Universidade de Aveiro Departamento de Eletrónica, Telecomunicações e Informática
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Gonçalo Daniel Correia

Iluminação Inteligente para Espaços Interiores

Indoor wireless architecture for Smart Lighting

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Eletrónica e Telecomunicações, realizada sob a orientação científica do Doutor Luís Filipe Mesquita Nero Moreira Alves, Professor auxiliar do Departamento de Eletrónica e Telecomunicações da Universidade de Aveiro, e do Mestre Nuno Rafael Lourenço, gerente da empresa Think Control.

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Dedico este trabalho a toda a minha família e namorada por todo o incondicional apoio.

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Palavras-chave

Iluminação de espaços interiores, Iluminação LED,Iluminação inteligente, Sensores, Controlo de iluminação, Bluetooth Low Energy.

Resumo

Esta dissertação propõe um sistema de iluminação para espaços interiores com o objetivo de ultrapassar as limitações dos sistemas atuais e melhorar a eficiência energética.

Este trabalho enquadra-se no projeto Smartlighting que tem o objetivo de desenvolver um sistema de gestão integrada para o edifício do IT2. Na sua fase inicial, o sistema foca-se principalmente no controlo da iluminação através do uso de sensores e tecnologias da Internet das Coisas.

Numa primeira fase, é feita uma análise do problema e das tecnologias envolvidas. Depois os requisitos para o sistema são identificados através da exploração de vários cenários de utilização. Daqui é desenvolvida uma solução conceptual que resulta do trabalho colaborativo do projeto Smartlighting. A solução apresentada é baseada em comunicação por *Bluetooth Low Energy* e gerida através de técnicas de Processamento de Eventos Complexos, constituindo assim uma topologia distinta das usadas atualmente em sistemas iluminação para espaços interiores.

A solução é depois analisada numa perspetiva de iluminação através de uma simulação de DIALux que visa validar a implementação no âmbito da norma europeia 12464, referente a sistemas de iluminação para espaços interiores. Desta simulação também resulta uma projeção da eficiência enérgica do edifício em termos de iluminação, considerando as funcionalidades que o sistema idealizado implementará. A solução é concretizada num protótipo que é avaliado de forma a validar a solução numa perspetiva de automação.

Keywords

Indoor Lighting, LED Lighting,Smart lighting, Sensors, lighting control, Bluetooth Low Energy.

Abstract

This dissertation proposes an indoor lighting solution to addresses the building energy consumption problematic and the constrains present in current indoor lighting systems.

The work presented results from the Smartlighting project that aims to develop an integrated building management system for the IT2 building. In its initial stage, this system focuses primarily in indoor lighting control, using sensors and IoT technologies.

First, the problem and the technologies involved are presented and reviewed. Then the project requirements are identified by exploring a set of use case scenarios. From this, a concept solution is presented that results from the Smartlighting project collaborative work. The proposed solution takes advantage of Bluetooth Low Energy and Complex Event Processing technologies to deliver a topology distinct from the indoor lighting system *status quo*.

The solution is then analysed in terms of a lighting application, via a DIALux simulation that aims to validate the implementation in the European Norm 12464 scope, referring to indoor lighting systems. From this simulation, it was also conducted an energy efficiency study referring to the building lighting, that took in consideration the functionalities implemented by the system. The solution is then materialized into a prototype to be evaluated in an automation perspective.

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UGR

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U_o

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UUID

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V

VLC

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WSAN

Wireless Sensor and Actuators Network

1. INTRODUCTION

Lighting is essential regarding functionality and productivity in any building or space with human interaction. However, being such a widely used and vital resource it is also a major energy expense.

Consequently, the evolution of lighting systems has been driven to meet higher energy efficiency standards without compromising functionality and comfort established by current technologies, and in fact improving them.

The up rise of the light-emitting diode (LED) as a lighting technology represented one big stride towards a more efficient lighting standard. Nonetheless, there is still room for improvement with extended automatization of lighting systems, such as daylight harvesting, supported by advancements made in sensor, microprocessors and wireless communication technologies, building towards a truly smart lighting system.

1.1. CONTEXTUALIZATION

Energy efficiency awareness is a major concern in urban and industrial planning and has been of growing importance not only in the rise of smart systems but also in legislation implemented. New regulations are slowly turning focus to the use of greener technologies and progressively ruling out older ones.

According to the U.S. Energy Information Administration, in the United States, lighting equates for roughly 14% of total electrical energy consumption in both domestic and commercial sectors, so it is meaningful to regard not only the environmental impact but also the cost of the lighting infrastructure in an economic perspective.[1] In Europe there is also a similar trend, as stated in the *Energy Efficiency Status Report* , lighting represents 10% of the total electrical energy consumption. This percentage has been decreasing, the Joint Research Centre estimates that this is due to the phasing-out use of incandescent light bulbs, in favour of more energy efficient light sources [2].

Combining the low efficiency of some lighting solutions with the rise of electricity prices, equates to a need for technologies with higher energy efficiency standards, as it is noticeable in Figure 1. Since 2005 (reference year) the European area has seen a growth in energy saving, reaching savings of 16,9% (in 2014). It is important to understand that these savings do not result only from the use of more efficient lighting technologies, they result of all the advances in different uses of energy. Nonetheless, they are a strong indicator of the need and focus of European entities (and others) to reduce energy waste.

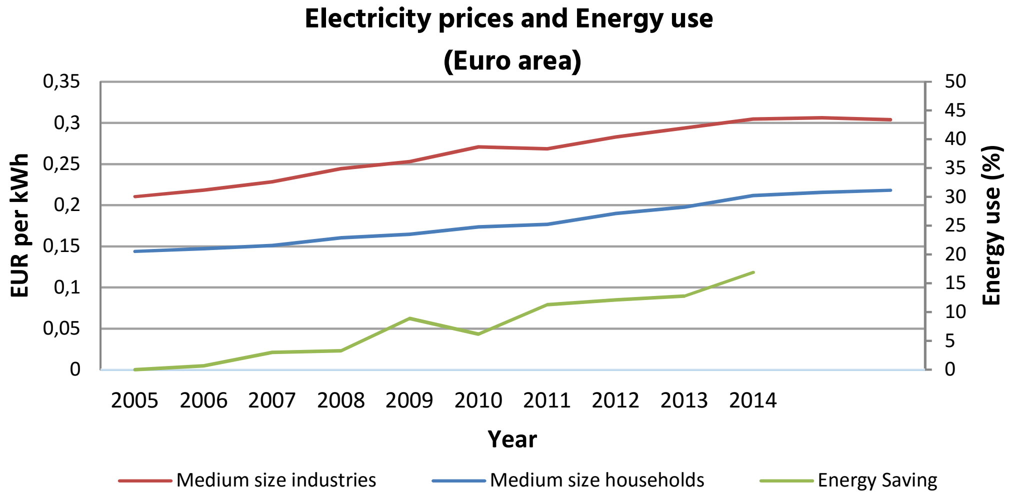

Figure 1: Electricity prices and energy savings through the years in the euro area [2]

These last few years have seen the rise of the LED as a lighting technology for its electrical properties that make it a more suitable standard for today’s energy aware solutions. To improve on that take, the focus is now on endowing lighting system with daylight harvesting and user presence awareness capabilities, to maximize energy savings.

