as to be less than the total quantity of vendor units in the first year for the three regions. Other constraints were defined for the nonlinear regression can be found in Table B.6-1.

Parameter	Constraints		
Region	Global	EMEA	NA
W_0	<=1038399	<=153500	<=660876
K_g		>=0,1; <=0,4	>=0,01 ; <=0,4
m		>=4; <=10	>=6 ; <=10

Table B.6-1 - Constraints Zweifel and Lasker re-parametrization of Gompertz- Vendor Units ONT/ONU – 2.5G GPON.

The result of the constrained nonlinear regression analysis is presented in Table B.6-2. To the temporal derivative of the market size and to analyze the fitting of the curve for new adopters for the global market, two more constraints were defined: $0{,}1 \leq K_g \leq 0{,}4$, $4 \leq m \leq 10$. For EMEA and NA were used the same constraints of the cumulative modeling, Table B.6-1.

The values of the estimated constants by the fitting of the Zweifel and Lasker re-parametrization of the Gompertz function were applied to the temporal derivative of the market size.

.Parameter	Region	Estimates for the cumulative market	Annual Market using cumulative market constants	Annual Market estimates using cumulative market constraints
W_0	Global	1038399,000		1038399,000
K_g		,161		,160
m		7,686		7,609
W_0	EMEA	152535,957		153500,000
K_g		,165		,102
m		7,025		8,453
W_0	NA	660876,000		622997,904
K_g		,073		,054
m		7,001		8,481
R square	Global	0,999	0,955	0,974
	EMEA	0,992	0,846	0,948
	NA	0,997	0,955	0,980

Table B.6-2 - Parameter estimates for Zweifel and Lasker re-parametrization

B.7 Gompertz-Laird to model GPON terminals

The Gompertz-Laird function is modeled to the Global GPON ONU vendor units, EMEA and NA. The starting values of the constants were defined as $W_0 = 0$, $K = 0{,}01$ and $L = 0$ and one only constant constraint were defined. As done, for the Zweifel and Lasker re-parametrization, here the starting point was also defined to be less or equal than the total quantity of vendor units ONT/ONU – 2.5 GPON in the first year. For global market $W_0 \leq 1038399$, for EMEA $W_0 \leq 152535$ and for NA $W_0 \leq 660876$.

The result of the constrained nonlinear regression analysis is presented in Table B.7-1.

Parameter	Region	Cumulative market	Annual market using cumulative constants	Annual market using cumulative market constraints
W_0	Global	1038399,000		63151
K		,161		,140
L		1,236		1,438
W_0	EMEA	152535,000		31575
K		,165		,118
L		1,158		1,121
W_0	NA	660876,000		8537
K		,073		,122
L		,514		1,217
R square	Global	0,999	0,146	0,967
	EMEA	0,992	0,543	0,941
	NA	0,997	-	0,960

Table B.7-1 - Parameter estimates for the Gompertz-Laird.

For the temporal derivative of the market size, to analyze the arrival of new adopters, several constraints to the constant were applied, Table B.7-2. The values of the estimated constants by the fitting of the Gompertz-Laird function were applied to the temporal derivative of the market size.

Parameter	Constraints		
Region	**Global**	**EMEA**	**NA**
W_0	<=1038399	<=152535	<=660876
K	>=0,09		>=0,07
L	>= 1		>= 1

Table B.7-2 - Constraints for the derivative of Gompertz-Laird.

B.8 Norton´s re-parametrization (type IIa) to model GPON terminals

Norton´s re-parametrization of the Gompertz function is modeled to the global GPON ONU vendor units, EMEA and NA. The starting values of the constants were defined as $W_0 = 0$, $K_g = 0$ and $A = 99999$. The starting point, W_0 was defined as to be less or equal than the total quantity of vendor units ONT/ONU – 2.5 GPON in the first year and the final market potential, A was defined to be bigger or equal than the 2019 cumulative total quantity for the three markets, Table B.8-1.

For the NA market the nonlinear regression stopped after 999 interactions because it reached the limit of the number of iterations, the second run used the starting values from previous analysis and also reached the limit of iterations. No improvement was observed after the 2nd run.

Parameter	Constraints		
Region	**Global**	**EMEA**	**NA**
W_0	<=1038399	<=152535	>=100;<=660876
K_g			>=0,01; <=1
A	>=602190415	>=56762240	>=172172009

Table B.8-1 - Constraints for Norton´s re-parametrization of Gompertz fit to Vendor Units ONT/ONU – 2.5G GPON.

The result of the constrained nonlinear regression analysis for the three regions is presented in Table B.8-2.

Parameter	Region	Cumulative market	Annual market (cumulative constants)	Cumulative market (optimization)	Annual market (optimization cumulative market constraints)
W_0	Global	1038399,000		81394,478	
K_g		,283		,229	
A		602190415,000		1302190415,000	
W_0	EMEA	152535,000		152535,000	
K_g		,275		,157	
A		56762240,000		196762240,000	

W_0	NA	412849,169		-	
K_g		,114		-	
A		172172370,942		-	
R square	**Global**	0,903	0,271	1,000	0,961
	EMEA	0,922	0,099	0,992	0,868
	NA	0,992	0,915	-	-

Table B.8-2–Parameter estimates for Norton´s re-parametrization.

To optimize the fitting of Norton´s model to the global market and NA region, new constraints to the nonlinear regression were applied to the constants as presented in Table B.8-3. The nonlinear regression for the global market stopped after 999 interactions because it reached the limit of the number of iterations, the second run used the starting values from previous analysis and stopped after 5 iterations because it could not improve.

Parameter	**Constraints**	
Region	**Global**	**EMEA**
W_0	>=100; <=1038399	>=100; <=152535
A	>=1302190415	>=196762240

Table B.8-3 - New constraints for Norton´s re-parametrization of Gompertz fit to Vendor Units ONT/ONU – 2.5G GPON.

The values of the constants obtained by the fitting of Norton´s function were applied to the temporal derivative of the market size. The results of the constrained nonlinear regression analysis using the constants obtained from the first constrained analysis and optimization are presented in Table B.8-2.

B.9 Logistic, Gompertz, Sharif-Khabir, and Floyd to model GPON terminals

To compare the performance of the fitting, a software tool [25], to estimate the parameters of technological growth from the International Institute for Applied Systems Analysis (IIASA) was used. The different market data was fitted to three-parameter logistic, Gompertz, Sharif-Khabir, and Floyd. In Table B.9-1 is possible to see the results of the fitting.

Region		A	**Time of inflection**	Δt	***R square***
Global	**Logistic**	802014888,83	9,153	7,541	0,999
	Gompertz	1511211080,15	10,578	14,916	0,999
	Sharif-Khabir	877126895,50	8,607	12,001	0,997
	Floyd	1009210289,24	8,662	17,675	0,998
EMEA	**Logistic**	145356081,92	12,276	11,941	0,997
	Gompertz	48540104,81	28914,866	-36613533,172	0,887
	Sharif-Khabir	87720407,72	8,797	14,818	0,987
	Floyd	100677977,89	8,848	21,720	0,997
NA	**Logistic**	148557872,327	15,091	14,025	0,999

	Gompertz	261040348110,371	88,475	108,777	0,999
	Sharif-Khabir	84281904,948	11,616	23,132	0,997
	Floyd	103692593,513	12,071	34,494	0,997

Table B.9-1 - Parameter estimates to growth models.

The fit of the first derivative of the Logistic curve to the global, EMEA, and NA vendor units for ONT/ONU – 2.5G GPON can be observed in Table B.9-2.

Region	**1st derivative using cumulative market constants**
	R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares)
Global	0,943
EMEA	0,928
NA	0,947

Table B.9-2- ANOVA for the derivative of Logistic curve using cumulative constants.

B.10 Zweifel and Lasker to model OLT - 2.5G GPON

The Zweifel and Lasker re-parametrization of Gompertz function is modeled to the Global GPON OLT vendor units, EMEA and NA are modeled to. The starting values of the constants were defined, $W_0 = 0$, $K_g = 0{,}01$ and $m = 0$. The starting point, W_0 was defined to be less than the total quantity of vendor units in the first year for the three regions. All constraints defined for the nonlinear regression can be found in Table B.10-1.

Parameter	**Constraints**		
Region	**Global**	**EMEA**	**NA**
W_0	<=181560	<=15868	<=110192
K_g	>=0,1 ; <=0,4		
m	>=4; <=10		

Table B.10-1 - Constraints Zweifel and Lasker re-parametrization of Gompertz- Vendor Units OLT – 2.5G GPON

The result of the constrained nonlinear regression analysis is presented in Table B.10-2. The same constraints used for the cumulative modeling were applied to the temporal derivative of the market size to analyze the arrival of new adopters. The values of the estimated constants by the fitting of the Zweifel and Lasker re-parametrization of the Gompertz function were applied to the temporal derivative of the market size.

Parameter	**Region**	**Cumulative market**	**Annual market**
W_0	**Global**	136258,351	43579,291
K_g		,193	,204
m		6,651	7,721
W_0	**EMEA**	15868,000	12755,769
K_g		,193	,112
m		6,448	8,066
W_0	**NA**	53621,685	153,789
K_g		,113	,254

m		5,229	10,000

Table B.10-2 - Parameter estimates for Zweifel and Lasker re-parametrization.

The *r square* of the Zweifel and Lasker re-parametrization to the Global, EMEA, and NA vendor units for OLT – 2.5G GPON can be observed in Table B.10-3.

Region	Cumulative Market	Annual market cumulative constraints	Annual Market using cumulative market constants
	***R square* = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares)**		
Global	0,999	0,978	0,956
EMEA	0,984	0,864	0,576
NA	0,991	0,790	0,079

Table B.10-3 - ANOVA for Zweifel and Lasker re-parametrization.

B.11 Norton´s to model OLT - 2.5G GPON

Norton´s re-parametrization of the Gompertz function is modeled to the global GPON OLT vendor units, EMEA and NA. The starting values of the constants were defined as $W_0 = 0, K_g = 0$ and $= 99999$. The starting point, W_0 was defined as to be less or equal than the total quantity of vendor units OLT – 2.5 GPON in the first year and the final market potential, A was defined to be bigger or equal than the 2019 cumulative total quantity for the three markets, Table B.11-1. The same constraints used for the cumulative modeling were applied to the temporal derivative of the market size to analyze the arrival of new adopters. The values of the estimated constants by the fitting of Norton´s function were applied to the temporal derivative of the market size.

Parameter	Constraints		
Region	**Global**	**EMEA**	**NA**
W_0	>=100; <=181560	>=100; <=15868	>=100;<=110192
K_g	>=0,01; <=1	>=0,01; <=1	>=0,01; <=1
A	>=94346120	>=9822574	>=4275658

Table B.11-1 – Constraints for Norton´s re-parametrization of Gompertz fit to Vendor Units OLT – 2.5G GPON

The result of the constrained nonlinear regression analysis for the three regions is presented in Table B.11-2.

Parameter	Region	Cumulative market	Annual market
W_0	Global	79043,620	11451,636
K_g		,211	,220
A		94346134,060	94346120,000
W_0	EMEA	11008,271	3865,999
K_g		,201	,182
A		9822574,000	11948866,128
W_0	NA	9866,216	3894,094
K_g		,199	,192

A		4275659,763	4456821,139

Table B.11-2 –Parameter estimates for OLT GPON Norton´s re-parametrization.

The *r square* of Norton´s re-parametrization to the global vendor units for OLT – 2.5G GPON can be observed in Table B.11-3.

Region	Cumulative Market	Annual market using cumulative constraints	Annual market using cumulative market constants
	***R square* = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares)**		
Global	0,999	0,971	0,952
EMEA	0,981	0,772	0,665
NA	0,986	0,762	0,699

Table B.11-3 - ANOVA for OLT GPON Norton´s re-parametrization.

B.12 Logistic, Gompertz, Sharif-Khabir, and Floyd to model OLT - 2.5G GPON

To compare the performance of the fitting, a software tool [25], to estimate the parameters of technological growth from the International Institute for Applied Systems Analysis (IIASA) was used.

The different market data was fitted to three-parameter Logistic, Gompertz (, Sharif-Khabir and Floyd. In Table B.12-1 is possible to see the results of the fitting.

		A	Time of inflection	Δt	*R square*
Global	**Logistic**	57377050,228	8,397	8,128	0,999
	Gompertz	78851497,084	8,457	13,026	0,998
	Sharif-Khabir	64821105,610	7,921	12,666	0,998
	Floyd	72654520,769	7,870	18,381	0,998
EMEA	**Logistic**	5914100,157	8,831	10,558	0,992
	Gompertz	13229549,855	11,811	22,435	0,995
	Sharif-Khabir	5268085,514	7,150	12,885	0,980
	Floyd	5909916,300	7,096	18,632	0,981
NA	**Logistic**	3161340,195	9,109	10,561	0,996
	Gompertz	10002694,177	14,653	27,322	0,992
	Sharif-Khabir	-	-	-	-
	Floyd	-	-	-	-

Table B.12-1– Parameter estimates to growth models.

The values of the estimated constants by the fitting of the Logistic function were applied to the temporal derivative of the market size in SPSS of the first derivative of the Logistic curve.

The ANOVA is presented in Table B.12-2

Region	Annual Market using cumulative market constants

	R square
Global	0,906
EMEA	0,529
NA	0,808

Table B.12-2 - ANOVA for the derivative of Logistic curve using cumulative constants.

Appendix C. Uncertainties related to investment in PON technologies

C.1 Taxonomy of Bi-Logistic

Perrin S. Meyer in [26], [27] described the taxonomy of bi-logistic curves. Depending on the order and magnitude of the overlap, the aggregate curve can take on a wide range of appearances, Table C.1-1 (bi-Logistic at the left, fisher-pry transform at the right).

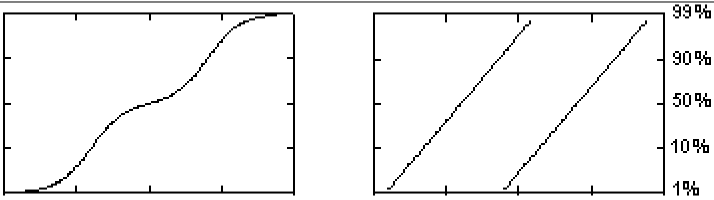
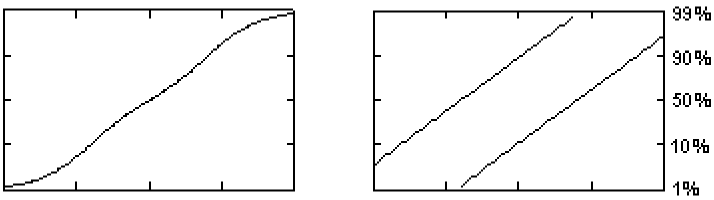
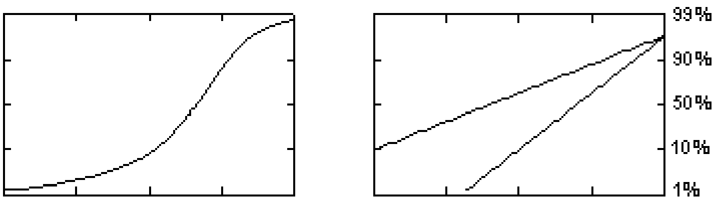
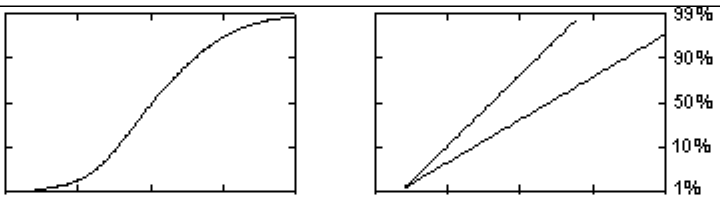
	Pattern	Description
Sequential		The second curve does not start growing until the first curve has nearly reached its saturation level.
Superposed		The second curve begins growing when the first curve has reached about 50% of saturation
Converging		Growth process where a first logistic growth is joined by a second faster curve, dubbed the “converging” logistic model, as the two pulses culminate about the same time.
Diverging		Where two logistic growth processes begin at the same time but grow with different rates and carrying capacities defined from the start.