Ideally a lighting system should integrate other building services such as heating, ventilation, air conditioning, security, etc. Having all building services managed under a single system truly maximize the building energy efficiency. This is where current indoor lighting solutions fall short, they are often constricted by proprietary and dated technologies that preclude interoperability with other building services.

Currently, concepts like the Internet of Things (IoT) are taking shape and growing into different purposes and functionalities. So a redesign of the lighting system concept in this technology scope may be a step towards overcome this issue.

1.2. OBJECTIVES

The fundamental objective of this project is to develop an indoor lighting system based on open source technology, capable of computing a multitude of sensorial information and perform operations over luminaires and other actuators, automatically compensating or reacting to changes in the environment, thus providing a more integrated user experience.

The main goal for the developed system is improved energy efficiency and user experience. Other objectives influence development, such as scalability with an architecture that is easy to replicate and to extend in device count, and interoperability by extending the system control to services other than lighting.

This dissertation focus on the lighting component, and it is expected that a lighting solution endowed with multiple features and functionalities is developed. Device development aims for a network integration, preferably based on Bluetooth Low Energy, easy to integrate and expand over multiple gateways. A working prototype endowed with the basic functionalities is expected.

1.3. STRUCTURE OF THE DISSERTATION

The dissertation document is divided into six chapters, the first and current chapter introduces the project by setting a contextualization and defining its objectives.

The second chapter is dedicated to reviewing fundamental concepts concerning the project scope. It presents the two main indoor lighting technologies, followed by a section dedicated to indoor lighting systems. A third section helps understand how lighting systems integrate a building management system, then some IoT technologies that can be used in this project scope are presented.

The project implementation starts to take shape in the third chapter by presenting a set of use cases that are used as a base for defining the system requirements. Then, a global system architecture is proposed to meet these requirements, followed by a more scrutinized view over the lighting component and solutions to implement features and functionalities identified previously.

The fourth chapter details the prototype development, based on the system idealized in the previous chapter. As expected for this dissertation, it focuses on the hardware layer of the system, more specifically in the wireless network of sensors and actuators. Also in this chapter, a DIALUX simulation is defined with the purpose of validating the implementation and estimating the impact in energy performance that some features may have.

The results from the tests conducted in the prototype, as well as the results from the simulation, are presented and analysed in the fifth chapter.

Finally, the six chapter presents several conclusions and proposes some future work.

1.4. ORIGINAL WORK AND CONTRIBUTIONS

From this project collaboration resulted a paper entitled "*SmartLighting - A platform for intelligent building management*" that was submitted and published in the *INForum 2016*. It also featured a live demo in the *Research Day UA 2016* and *TechDays 2016* forum.

2. INDOOR LIGHTING SYSTEMS- TECHNOLOGY REVIEW

The purpose of this chapter is to review several concepts regarding indoor lighting systems, building automation systems and Internet of Things (IoT) technologies. It serves as the base work of the project by showing the advantages but also the limitations of the current indoor lighting and building automation technologies that motivated this new take on these systems.

This chapter is divided into three main content sections. The first one starts by reviewing two main lighting technologies, fluorescent and LED, mainly because these are the most used in indoor lighting.

In the second section, titled "*Indoor Lighting Systems*", an overview of current solutions and technologies is presented, and some relevant regulation is reviewed. The third section is used to further explain how the lighting system fits into the concept of building automation. It is then defined the concept of IoT and reviewed some technologies that can be used in the scope of this project. Lastly, a concluding remarks section closes the chapter.

2.1. LIGHTING

Lighting is an indispensable service in virtually any indoor space. Being such a vital service in many buildings with human activity e.g. offices, hospitals, schools, etc. it also represents a considerable part of its energy expenses. Subsequently the need for an energy efficient lighting solution drives the advancement in technology forward, towards lighting technologies with smaller energy footprints.

When considering different lighting systems there are many factors that come into play, however energy efficiency and lifespan have come to support a progressive integration of LED technology not only in indoor but lighting systems in general. The growing momentum of the LED movement is quite present in our daily lives, however it is crucial to have a firm grasp in lighting concepts and technologies to make an educated decision when designing a lighting solution.

Considering the purpose of this project and the main technologies used in indoor lighting, this chapter starts by the characterization of multiple lighting concepts to define and understand the mechanics of current light sources. Then it compares the two technologies that come into play in this project, fluorescent and LED as the proposed new lighting technology.

i) LIGHTING SOURCE PERFORMANCE METRICS

Characterizing a light source is not a straightforward task, it implies an overview of multiple components that may not be entirely objective. To mitigate this problem and to compare light sources in terms of intensity, colour, efficiency and lifespan, the following parameters can be used.

Colour temperature

This parameter relates to the colour emitted by a light source and has direct dependency with the light source temperature. As a light source heats, its light colour temperature evolves from a deep red towards blue and violet tones.

The only manufactured light source technology that has this light to temperature relation is the incandescent type. Much like the sun, incandescent light bulbs spectrum follows the radiation spectrum of a black-body, even though they are not perfect radiators, their colour temperature accurately reflects their actual temperature. [3]

The same is not valid for other lighting technologies due to the fact that their topology is not incandescent, and so, their light colour does not directly reflect their temperature and their colour temperature is measured by a correlated colour temperature measurement [4]. This value is strictly visual and they are used in the lighting industry to convey the notion of warmth or coolness to a light from a certain source. [5]

Colour rendering index

Contrasting with the colour temperature measure, colour rendering index (R_a) represents the capability of a light source to lit surfaces or objects colours compared to a reference source, normally daylight. These two parameters particularly differ because R_a is less objective, more relative to the user's colour perception.

The higher the difference in colour temperature of the same object lit by a light source and than by the reference source, the lower is R_a for that light source. R_a max is 100 that represent a perfect colour reproduction, this measure is highly dependable of the light source technology [6].

Lumens and Lux

Also important when measuring light is the unit of lumens and lux. The unit for illuminance is lux (lx) and it measures the luminous flux per area, lumens (lm) measure purely luminous flux emitted by a light source. The lux unit has a 1:1 relation with lumen per square meter, and is the more used unit when it comes to photometric light measures.

Lifespan

One particularly important point, from an economic point of view, when comparing lighting technologies is the life span of a light source. It is typically defined by the number of working hours under which a light source is able to maintain an output level. This is not an absolute concept and depends on many factors, like operating voltage and light source temperature, frequency of switching etc. Nonetheless, this is a value suited to compare the durability of different light technologies and configurations, because it usually results from a series of tests under controlled conditions. [7]

Lifespan can represent the time that the light source is operational (e.g. in an incandescent lightbulb this represents the time it takes for the filament to break), or it can be a decreased output performance over time, e.g. in a LED light source, over time there is degradation of light output, meaning that for the same voltage, after its lifespan, the LED outputs 70% or less than its original performance, even though it is functional. There are even different criterions used to measure the LEDs lifespan, L70/B50 per example takes into consideration the end of life brightness (70%) and the relative number of LEDs that output this light level in a light source (50%). [8]

Energy efficiency and application efficacy

When considering lighting sources, efficiency plays a crucial role as it is important to distinguish the concept of application efficacy and energy efficiency. The latter refers to what is commonly known as the ratio of input power to output lighting level, application efficacy is a more relative concept because it defines the efficacy of a light source when providing a certain illuminance requirement for an application [9].

Regarding energy use, most literature don't distinguish between efficacy and efficiency beyond the units used (efficiency is measured as a percentage and efficacy as lm/W (lumen per watt), nevertheless when comparing technologies, it is more suited the use of energy efficacy measure.

Lighting Solutions Quality Parameters and Metrics

Of the three guidelines for indoor lighting designing, functionality should be a priority as it may render a system unfit if it fails to comply with basic standards. Lighting related issues like flickering and glare are unacceptable in lighting systems, as so, it is important to understand them:

Flicker

Defined as "the rapid fluctuation of light output in a cyclical manner" in the publication *Flicker Parameters for Reducing Stroboscopic Effects from Solid-state Lighting Systems* from the *Lighting Research Center* [10], flicker may not be perceived equally by different people as it is subject to individual sensitivity. Nonetheless is established that perceived flicker occurs bellow 100 Hz frequency but indirect perception of flickering and stroboscopic effect has been reported in higher frequencies, as stated in the article.

As a health concern flicker can cause adverse health effect like eye strain, fatigue and headaches, it can also represent a safety problem in some environments because it may cause the perception of stroboscopic effect [11].

Glare

Glare is a visual sensation that results from direct or indirect highly bright light, it is subject to the individual sensitivity and depends of different factors like the angle between the subject and light source, surface reflectiveness (in case of indirect glare), brightness of the lighting source, etc. Usually it is categorized in two forms, disability glare if it impairs the subject view or discomfort if it translates to an increased difficulty in perceiving a scene of object. [12]

Also important in designing an indoor lighting solution are the metrics used, these standards provide the designer with measurements to quantify a lighting scenario:

Unified Glare Rating (UGR)

UGR is a model that estimates the probability of direct glare by luminaires. To determine a luminaire UGR, it is necessary to use parameters such as room size, surface reflectiveness and the observer orientation in the room are considered. [13]

Illuminance Uniformity (U_o)

The ratio between highest and lowest illuminance defines the U_o of a space. The closer the value is to "1" more uniformly lit is the space. Visual comfort is affected by strong contrasts in light intensity, this is especially truth in computer related tasks.

Depth perception can also be affected by sharp drops in illuminance intensity, this problem is present in spaces with low U_o but not in spaces divided into areas with a good Uo ratio.[14]

UGR and U_o are two of the most important metrics used in indoor lighting, however they only quantify a space lighting. Having an objective characterization of the luminaires is as important and it is measured with the following metrics:

Light Distribution Curve

Figure 2 represents an actual light distribution curve, it expresses in a polar diagram the light level as a function of viewing angles. They typically convey information about the light distribution in the longitudinal perspective (red curve in Figure 2) and its perpendicular axis (blue curve). These measurements are made by highly specialized machinery (Goniophotometers [15]) that rotates the luminaire through the measured axis while a fixed photometer sensor gathers the data.

The data from the light distribution curve is often used in simulations to compute isolux diagrams that measure a luminaire light intensity area at a horizontal plane. [16]

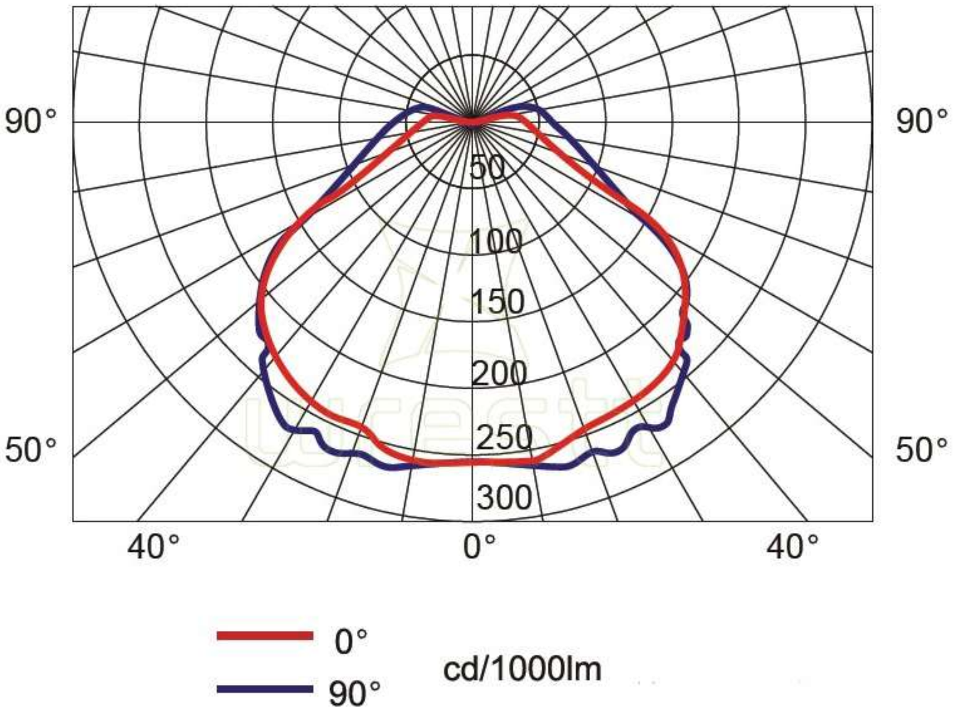

Figure 2: Luminaire Light distribution curve example [79]

Isolux diagram

An Isolux diagram conveys the illuminance at the plane with a certain height by displaying isolux curves that represent different lux levels as showed in Figure 3. These diagrams can show a plane illuminance level with one or multiple light sources.

Both characterizations are often used in tools like DIALux [17] that provide a virtual model of the physical luminaire. This lighting simulations can have multiple purposes, they can be used to render lighting scenes, check if a lighting deployment complies with regulation standards and perform efficiency and energetic evaluations.