Table C.1-1 – Taxonomy of the bi-logistic.

C.2 Bi-Logistic to model GPON terminals

The fitting of the sum of the Bi-Logistic function to the data is done by SPSS using the Non-Linear Regression. The starting values of the constants were defined, $\mathrm{A} = 99999$, $K_g = 0{,}01$, $T_i = 0{,}01$ $A_1 = 99999$, $K_{g1} = 0{,}01$, $T_{i1} = 0{,}01$. To estimate the initiate parameters we are going to use the results previously obtained by the fit of the Logistic curve to the GPON ONU/ONT 2.5G GPON and also the a priori knowledge of the system to derive estimates reasonably and efficiently.

From the visual analysis to the Global, EMEA, and NA vendor units for ONT/ONU 2.5G GPON, were defined the constraints for the software analysis, Table C.2-1. The upper asymptote was defined based on the results of the fit of the Logistic curve.

Parameter	Constraints		
Region	Global	EMEA	NA
K_g	>=0,1; <=1	>=0,1; <=1	>=0,01; <=1
T_i	>=2;<=5	>=2;<=7	>=1;<=5
A	<=189415717	<= 19623836	<= 6190337
K_{g1}	>=0,1; <=1	>=0,1; <=1	>=0,1; <=0,4
T_{i1}	>=5;<=12	>=7;<=13	>=14;<=17
A_1	>=189415717	>=19623836	>=60471514
$A + A_1$	= 802014888	= 145356081	=148557872

Table C.2-1 – Constraints Bi-Logistic –Vendor Units ONT/ONU – 2.5G GPON.

The result of the constrained nonlinear regression analysis for three markets is presented in Table C.2-2, which summarizes the model-estimated value of each parameter.

The same constraints used for the cumulative modeling were applied to the temporal derivative of the market size to analyze uncertainties. The results of the constrained nonlinear regression analysis are presented in Table C.2-2.

The values of the estimated constants by the fitting of the Bi-Logistics function were applied to the temporal derivative of the market size, Table C.2-2.

	Region	Cumulative market	Annual market
A	Global	36976922,267	33992980,565
	EMEA	9765232,302	19623836,000
	NA	4202238,255	6081341,149
K_g	Global	,748	,776
	EMEA	,785	,624
	NA	,406	,233
T_i	Global	4,665	5,000
	EMEA	4,588	6,086
	NA	4,957	1,000
A_1	Global	765037965,733	768021907,435
	EMEA	135590848,698	125732245,000
	NA	144355633,745	142476530,851
K_{g1}	Global	,620	,596
	EMEA	,459	,583
	NA	,358	,332
T_{i1}	Global	9,324	9,797
	EMEA	12,408	12,973
	NA	14,918	15,489

Table C.2-2- Parameter estimates for Bi- Logistic.

The r square values obtained are presented in Table C.2-3.

Region	Cumulative Market	Annual Market using cumulative constraints	Annual Market using cumulative market constants
	R square **= 1 - (Residual Sum of Squares) / (Corrected Sum of Squares)**		
Global	0,999	0,978	0,950
EMEA	0,999	0,987	0,945
NA	0,999	0,989	0,932

Table C.2-3 - ANOVA table for Bi-Logistic.

C.3 Bi-Gompertz to model GPON terminals

The fitting of the Bi-Gompertz function to the data is done by SPSS using the Non-Linear Regression.

The starting values of the constants were defined, $\mathrm{A} = 99999$, $K_g = 0{,}01$, $T_i = 0{,}01$ $A_1 = 99999$, $K_{g1} = 0{,}01$, $T_{i1} = 0{,}01$.

To estimate the initiate parameters we are going to use the results previously obtained by the fit of the Gompertz curve to the GPON ONU/ONT 2.5G GPON, and also the a priori knowledge of the system to derive estimates reasonably and efficiently.

As was done for the analysis of the Bi-logistic, for the Bi-Gompertz the procedure will be similar. From the market analysis, were defined the simulation constraints, Table C.3-1.

The upper asymptote for the global market, $\boldsymbol{A+A_1}$was defined based on the results of the fit of traditional Gompertz.

The upper asymptote for the EMEA and NA market, $\boldsymbol{A+A_1}$were defined based on the results of the fit of Norton´s re-parametrization.

Parameter	Constraints		
Region	**Global**	**EMEA**	**NA**
$\boldsymbol{K_g}$	>=0,1; <=0,4	>=0,1; <=0,4	>=0,01; <=1
$\boldsymbol{T_i}$	>=2;<=5	>=2;<=7	>=1;<=5
$\boldsymbol{A}$	<=189415717	<= 19623836	<= 6190337
$\boldsymbol{K_{g1}}$	>=0,1; <=0,4	>=0,1; <=0,4	>=0,1; <=0,4
$\boldsymbol{T_{i1}}$	>=5;<=12	>=7;<=14	>=15;<=17
$\boldsymbol{A_1}$	>=189415717	>=19623836	>=60471514
$\boldsymbol{A+A_1}$	= 1504689769	= 196762240	=172172370

Table C.3-1 – Constraints Bi-Gompertz – Global Vendor Units ONT/ONU – 2.5G GPON

The result of the constrained nonlinear regression analysis for three markets is presented in Table C.3-2. The same constraints used for the cumulative modeling were applied to the temporal derivative of the market size to analyze the arrival of new adopters. The results of the constrained nonlinear regression analysis are presented in Table C.3-2

The values of the estimated constants by the fitting of the Bi-Gompertz function were applied to the temporal derivative of the market size.

	Region	Cumulative market	Annual market (1st derivative)
$\boldsymbol{A}$	**Global**	29429156,985	47520586,751

	EMEA	13818225,360	18983065,679
	NA	5500437,491	6116864,585
K_g	**Global**	,219	,130
	EMEA	,345	,400
	NA	,406	,424
T_i	**Global**	4,720	5,000
	EMEA	3,524	4,847
	NA	1,640	1,844
A_1	**Global**	1475260612,015	1457169182,249
	EMEA	182944014,640	177779174,321
	NA	166671933,451	166055506,357
K_{g1}	**Global**	,212	,211
	EMEA	,189	,228
	NA	,148	,153
T_{i1}	**Global**	10,647	11,083
	EMEA	12,991	13,453
	NA	15,126	15,437

Table C.3-2 - Parameter estimates for Bi- Gompertz.

Table C.3-3 presents the cumulative and derivative fit for the Global, EMEA, and NA markets respectively using the constants obtained by the fit of the Bi-Logistic and a model fit using the same constraints of the cumulative market.

Region	**Cumulative Market**	**Annual Market using cumulative constraints**	**Annual Market using cumulative market constants**
	***R square* = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares)**		
Global	1,000	0,986	0,968
EMEA	0,998	0,963	0,923
NA	1,000	0,998	0,975

Table C.3-3 - ANOVA table for Bi-Gompertz.

C.4 Bi-Logistic to model GPON OLT

The Bi-Logistic fit to the data is done by SPSS using the Non-Linear Regression. The starting values of the constants were defined, $\mathrm{A} = 99999$, $K_g = 0{,}01$, $T_i = 0{,}01$ $A_1 = 99999$, $K_{g1} = 0{,}01$, $T_{i1} = 0{,}01$. As previously for the ONT/ONU markets, to estimate the initiate parameters we are going to use the results previously obtained by the fit of Logistic curve to the GPON OLT 2.5G GPON and also the a priori knowledge of the system to derive estimates reasonably and efficiently.

The constraints for the SPSS fit, Table C.4-1, of the Bi-Logistic function, were defined based on visual analysis of the different markets. The upper asymptote for the Global market was defined based on the results of the fit of the Logistic curve. For the EMEA and NA markets, the upper asymptotes, $\boldsymbol{A} + \boldsymbol{A_1}$were first defined based on the results of the fit of the logistic function, but SPSS did not obtain a good fit using these constraints and they were removed. The top asymptote of the first curve for the EMEA market was defined to be less than the cumulative total units in 2016 and for the NA market was defined to be less than the cumulative total units in 2014.