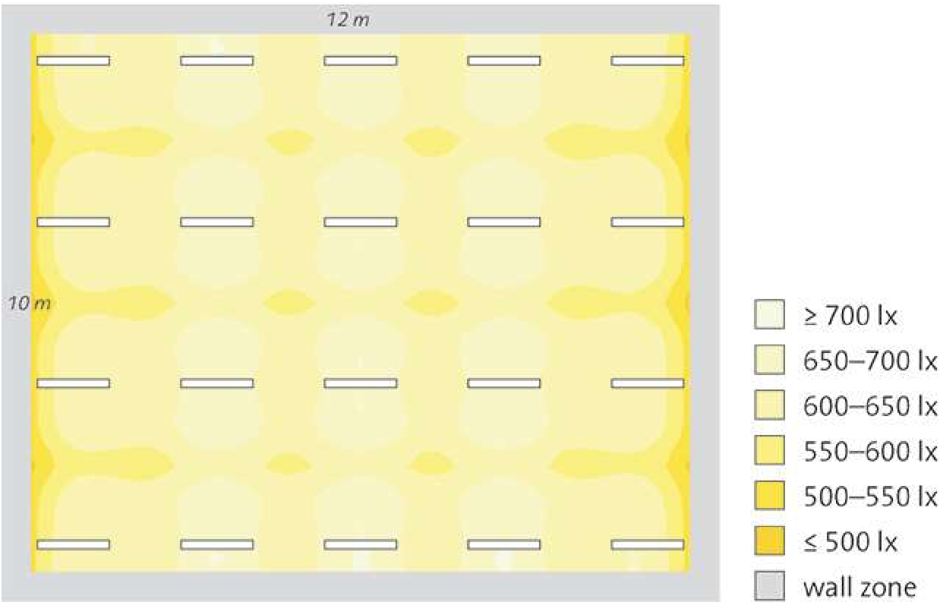

Figure 3: Isolux diagram [72]

ii) LIGHTING TECHNOLOGIES

Fluorescent and LED are the most widely used technologies in indoor lighting systems, in the scope of this project it is expected to change the IT2 (*Instituto de Telecomunicações*) building linear fluorescent lamps (LFL) luminaires for LED luminaires, so it important to support this decision by studying both technologies and understanding advantages and disadvantages [18].

Fluorescent

Compact fluorescent light (CLF) lamps are typically formed by a phosphor coated tube that encloses a noble gas, connected to an electronic ballast to regulate power. CLF technology is based on the principle that, when excited by a current, the mercury vapour on a gas will emit a short wave ultraviolet light. The mercury from the noble gas (noble gas (typically argon or xenon) evaporates and produces an ultraviolet (UV) light that causes the phosphor coating in the tube to glow with visible light. [19]

The fluorescent principle, obtained from the reaction of the phosphor coating to the UV light is a different approach to the resistance principle found in the incandescent technology, and although being initially more expensive, this added value is rendered in a superior life span and efficiency.

Compared to the tungsten incandescent light bulb, a compact fluorescent lamp(CFL) can have up to 9 times longer life span[20]. Obviously, life span strongly depends of the fluorescent lamp type but in a broad scope they are a step up from the incandescent technology [21].

One major concern with the CFL is the presence of mercury in each light source, as it is toxic and thus requires a proper disposal and handle in the event of a lamp break. This makes the CFL a potential problem if not handled and maintained accordingly to manufacturer indications, making it a not so green technology when compared to the LED.

The light-emitting diode (LED)

Because it is based on a solid-state semiconductor and has no need for a glass like encapsulation, the LED makes for a more robust light source. At its core, the LED is a semiconductor, more precisely a diode in a PN junction and when activated it emits photons as a by-product of the electron-holes recombination, this is the electroluminescence effect that allows for a greener and efficient technology [22].

The light color is determined by the junction material used in its construction, however to produce a white light LED there are two conventional techniques. RGB method consists in combining green, red and blue LEDs to output a white light, and the phosphor method works somewhat similar to the fluorescent technology, by using a phosphor coating and a blue (or UV) light LED, a percentage of blue photons are converted into yellow photons by reacting with the coating and the final white light results from the combination those two lights [23].

One setback of using LED technology is the initial cost, it is still one of the most expensive light sources on the market, nevertheless it is also one of the most efficient technologies [9] making up for the initial investment in the long run. In fact, roughly 90% of the energy is converted into light, reaching a performance level not matched by its technology counterparts [24].

In spite of its disadvantages, on a broad scope the LED is still the best option when it comes to light source technologies, especially for its superior efficiency and lifespan. As the market shifts to a future based on LED, the trend on higher efficiency and lower cost acquisition is expected to continue. [9] Furthermore, LED can support Visual Light Communication [25] (VLC), this can open up opportunities such as indoor location systems and even Li-Fi [26].

iii) TECHNOLOGY COMPARISON AND CONCLUSIONS

To a further understanding on the current state of lighting technologies, it is relevant to compare and analyse concrete and specific data relative to the performance in several aspects key to lighting applications. The data may differ from various sources due to the multiple products on the market from different manufactures with unique performances, but a more extensive and broad analyses of the results shows the same convergence of the differences between each type of technology.

Lighting Type	**Efficacy (lumens/watt)**	**Lifetime (hours)**	**Colour Rendering Index(R_a)**	**Colour Temperature (K)**
Linear Fluorescent Lamp(LFLs)	65–110	7000-24,000	50–95 (fair to good)	2700–6500
Compact Fluorescent Lamps(CFLs)	33–70	10,000	77–88 (good)	2700–6500
Cool White LEDs	60–94	25,000-50,000	70–90 (fair to good)	5000
Warm White LEDs	27–88	25,000-50,000	70–92 (fair to good)	3300

Table 1: Technology comparison[27]

Table 1 is a selection of an article published by the Office of Energy Efficiency and Renewable Energy [27] and in a first evaluation it stands out the efficacy that is topped by the linear fluorescent lamp shortly followed by the LEDs.

As stated above, LEDs are a greener and more robust technology than fluorescent and offer support for other features. However, past these factors, the choice between these two technologies ultimately is about the costs associated with lighting and the performance offered. Thus, based the Table 1 (and supported by other sources [28],[29]), the lifetime of the LED far surpasses the ones of the other technologies. Taking into consideration the fact that its energy efficiency is fairly similar to the fluorescent technology, the LED is considered a more suited lighting solution.

A potential counter argument is the cost of acquisition of each technology, as already mentioned the LED has the highest acquisition cost of all. Therefore, if the long term savings provided with the LED, in comparison to fluorescent technology, do not compensate the initial investment, LEDs may not be an economically viable option. A detailed analysis based on this issue in the article "Are LEDs cost-effective?" by LED Evolution [30] shows that the LED cost of acquisition is 14 times higher than the incandescent type bulb and around 5.8 times more than the fluorescent. However, in a time span of 100 000 hours it represents a saving of 78% and 43% when compared to the incandescent and fluorescent light sources, respectively.

It is noteworthy that this data is highly time relative due to the fast paced evolution of LED technology, it is expected to achieve higher energy performance and as the future seems to be towards the use of LEDs is not unfeasible to expect a progressively lower acquisition cost [9].

2.2. INDOOR LIGHTING SYSTEMS

These technologies serve as a base for indoor lighting systems, they are the endpoints that convey illumination, although being an essential part, a lighting system is more than luminaries.

i) INTRODUCTION

Modern times brought a new perspective to lighting, deeper integration with design that is set to enhance visually a space or object. Functionality and efficiency are not the only concern of a lighting system implementation as light itself is a part of the visual experience, especially in interior design.

Buildings like museums, theatres and historical monuments have an architectural value that is enhanced with an integrated lighting design, accomplished by balancing factors such as light direction, colour, intensity, and the crucial use of daylight.