	Constraints		
Parameter	**Global**	**EMEA**	**NA**
K_g	>=0,1; <=1	>=0,01; <=1	>=0,01; <=1
T_i	>=2;<=5	>=2;<=7	>=0,1;<=5
A	>=0; <= 8294402	>=0; <= 2358143	>=0;<= 615750
K_{g1}	>=0,1; <=0,4	>=0,1; <=1	>=0,1; <=1
T_{i1}	>=9;<=12	>=10;<=14	>=6;<=10
A_1	>= 8294402	>=2358143	>= 615750
$A + A_1$	= 57377050		

Table C.4-1 – Constraints Bi-Logistic –Vendor Units OLT – 2.5G GPON.

The result of the constrained nonlinear regression analysis for three markets is presented in Table C.4-2 and Table C.4-3, it summarizes the model-estimated value of each parameter, as well as the temporal derivative of the market size using the same, constraints used for the cumulative modeling, for the respective market.

	Region	Cumulative market	Annual market
A	**Global**	6937546,802	7255576,692
	EMEA	1370646,505	2333313,798
	NA	224491,302	332773,928
K_g	**Global**	,833	,606
	EMEA	,962	,610
	NA	,948	,974
T_i	**Global**	4,811	5,000
	EMEA	3,975	5,481
	NA	,243	,162
A_1	**Global**	52520294,419	54318174,030
	EMEA	6438476,921	5113055,796
	NA	2114606,916	2229847,364
K_{g1}	**Global**	,586	,553
	EMEA	,636	,863
	NA	,711	,657
T_{i1}	**Global**	9,012	9,517
	EMEA	10,739	11,388
	NA	8,092	8,729

Table C.4-2 - Parameter estimates for Bi-Logistic.

Region	Cumulative Market	Annual Market using cumulative constraints	Annual Market using cumulative market constants
	***R square* = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares)**		
Global	1,000	0,975	0,943
EMEA	0,999	0,975	0,911
NA	0,999	0,930	0,826

Table C.4-3 - ANOVA table for Bi-Logistic

C.5 Bi-Gompertz to model GPON OLT

The fitting of the Bi-Gompertz function to the data is done by SPSS using the Non-Linear Regression. The starting values of the constants were defined, $\mathrm{A} = 99999$, $K_g = 0{,}01$, $T_i = 0{,}01$ $A_1 = 99999$, $K_{g1} = 0{,}01$, $T_{i1} = 0{,}01$.As previously stated, to estimate the initiate parameters we are going to use the results previously obtained by the fit of Norton´s curve to the GPON OLT 2.5G GPON and also the a priori knowledge of the system to derive estimates reasonably and efficiently.

From the visual analysis to the global vendor units for OLT 2.5G GPON of the different markets, were identified the market disturbances, as so, the constraints were defined based on these disturbances, Table C.5-1. The upper asymptote, $\boldsymbol{A} + \boldsymbol{A_1}$was defined based on the results of the fit of Norton´s model for the global market. For EMEA and NA market SPSS did not obtain a good fit using these constrain and it was removed. The top asymptote of the first curve was defined to be higher than the cumulative total units in 2013 for the global market, 2016 for EMEA, and 2014 for the NA market, Table C.5-1.

Parameter	Constraints		
Region	**Global**	**EMEA**	**NA**
$\boldsymbol{K_g}$	>=0,1; <=1	>=0,01; <=1	>=0,01; <=1
$\boldsymbol{T_i}$	>=2;<=5	>=2;<=7	>=0,1;<=5
$\boldsymbol{A}$	>=0; <= 8294402	>=0; <= 2358143	>=0;<= 615750
$\boldsymbol{K_{g1}}$	>=0,1; <=0,4	>=0,1; <=1	>=0,1; <=1
$\boldsymbol{T_{i1}}$	>=5;<=12	>=12;<=14	>=6;<=10
$\boldsymbol{A_1}$	>= 8294402	>=2358143	>= 615750
$\boldsymbol{A + A_1}$	= 94346134		

Table C.5-1 - Constraints Bi-Gompertz – Global Vendor Units OLT – 2.5G GPON

The result of the constrained nonlinear regression analysis for three markets is presented in Table C.5-2 and Table C.5-3, it summarizes the model-estimated value of each parameter. The same constraints used for the cumulative modeling were applied to the temporal derivative of the market size to analyze the arrival of new adopters.

The values of the estimated constants by the fitting of the Bi-Gompertz function were applied to the temporal derivative of the market size.

	Region	Estimates for the cumulative market	Estimates for the annual market
A	Global	8169688,931	2294452,578
	EMEA	2252502,765	2325989,134
	NA	615750,000	607843,170
K_g	Global	,313	,892
	EMEA	,446	,424
	NA	,267	,340
T_i	Global	4,288	2,856
	EMEA	4,085	4,806
	NA	2,153	,349
A_1	Global	86176445,069	92051681,422
	EMEA	10397459,038	14723807,483
	NA	2055129,628	2194592,603
K_{g1}	Global	,224	,221
	EMEA	,292	,255
	NA	,442	,428
T_{i1}	Global	9,795	9,986
	EMEA	12,006	13,604
	NA	8,024	8,510

Table C.5-2 - Parameter estimates for Bi-Gompertz.

Region	Cumulative Market	Annual Market using cumulative constrains	Annual Market using cumulative market constants
	***R square* = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares)**		
Global	1,000	0,983	0,983
EMEA	0,999	0,979	0,925
NA	0,999	0,932	0,863

Table C.5-3 - ANOVA table for Bi-Gompertz.

C.6 Multi-Gompertz and Multi-Logistic to model EMEA GPON terminals

The fitting of the Multi-Gompertz and Multi-Logistic functions to the GPON ONU/ONT 2.5G GPON EMEA market data is done by SPSS using the Non-Linear Regression. The starting values of the constants were defined, $\mathrm{A} = 99999$, $K_g = 0{,}01$, $T_i = 0{,}01$ $A_1 = 99999$, $K_{g1} = 0{,}01$, $T_{i1} = 0{,}01$, $A_2 = 99999$, $K_{g2} = 0{,}01$, $T_{i2} = 0{,}01$. In Table C.6-1 is possible to see the defined constraints to SPSS. For the first curve was defined the upper asymptote was less than the cumulative quantity in 2012. The second curve asymptote less than the cumulative quantity in 2017.

Parameter	Constraints Multi-Gompertz	Constraints Multi-Logistic
K_g	>=0,1; <=1	>=0,1; <=1,5
T_i	>=0,1;<=5	
A	>=0;<=6678927	
K_{g1}	>=0,1; <=1	
T_{i1}	>=5;<=9	
A_1	>=6678927; <=32923002	
K_{g2}	>=0,1; <=1	>=0,1; <=1,5
T_{i2}	>=11;<=14	
A_2	>=32923002	

Table C.6-1 - Constraints Bi-Gompertz and Bi-Logistic – EMEA Vendor Units ONT/ONU – 2.5G GPON.

The result of the constrained nonlinear regression analysis is presented in Table C.6-2 for the Multi-Gompertz and Multi-Logistic functions, column: estimates for the cumulative market, it summarizes the model-estimated value of each parameter. The same constraints used for the cumulative modeling were applied to the temporal derivative of the market size to analyze the arrival of new adopters. The results of the constrained nonlinear regression analysis are presented in Table C.6-2, columns: Estimates for the annual market (1st derivative).

	Multi-Gompertz		Multi-Logistic	
Parameter	Estimates for the cumulative market	Estimates for the annual market (1st derivative)	Estimates for the cumulative market	Estimates for the annual market (1st derivative)
A	5029341,039	6611488,488	4874641,449	4181354,233
K_g	,859	,897	1,240	1,369
T_i	1,586	3,055	2,620	2,926
A_1	27986289,672	32254062,665	27389611,025	30101764,085
K_{g1}	,481	,473	,745	,711
T_{i1}	6,153	7,522	7,027	7,551
A_2	76983368,602	63610095,722	69224935,092	45751485,939
K_{g2}	,437	,534	,955	1,165
T_{i2}	11,190	11,594	11,542	11,415

Table C.6-2 - Parameter estimates for Multi-Gompertz and Multi-Logistic.