The visual appeal of light can also be used with a more practical propose, for example in stores, that use light for a more visual appealing image and to highlight products.

This aesthetic concern is one important aspect in a lighting system and it is possible to resume two more fundamental concepts. First functionality, it is crucial to provide the right illumination for each task as it under illumination is unacceptable, over illumination can also be an issue that affects the task performance and the systems efficiency.

Efficiency is precisely the second key aspect in a lighting installation and it has been the main concern in recent times. LEDs allowed for an increased performance in lighting but to truly maximize the energy efficiency, lighting systems must react to the environment to better suit the illuminance needs in each scenario. That has been accomplish with the use of sensors and microprocessing units, they collect and analyse information to dynamically match the lighting scenario with spaces requirements.

Thus, designing a smart lighting system capable of collecting information, reacting to changes in the environment and provide enhanced features that go beyond switching on or off a luminaire, is the modern challenge of the lighting industry. Several mature solutions have been in play for some time now, however they are constrained by proprietary technologies and protocols, isolating themselves in a world that is evolving towards a communion of information, within the concept such as the Internet of Things. [31]

ii) INDOOR LIGHTING SYSTEM PROTOCOLS

As identified in the introduction, designing a lighting system has three main guidelines, energy efficiency, functionality and aesthetics. The lighting end can be characterized by the measurements set in the previous section, however a lighting system is more than a group of luminaires. Another crucial component in a lighting installation is the lighting control systems, that can range from a simple on/off switch, to dimmers or even sophisticated mobile application.

The interconnection between lighting devices and lighting controls can have two distinct topologies. It can be a simple and common stand-alone connection where the controls directly connect to the lighting gear or a more sophisticated network topology where each control and lighting end point is viewed as a network node. Having a lighting system based on a logical network topology opens up a wider array of options when compared to the traditional stand-alone, it allows for customization, greater energy efficiency at long term and the possibility of combining different lighting controls. As an example, a luminaire can be turn off by a switch or the absence of users conveyed by sensor information. [32, p. 314]

A network based indoor lighting system requires a communication protocol to interchange information and commands between the network nodes. The main industry standards for lighting protocols are the following:

DALI (Digital Addressable Lighting Interface)

DALI is a data protocol and transport mechanism developed by several manufactures of lighting equipment. It is one of the most used standards for lighting systems with a network based solution, making up for 43% of the indoor lighting market in 2014 [33].

Systems based on DALI are usually formed by a central control unit and DALI compliant lighting devices of different types (limited at 64 devices per line). The control unit can communicate with one or broadcast for multiple devices as every entity is identified by an address. Devices can be grouped together and doing so allows the control unit to transmit to a group as whole and to control the lighting level at a single room.

Hardware wise, DALI systems require an independent pair of wires to form the bi-directional communication bus on the DALI network.

From the main standard specification, several different versions with proprietary extensions have been developed by lighting component manufacturers, as they try to differentiate themselves from the market. However, this interoperability is then limited to the basic standard DALI features, and it is also common that devices implement standard features in a different manner, thus leading to non-uniform behaviour [34].

Nonetheless, DALI is undoubtedly one of the most used and complete protocols for digital lighting controls, which has been evolving ever since its creation in the 90's. Supported by a multitude of manufactures it is also in the process of widening its type of control devices with the development of DALI 2. However, DALI has some designing limitations, the system support for automation rules is beyond DALI, i.e. DALI by itself is not capable of supporting automated responses to events. Another major constrain in DALI is the installation and configuration, i.e. a system based on this protocol involves additional wiring in the infrastructure and a potentially complicated initial configuration and installation[35].

X10

In 1975, X10 was developed by Pico Eletronics as a communication protocol among home automation devices. Communications on X10 systems are transmitted through the power line via a RF signal, making it an advantage in terms of installation. This also comes with the disadvantages of having a system that is more susceptible to attenuation and noise.

As a communication system, X10 also suffers from a poor responsiveness and since most of its devices are based on one-way communication topology, transmissions are not properly acknowledged (there devices that have an acknowledge mechanic but tend to be more expensive)[36][37].

1-10V

0-10V lighting control is one of the oldest and simplest protocols, it uses a control signal between 0 and 10 Volts that correspond to 0% and 100% light output, respectively.

The attractiveness of this system is simplicity, but it comes at a cost of limitation in terms of functionality and implementation, as an example, the length of the control wiring can affect the light output as it causes a voltage drop from the beginning of the line to its end.[38]

Another important topic to retain about 1-10V systems is that normally the control of the light output is limited to a minimum dimming of 10% and they require a switch or relay to turn off the light output completely.[39]

DSI (digital serial interface)

In 1991 Tridonic started to develop DSI (digital serial interface), a protocol of lighting control systems that would eventually become the precursor of DALI.

Compared to DALI, DSI is a simpler protocol, the devices in a DSI system are not addressable, this means that replacing a device can be done by simple switching the hardware.

On the other hand, each control channel requires a dedicated wire to communicate, increasing the complexity of implementing large systems due to multiple wires. With this protocol, interoperability is also limited to one manufacturer.

DMX512

First developed for theatrical and professional lighting, since its creation in 1986 by Engineering Commission of *United States Institute for Theatre Technology,* DMX 512 has been transforming and expanding into a lighting control protocol fitted not only to indoor but also to outdoor lighting.

A DMX solution is a digital centralized control system, a controller operates multiple devices in a unidirectional network. It works in a daisy chain topology, each device has an IN and an OUT port that, in the edges of the chain, connect to the controller and a terminator, respectively.

Tipically, one device is associated with one address that needs to be pre-programmed with, but it is also possible to configure multiple devices to listen for only one address, or one device to listen for multiple addresses.

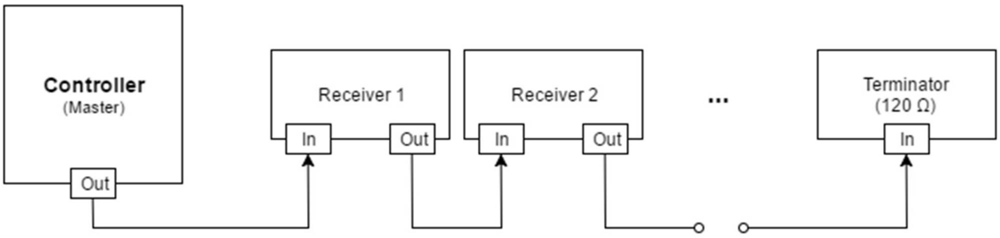

Figure 4: DMX512 Daisy chain

The communication line is unidirectional, and so there is no feedback or acknowledge to messages sent by the controller, however the DMX512 is surprisingly robust much due to the proprietary infrastructure of devices and cabling. More so, each message is transmitted multiple times to increase the probability of at least one reaching its destination. Unidirectional communication proves to be one major limitation in a building management scenario, the fact that DMX512 does not support device information to be transmitted back to the central node makes it inappropriate to serve as the base of a more sophisticated building management system.

iii) LIGHTING CONTROL SYSTEMS

From a flexibility point of view, lighting control systems can be distinguished into open systems that are based on open and public protocols and technologies, or systems that are built on proprietary technology. Open systems have a more inviting architecture that allows the combination of different solutions from different manufactures and because they are based on open technologies, interoperability with other systems is a possibility.