Appendix D. Forecasts

D.1 XG(S)-PON market share

Table D.1-1 presents the vendor units for ONT/ONU – XG(S)-PON for Global level, EMEA, and NA from OMDIA market share 2Q20 for PON [24].

	Annual vendor units			Cumulative vendor units		
year	**Global**	**NA**	**EMEA**	**Global**	**NA**	**EMEA**
2015	1777	0	1396	1777	0	1396
2016	69509	1700	1019	71286	1700	2415
2017	64369	3278	912	135655	4978	3327
2018	58316	1450	3330	193971	6428	6657
2019	291737	2266	25988	485708	8694	32645

Table D.1-1 - Vendor Units ONT/ONU - XG-PON1 and XGS-PON, cumulative and annually.

Table D.1-2 is presented the vendor units for OLT – XG(S)-PON for Global level, EMEA, and NA from OMDIA market share 2Q20 for PON [24].

	Annual vendor units			Cumulative vendor units		
year	**Global**	**NA**	**EMEA**	**Global**	**NA**	**EMEA**
2015	1032	-	876	1032	-	876
2016	50908	306	3277	51940	306	4153
2017	77189	504	13213	129129	810	17366
2018	274308	1216	12164	403437	2026	29530
2019	1021661	28962	92435	1425098	30988	121965

Table D.1-2 - Vendor Units OLT - XG-PON1 and XGS-PON, cumulative and annually.

D.2 Forecasting XG(S)-PON terminals with Bi-Gompertz and Bi-Logistic

The starting values of the constants for the fit of the Global XG-PON1 and XGS-PON ONU vendor units were defined as $W_0 = 0$, $K_g = 0$ and $A = 99999$. The starting point, W_0 was defined as to be less or equal to the total quantity of vendor units in the first year and the final market potential. The forecast of the XG(S)-PON ONT/ONU using the Bi-Logistic will be done using the same approach as for the Bi-Gompertz. With the available data from the market, from 2015 to 2019, a logistic curve will be fitted, and this will be the first component of the Bi-Logistic model, Table D.2-1.

The starting values of the constants for SPSS using the Non-Linear Regression were defined as $\mathrm{A} = 99999$, $K_g = 0{,}01$, $T_i = 0{,}01$ for the Logistic curve.

Function	Parameter	Constraints		
	Region	Global	EMEA	NA
Norton´s	W_0	<=1777	<=1396	<=1700
	K_g	>=0,01; <=1		
Logistic	K_g	≥0,01;<=1,5	≥0,01;<=1,6	≥0,01;<=1,5
	T_i	>=1; <=5	>=1; <=5	>=1; <=5

Table D.2-1 - Constraints for Norton´s re-parametrization of Gompertz and Logistic to Vendor Units ONT/ONU XG(S)-PON

The result of the constrained nonlinear regression analysis for the three regions is presented in Table B.8-2–Parameter estimates for Norton´s re-parametrization.

Parameter	Region	Norton´s	Logistic
W_0	Global	1777	-
K_g		0,387	1,292
A		2149203,681	616626,209
T_i		5,064	3,266
W_0	EMEA	6,923	-
K_g		0,233	1,589
A		7767367,483	191779,034
T_i		11,305	5,000
W_0	NA	1700	.
K_g		0,803	1,143
A		9915	9477,740
T_i		0,706	1,122

Table D.2-2 - Parameter estimates for Norton´s re-parametrization and Logistic.

The *r square* of the fit is presented in Table D.2-3.

Region	Cumulative Market	
	R square **= 1 - (Residual Sum of Squares) / (Corrected Sum of Squares)**	
	Norton´s	Logistic
Global	0,946	0,940
EMEA	0,982	0,986
NA	0,978	0,934

Table D.2-3 - ANOVA for Norton´s re-parametrization and Logistic for the XG(S)-PON market

The fit of Norton´s re-parametrization and Logistic function to the global vendor units for ONT/ONU – XG(S)-PON can be observed in Figure D.2-1 left, EMEA center, and NA right.

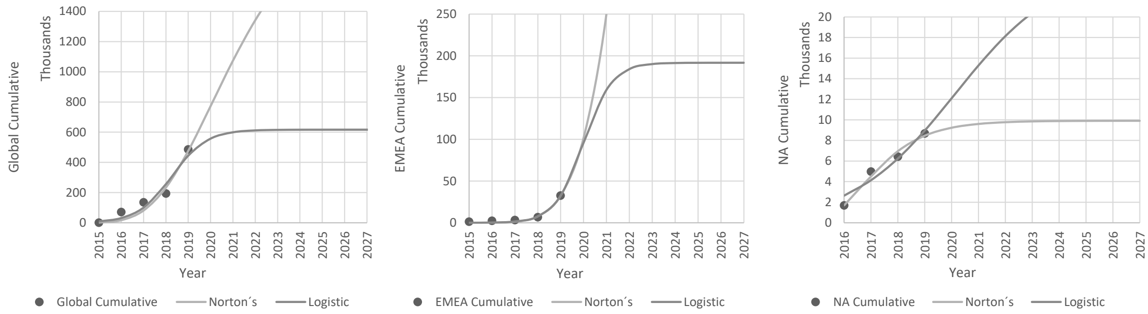


Figure D.2-1 - Norton´s re-parametrization and Logistics fit the Global units for ONT/ONU XG(S)-PON (left), EMEA (middle), NA (right).

The values of the constants obtained by the fit of Norton´s and Logistic model (will be used as the first component of the Bi-Gompertz and Bi-Logistic, respectively, for the analyzed markets. By using the historical behavior of market diffusion of GPON and assuming that the future XG(S)-PON ONT/ONU markets will have similarities. Different forecasts scenarios, for the second component of the Bi-Gompertz and Bi-Logistic, were defined and are presented in Table D.2-4, based on the historical pattern of GPON diffusion.

Region	Forecast Scenario (FS)	A (final market potential)	K_G (growth rate coefficient)	T_i (time at inflection)
EMEA	FS1	At least the total ONT/ONU 2.5G GPON cumulative market in 2019, is, 56762241	Same as found for GPON market by applying: Bi-Gompertz, 0,189; Bi-Logistic, 0,459.	Taking into account the market till 2019 and the: 1st component of Gompertz, 15,991 years; 1st component of Logistic, 16,408 years.
	FS2		10% higher than found for GPON market, due to already installed FTTH/network, this is 0,289. Double than found for GPON market, this is, 0,918.	Taking into account the market till 2019 and the: 1st component of Gompertz, 11,991 years; 1st component of Logistic, 11,1 years.
	FS3			Same as found for GPON market by applying: Bi-Gompertz, 12,991 years; Bi-Logistic, 12,408 years.
	FS4	At least 50% of the total ONT/ONU 2.5G GPON cumulative market in 2019, this is, 28381120		
NA	FS1	At least the total ONT/ONU 2.5G GPON cumulative market in 2019, this is, 32172009 units	Same as found for GPON market by applying: Bi-Gompertz, 0,148; Bi-Logistic, 0,358.	Same as found for GPON market by applying: Bi-Gompertz, 15,126 years; Bi-Logistic, 14,918 years.
	FS2		Double than found for GPON market, due to already installed FTTH/network, this is, 0,296 for Bi-Gompertz and 0,716 for Bi-Logistic.	Taking into account the market till 2019 and the: 1st component of Gompertz, 9,5 years; 1st component of Logistic, 11,918 years.
	FS3			

	FS4	At least 50% of the total ONT/ONU 2.5G GPON cumulative market in 2019, this is, 16086004 units		Taking into account the market till 2019 and the: 1st component of Gompertz, 10,126 years; 1st component of Logistic, 10,918 years.