That is not the case with proprietary systems because products must be from the same manufacture to work in tandem, this is in fact a disadvantage not only in interoperability and flexibility but also for the user, in the interest of price and technology features. In spite of all this, proprietary system can be a better solution in specific lighting scenarios, also some technology features can prove to be a decisive factor in an application. [40]

This subchapter reviews two existing lighting smart systems to understand what is already implemented and what can be improved.

LITECOM

Developed by Zumtobel, LITECOM is a control system with a main focus on lighting, which also supports other building services such as windows or blinds, and other automation capabilities. It is a professional system, tailored for offices, factories, museums, etc. , with a focus on functionality and efficiency.

The basic topology of the system is constituted by a central control unit that supports 3 DALI lines and a Luxmate (LM) bus used to connect a number of control panels, switches and even motors to operate blinds, screens, etc.

It is a system designed to achieve a high energy efficiency rating, based on its lighting control features that take into consideration the time of day and the lighting scenario requirements. Crucial to this control is the use of sensors, that endow the system with presence and daylight information. Daylight harvesting takes into consideration multiple information, such as the illumination level, sun’s position and incident light in the windows vicinity to avoid glare and determine the artificial light level needed to complement the lighting scenario [41].

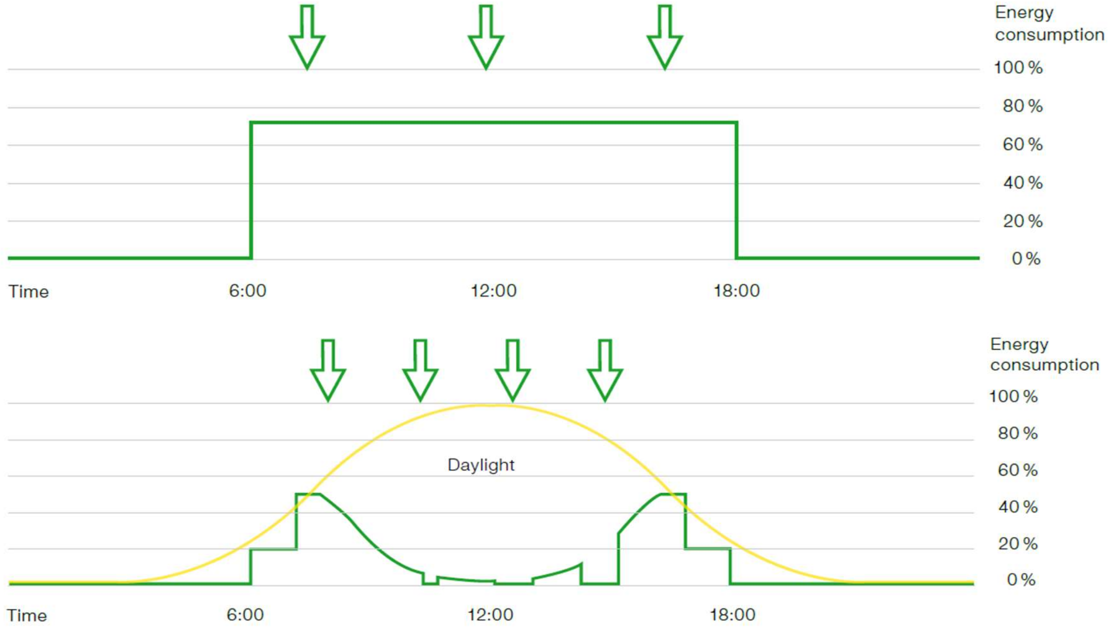

Figure 5: LITECOM daylight integration and presence awareness [41]

Control over luminaires is commissioned to the users via control panels and a mobile app, it allows the creation of custom lighting scenario and the tuning of light intensity and colour.

Hardware wise, the LITECOM control system requires compatible DALI drivers and devices which are limited to 64 per line. Additional control units can be added to expand the number of devices supported.

Cree Smartcast Technology

One of the differentiating features of Cree Smartcast Technology systems is simplicity in of installation of the lighting control solution. That simplicity is accomplished with wireless communication of the LED luminaires, sensors and switches, from embedded IEEE 802.15.4 radios using a proprietary network and application protocol. The absence of extra communication wiring significantly reduces the cost and time required for installation.

Another key feature of the system is the LED luminaire design that incorporates the sensing module in the LED fixture, reducing the amount of installation gear. Sensor wise, just like the LITECOM it has passive infrared sensor (PIR) and a lighting sensor.

By taking advantage from the light sensor on the luminaire, the system has auto grouping functionality, the luminaires recognize the others surrounding them by sensing light in a sequential turning on and off of all luminaires on a configuration procedure. After this configuration, it is possible to address a group of luminaires in a room.

iv) REGULATION

Regardless of the light source technology used, a lighting system needs to comply with the minimum standards set national and/or international regulation. In Europe, the most important norm in indoor lighting is EN 12464. It covers a wide range of situations and scenarios and sets a minimum for multiple lighting metrics that should be taken into consideration in any installation.

EN 12464-1

The European Norm 12464-1 regulates mainly indoor lighting and lighting applications. It's the result of several years of work from the European Technical Commission and was approved in 2002 as a conglomerate of all the diverse lighting laws at all the different countries. Over the years it was subject of multiple reviews that culminated in an updated version in 2011 and it has been in place since then.

The scope of this standard is the establishment of minimum lighting values that assure user comfort and cover health issues related with visual stimulation with an efficiency perspective on a variety of scenarios and tasks. This standard also iterates the documenting and calculation that should support a lighting system.

Application

One important aspects in this norm is that it covers a variety of lighting scenarios and specifies the lighting requirements of different tasks and spaces. For each application, it is imperative that these four criteria are met:

- Minimum average illuminance (E_m) per task;
- The maximum UGR;
- Minimum R_a required;
- Illuminance Uniformity (Uo);

This subsection defines lighting components for a space, the EN-12464 specifies recommended values for these measurements that depend mostly of the type of tasks performed.

Vertical Illumination

In indoor space lighting it is important not only to maintain a minimum illuminance level but also a sufficient vertical illumination to assure visual comfort. Vertical illumination translates into ceiling and wall illumination that have a strong impact on visual comfort and performance, mainly because of the user depth perception.

As a minimum, the EN 1264 standard sets a 30 lx level for ceiling illuminance and 50 lx for walls, both with a uniformity no less than 0.1. [42]

Because different spaces have different needs these levels are adjusted for offices, hospitals and classrooms to 50 lx on ceilings and 75 lx on walls. It is crucial to point out that these are a minimum mandatory values, and they may actually be exceeded and adjusted to different spaces as the lighting designer sees fit. [13]

Cylindrical Illuminance

Another key component for visual comfort is cylindrical illuminance (E_z), it establishes the vertical light level at panoramic view. The minimum value for this parameter determines if other persons faces are sufficiently lighted.