Table D.2-4 - Forecast scenarios for the Bi-Gompertz and Bi-Logistic XG(S)-PON ONT/ONU.

The forecast of the Bi-Gompertz to the EMEA and NA vendor units for ONT/ONU – XG(S)-PON can be observed in Figure D.2-2, left side and right side, respectively, using the constant obtained by the fit of Norton´s re-parametrization and the values for the constants defined on the forecast scenarios, Table D.2-4.

On the same graphics is possible to observe and compare the wireline broadband access equipment forecast from Ovum, March 2019 (pre-pandemic)[28] (squares) and the forecast from OMDIA 2019-2025, July 2020 [29] (triangles).

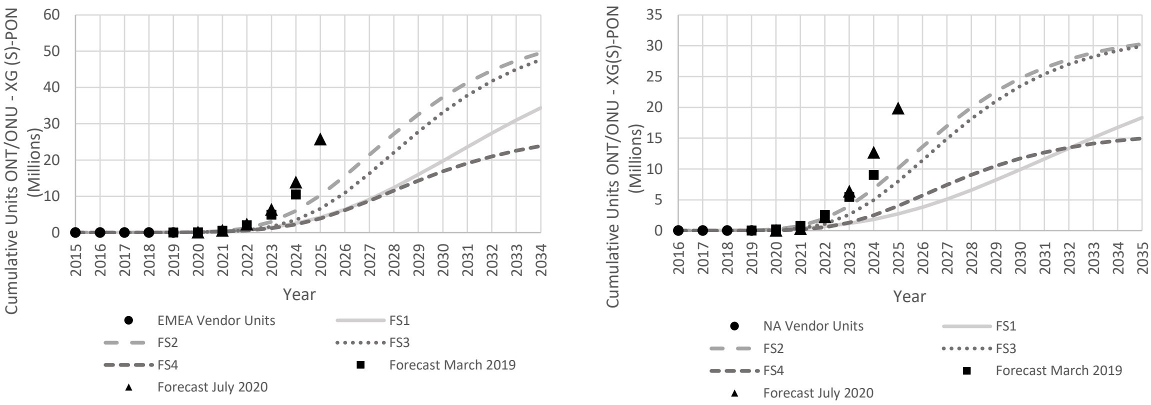


Figure D.2-2 - Forecast for the EMEA and NA Vendor Units ONT/ONU – XG(S)-PON using Bi-Gompertz, left side and right side, respectively.

The values of the estimated constants by the fitting of the Bi-Gompertz function were applied to the temporal derivative of the market size.

Figure D.2-3 presents the derivative fit for the EMEA (left side) and NA (right side) markets respectively using the constants of the Bi-Gompertz. As for the cumulative market, on the same graphics is possible to observe and compare the wireline broadband access equipment forecast from Ovum, March 2019 (pre-pandemic)[28] (squares) and the forecast from OMDIA 2019-2025, July 2020 [29] (triangles).

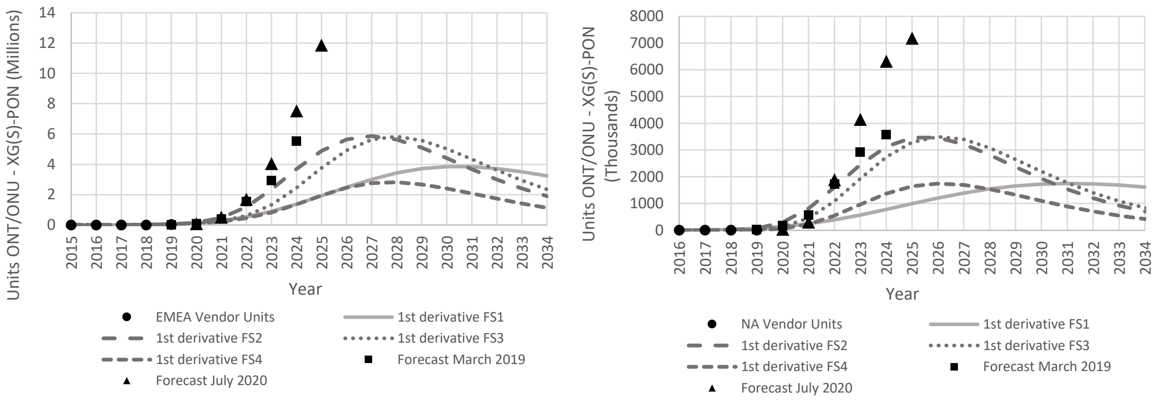


Figure D.2-3 - Bi-Gompertz derivative fit forecast to the EMEA and NA vendor units ONT/ONU – XG(S)-PON, left side and right side respectively.

The fit of the Bi-Logistic to the EMEA and NA vendor units for ONT/ONU – XG(S)-PON can be observed in Figure D.2-4 right side and left side, respectively, using the constant obtained by the fit of Logistic Function, and the values for the constants defined on the forecast scenarios, Table D.2-4

On the same graphics is possible to observe and compare the wireline broadband access equipment forecast from Ovum, March 2019 (pre-pandemic)[28] (squares) and the forecast from OMDIA 2019-2025, July 2020 [29] (triangles).

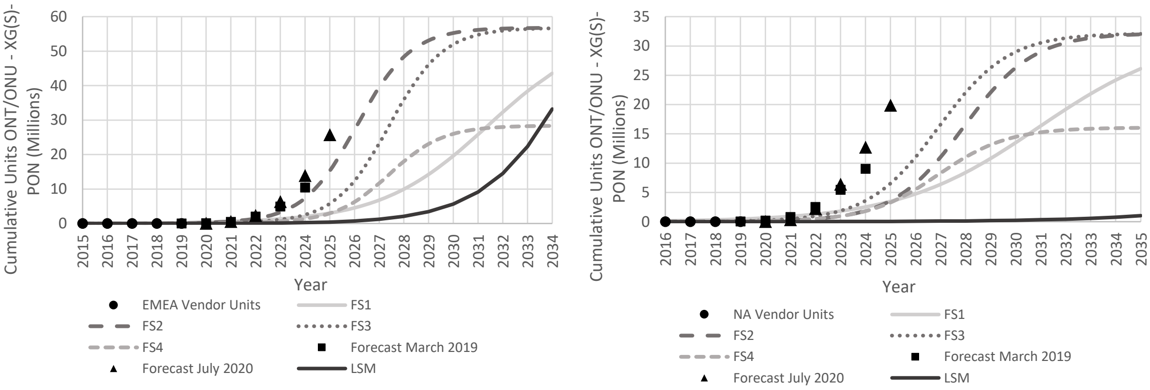


Figure D.2-4 - Forecast for the EMEA and NA Vendor Units ONT/ONU – XG(S)-PON using Bi-Logistic and LSM, left side and right side, respectively.

The simple logistic substitution model (LSM) in EMEA, this is, the Fisher and Pry model, was also applied using GPON data for each region as the old technology. For the LSM the inflection time occurs in September 2035 and the length of time interval to the XGS-PON market growth from 10% to 90% of the total market is 9,4 years.

For the LSM of the NA market, the inflection time occurs in 2052, and the length of time interval to the XGS-PON market growth from 10% to 90% of the total market is almost 18 years. The values of the estimated constants by the fitting of the Bi-Logistic function were applied to the temporal derivative of the market size.

Figure D.2-5 presents the derivative fit for the EMEA (left side) and NA market (right side) respectively using the constants of the Bi-Logistic and LSM (right side). As for the cumulative market, on the same graphics is possible to observe and compare the wireline broadband access equipment forecast from Ovum, March 2019 (pre-pandemic)[28] (squares) and the forecast from OMDIA 2019-2025, July 2020 [29] (triangles).