The height for measure depends on the space usege, but falls in two categories: 1.2 meters for desk work; and 1.6 meters for standing work. In both cases the cylindrical illuminance should be at least 50lx with 0.1 of uniformity, unless the space is a classroom, office or conference room and in that case the minimum is 150lx [13][43].

Modelling

Modelling is defined as the ratio of cylindrical and horizontal illuminance. It concerns the perception of shapes and shades of objects, a room lighting should reveal forms and textures clearly to enhance the appeal of a space and objects in it. The shadows are essential to good modelling as they should be formed without confusion.[13]

Work space definition

The EN12464-1 provides a high level of freedom to the lighting designer to define workspaces, it allows multiple and dynamic settings of task areas within a workroom.

For example, traditionally an office it was defined a task area that required a minimum average illuminance level and uniformity that depended of the task developed. This setting is still valid, but within the scope of this standard the workroom can now be breakdown into several task areas that need to be lit accordingly to the task at hand (Figure 6). When developing a workroom with different task areas it is crucial to adjust to each situation but in a broad scope, all the setting must abide by the following regulation:

- The immediate surroundings of a task area should be lit with a level below the task area average illuminance. As showed in Figure 6, the immediate surroundings of a task require only 300 lx (one level lower than the task area) and the circulation area 100 lx (one level below the surrounding area).

This provides an overall lower light setting without compromising the task and convey sharp contrasts in brightness.

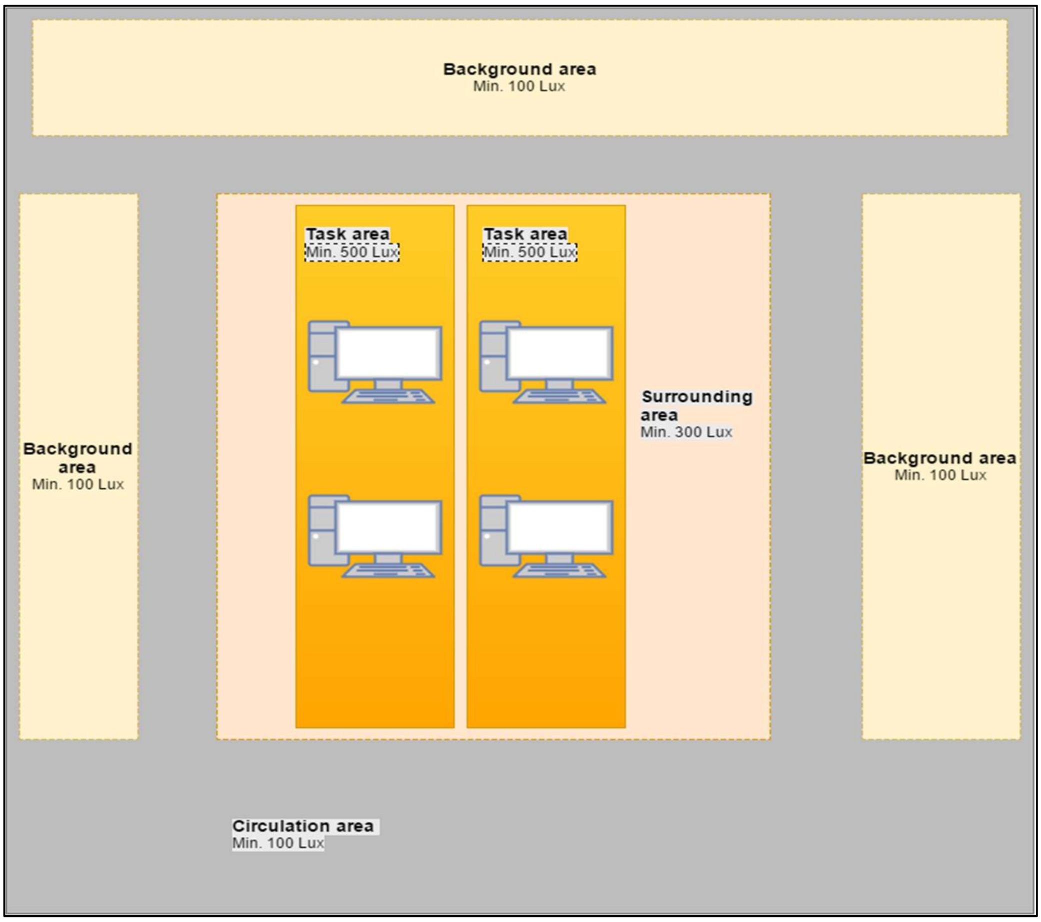

Figure 6: Task area example

- The task area should be illuminated as uniformly as possible and this ratio cannot be less than 0,1. In continuously occupied areas, the maintained illuminance shall be not less than 200 lx.
- As recommendation, it also states that the required maintained illuminance should be increased, when:
  — Visual work is critical;
  — Errors are costly to rectify;
  — Accuracy or higher productivity is of great importance;
  — The visual capacity of the worker is below normal;
  — Task details are of unusually small size or low contrast;
  — The task is undertaken for an unusually long time;
- The required maintained illuminance may be decreased when:
  — Task details are of an unusually large size or high contrast;
  — The task is undertaken for short amounts of time;

EN-15193

The European Norm 15193 (EN-15193) aims to establish metrics and methodologies to measure a building energy performance in lighting. The most used measure is the Lighting Energy Numeric Indicator (LENI) which abides by the following formula:

$$LENI = \frac{W}{A}$$

Equation 1: LENI Equation

In which:

$$W = W_L + W_p$$

And:

$$W_L = \sum \{(P_n * F_c) * [(t_D * F_O * F_D) + (t_N * F_o)]\} /1000$$

$$W_P = \sum \left\{\left[P_{PC} * \left(t_y - (t_D + t_N)\right)\right] + (P_{em} * t_e)\right\} /1000$$

The various terms are: The total installed charging power for emergency lighting (P_{em}); Total installed control circuit parasitic power (P_{PC}); Total installed lighting power (P_n); Daylight operating hours (t_D); Non-daylight operating hours (t_N); Annual operating time ($t_o = t_D + t_N$); Standard year time (t_y); Emergency lighting charge time (t_e); Constant illuminance factor (F_c); Occupancy dependency factor (F_O); Daylight dependency factor (F_D);

LENI is an extensive metric that takes into account a considerable number of factors about the building use, location and infrastructure to deliver an accurate reading its lighting expenses per year.

As explained in the paper "*Estimation of electrical lighting energy use in buildings: a method comparison*" [44] and they have a strong impact in the precision of the LENI metric. The paper also reports that over simplifications, the use of standard values and disregarding factors like building orientation and daylight availability, leads to over estimations of the actual building lighting consumption. Optimal results can be achieved through data gathered over an extended period of time about the building occupancy and hardware power consumption.