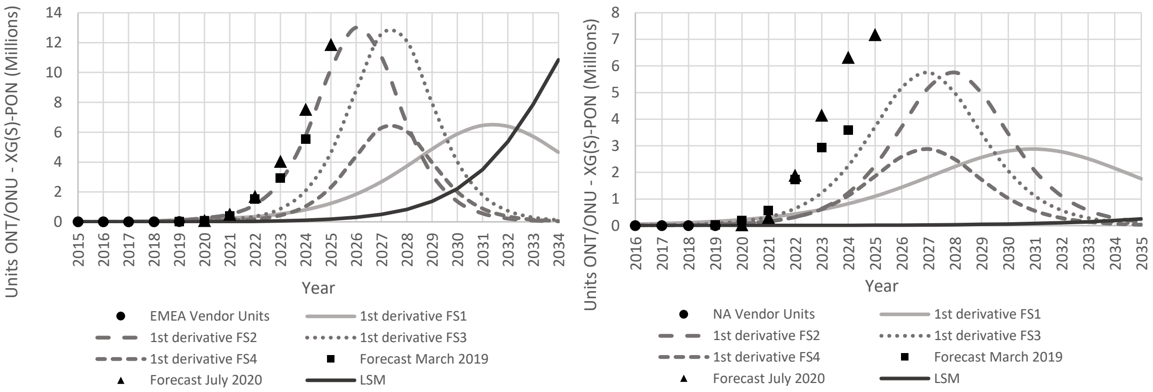


Figure D.2-5 - Bi-Logistic derivative fit forecast to the EMEA and NA vendor units ONT/ONU – XG(S)-PON, left side and right side, respectively.

D.3 Forecasting XG(S)-PON OLT with Bi-Gompertz and Bi-Logistic

The forecast of the OLT XGS-PON market will be done using Bi-Gompertz and Bi-Logistic curves.

Taking into account the available data were first modeled a traditional Gompertz and a Logistic curve for the first component of each Bi curve.

Due to adjustments and for the most accurate forecast using the Bi-Gompertz curve, for the Global market the fitting was only done from 2015 till 2017 and for the EMEA market from 2015 till 2018.

The starting values of the constants for SPSS using the Non-Linear Regression constants for the fit of the Global XG-PON1 and XGS-PON OLT vendor units were defined as $A = 999$, $K_g = 0{,}01$, $T_i = 0{,}01$. The constraints for the modeling can be found in Table D.3-1.

Function	Parameter	Constraints		
	Region	Global	EMEA	NA
Gompertz	K_g	>=0,01; <=5		
	T_i	>=0,01; <=10		>=1; <=10
Logistic	K_g	≥0,01;<=2,5		≥0,01;<=3
	T_i	>=1; <=7		>=1; <=7

Table D.3-1 - Constraints for Gompertz and Logistic to Vendor Units OLT XG(S)-PON.

The result of the constrained nonlinear regression analysis for the three regions is presented in Table D.3-2. The ANOVA provides *r square* values for the three markets superior to 0,9 meaning that the model accounts for about 90 % of the variability in the dependent variable for the analyzed markets.

Parameter	Region	Gompertz	*R SQUARE* (Gompertz)	Logistic	*R SQUARE* (Logistic)
K_g	Global	1,459	0,999	2,461	0,993
A		170129,628		1723763,174	

T_i		1,117		5,425	
K_g	EMEA	0,961	0,999	2,469	0,979
A		41168,556		151061,320	
T_i		1,851		5,484	
K_g	NA	2,905	0,999	2,970	0,990
A		35742,472		42568,087	
T_i		2,351		5,712	

Table D.3-2 - Parameter estimates for Gompertz and Logistic.

The different forecasts scenarios, based on the historical pattern of GPON diffusion, for the second component of the Bi-Gompertz and Bi-Logistic, were defined and are presented in Table D.3-3.

Region	Forecast Scenario	Final market potential	K_G (growth rate coefficient of the second component)	T_i (time at the inflection of the second component)
EMEA	FS1	At least the total OLT 2.5G GPON cumulative market in 2019, this is 4911287.	Same as found for GPON market by applying: Bi-Gompertz, 0,292; Bi-Logistic, 0,636.	Earlier inflection, than what happened for GPON OLT market: Bi-Gompertz, 9 years; Bi-Logistic, 9,739 years
	FS2		10% higher than found for GPON market, due to already installed FTTH/network: Bi-Gompertz, 0,392; Bi-Logistic, 0,736.	
	FS3		20% higher than found for GPON market, due to already installed FTTH/network: Bi-Gompertz, 0,424; Bi-Logistic, 0,836.	Earlier inflection: Bi-Gompertz, 7 years; Bi-Logistics, 8,739 years;
	FS4	At least 50% of the total OLT 2.5G GPON cumulative market in 2019, this is 2455644.		
NA	FS1	At least the total OLT 2.5G GPON cumulative market in 2019, this is 2137829.	Same as found for GPON market by applying: Bi-Gompertz, 0,442; Bi-Logistic, 0,711.	Same as found for GPON OLT market by applying: Bi-Gompertz, 8,024 years; Bi-Logistic, 7,024 years.
	FS2		10% higher than found for GPON market, due to already installed FTTH/network: Bi-Gompertz, 0,542; Bi-Logistic, 0,811.	Earlier inflection: Bi-Gompertz, 7,024 years; Bi-Logistic, 7,6 years.
	FS3		20% higher than found for GPON market, due to already installed FTTH/network: Bi-Gompertz, 0,642; Bi-Logistic, 0,911.	
	FS4	At least 50% of the total OLT 2.5G GPON cumulative market in 2019, this is 1068915.		

Table D.3-3 - Forecast scenarios for the Bi-Gompertz and Bi-Logistic XG(S)-PON OLT.

The forecast using the Bi-Gompertz to the EMEA and NA vendor units for OLT – XG(S)-PON can be observed in Figure D.3-1, left side and right side, respectively, using the constant obtained by the fit of Gompertz function, and the values for the constants defined on the forecast scenarios, Table D.3-3.

On the same graphics is possible to observe and compare the wireline broadband access equipment forecast from Ovum, March 2019 (pre-pandemic)[28] (squares) and the forecast from OMDIA 2019-2025, July 2020 [29] (triangles).

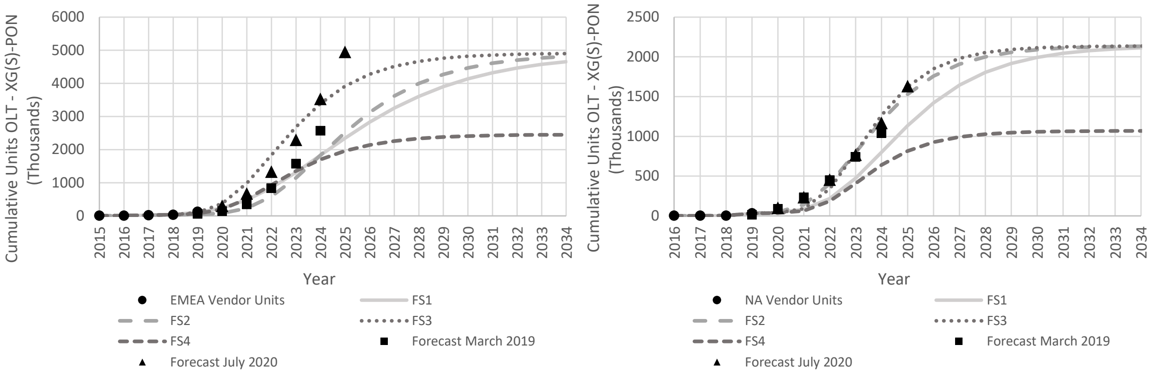


Figure D.3-1 - Forecast for the EMEA and NA Vendor Units OLT – XG(S)-PON using Bi-Gompertz, left side and right side, respectively.

The values of the estimated constants by the fitting of the Bi-Gompertz, Table D.3-2, and Table D.3-3 were applied to the temporal derivative of the market size.

Figure D.3-2 presents the derivative fit for the EMEA, left side, and NA market, right side, respectively using the constants of the Bi-Gompertz. As for the cumulative market, on the same graphics is possible to observe and compare the wireline broadband access equipment forecast from Ovum, March 2019 (pre-pandemic)[28] (squares) and the forecast from OMDIA 2019-2025, July 2020 [29] (triangles).

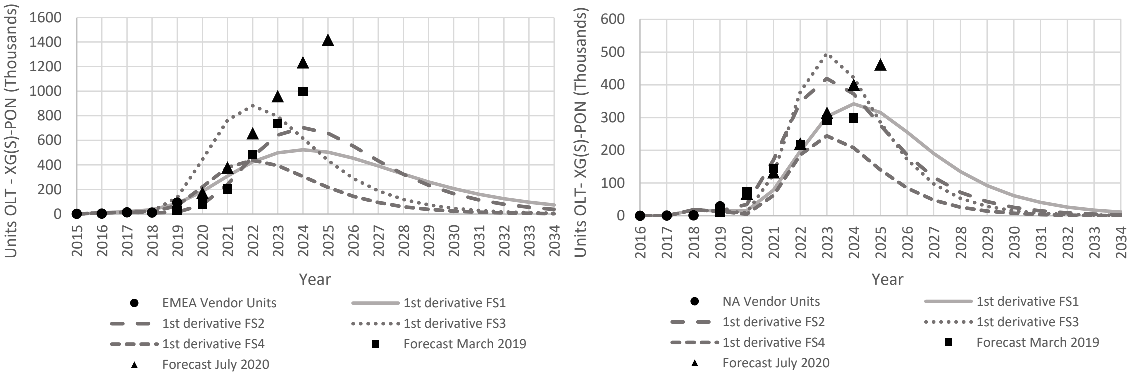


Figure D.3-2 - Bi-Gompertz derivative fit forecast to the EMEA and NA vendor units OLT – XG(S)-PON, left side and right side, respectively.

The fit of the Bi-Logistic to the EMEA and NA vendor units for OLT – XG(S)-PON can be observed in Figure D.3-3, left side and right side, respectively, using the constant obtained by the fit of Logistic Function and the values for the constants defined on the forecast scenarios, Table D.3-3.

The simple logistic substitution model (LSM), this is, the Fisher and Pry model, was also applied using GPON OLT market data for each region as the old technology, Figure D.3-5.

On the same graphics is possible to observe and compare the wireline broadband access equipment forecast from Ovum, March 2019 (pre-pandemic)[28] (squares) and the forecast from OMDIA 2019-2025, July 2020 [29] (triangles).

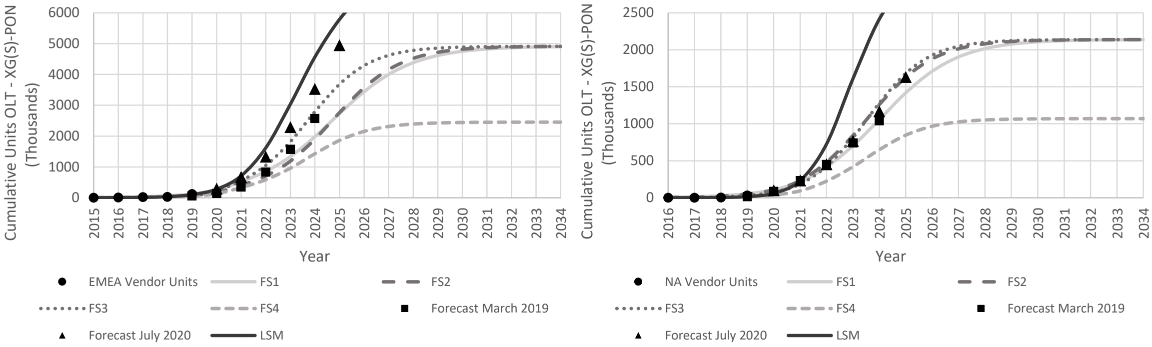


Figure D.3-3- -Forecast for the EMEA Vendor Units OLT – XG(S)-PON using Bi-Logistic

In LSM fraction for the EMEA market is possible to observe in Figure D.3-4, the inflection time occurs in the third quarter of the 2022 year and the length of time interval to the XGS-PON market growth from 10% to 90% of the total market is 4,65 years. The inset presents the LSM Fischer-Pry transform.

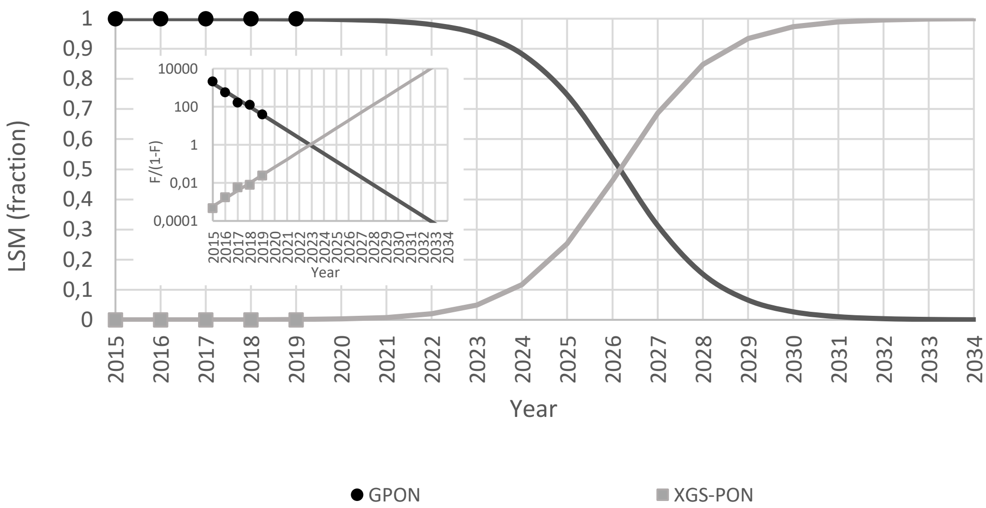


Figure D.3-4 - LSM for the EMEA vendor units for OLT – XG(S)-PON. In the inset, the LSM Fisher-Pry transform.

In the LSM for the NA market, the inflection time occurs in the third quarter of the 2022 year and the length of time interval to the XGS-PON market growth from 10% to 90% of the total market is 3,64 years, Figure D.3-3 left side- LSM

The values of the estimated constants by the fitting of the Bi-Logistic function Table D.3-2 and Table D.3-3 were applied to the temporal derivative of the market size.

Figure D.3-5 presents the derivative fit for the EMEA and NA market respectively using the constants of the Bi-Logistic. As for the cumulative market, on the same graphics is possible to observe and compare the wireline broadband access equipment forecast from

Ovum, March 2019 (pre-pandemic)[28] (squares) and the forecast from OMDIA 2019-2025, July 2020 [29] (triangles).

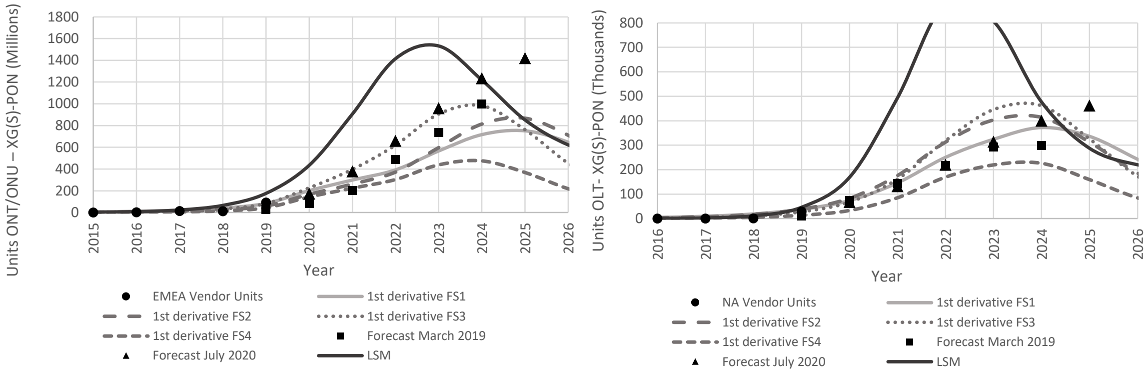


Figure D.3-5 - Bi-Logistic derivative fit forecast to the EMEA and NA vendor units OLT – XG(S)-PON, left side and right side, respectively.

Appendix E. Bibliography Appendices

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