Simulation parameters

The EN-15193 covers the following system setups when estimating a building energy consumption (regarding lighting):

System setup	Occupancy dependent lighting control system factor
Manual On/Off Switch	1.00
Manual On/Off Switch	0.95
Auto On / Dimmed	0.95
Auto On / Auto Off	0.90
Manual On / Dimmed	0.90
Manual On / Auto Off	0.80

Table 2 : Occupancy dependent control factor on different setups

Portaria n.o 349-D/2013

Portaria n.o 349 is a set of regulations regarding buildings energy performance that results from Portuguese (*Decreto-Lei n.º 118/2013*) and European (*Diretiva n.º 2010/31/UE*) norms [44]. The most relevant (to this project) points addressed by this directive concerning indoor lighting system states that the use of light output control equipment can have the following features [44]:

- Control due to presence detection
- Control due to natural light detection
- Regulation of light output due to natural light detection
- Time schedule regulation
- Interface regulation
- Maintenance scheduling due to the network inputs of status, consumption and operating time

2.3. BUILDING AUTOMATION SYSTEMS

The purposes of a BAS are somewhat similar to the ones defined for the indoor lighting systems, focusing more in functionality and efficiency than in aesthetics. Conceptually, they unify the building services control under one system, like heating, ventilation and air condition (HVAC), security and access, emergency systems, etc.

Having different set of services means that the BAS functionalities can range from monitoring to a more control driven functionality to its multiple services. Monitoring and analysing information can endow the system with the capability of anticipating malfunctions and computing pre-emptive interventions to assure that its services have the minimum downtime possible.

Much like indoor lighting control system, BAS also need a communication protocol to uniformly exchange information and commands. The most important and used are KNX, LonWorks and BACnet.

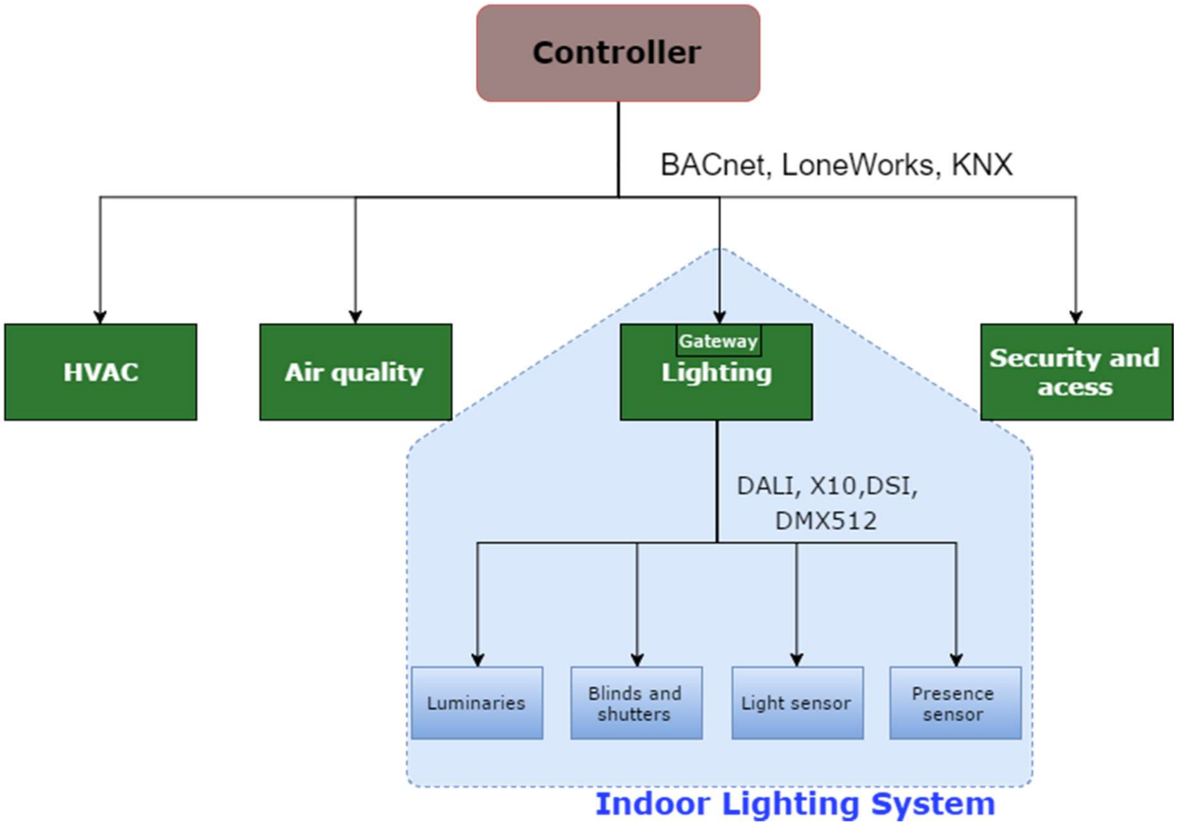

Figure 7: BAS with indoor lighting system integration

Lighting is one the potential (and most important) services to be included into a BAS, however as seen in the previous section, indoor lighting system also run communication protocol. And so, to be integrated into a BAS it is necessary to have a gateway that functions as protocol translator as showed in Figure 7.

2.4. THE IOT PERSPECTIVE

The conjugation of protocols at both levels allied with the hardware proprietary constrictions can cause compatibility problems or lock-in situations, where the building manager is tied to one manufacturer’s hardware due to interoperability issues.

To overcome this problem, this project's take on BAS is based in internet of things (IoT) concept. The IoT aspires to extend internet to devices beyond computers, smartphones and such. Making up for a network of everyday objects that can share and analyze information to achieve otherwise impossible solutions and operations. [46]

IoT has extensive applications that can range from commercial and personal solutions of home automation, to bigger scale of industrial applications with a communion of large volumes of data that may enable enhanced operational efficiency. [47]

The IoT trend is growing and evolving towards different markets and ends, according to a *Business Insider* report ("*How the 'Internet of Things' will impact consumers, businesses, and governments in 2016 and beyond*") 34 billion devices are expected to be connected to the internet by 2020, based on the 10 billion in 2015, this forecast also states that this growth will be supported mainly by the business and government sectors, backed by the consumers' adoption to IoT systems. [48][49][50]

One major focus in IoT is the use of sensors, alongside actuators, in what is called a wireless sensor and/or actuators network (WSAN). Capable of harvesting different types of information through sensors and perform physical operations via the actuators. The sensors and actuators can be seen as network of objects that require a transceiver to communicate, a controlling unit to process the information and a power supply. Another basic component in a WSAN is the communication protocol, it is crucial to have a standard language across all devices to send and receive information. Furthermore, a communication protocol must take into consideration one major aspect in WSANs, the devices that comprise a WSAN are usually battery powered and so communication and data processing need to be designed with a low power operating purpose to extend battery life as much as possible.

i) COMMUNICATION PROTOCOLS

Much like in a BAS services communicates through a common protocol, a WSAN has an array of devices that need to communicate. So, the following IoT communication protocols have the potential to replace or emulate the indoor lighting system and BAS communication protocols.

Bluetooth Low Energy

Bluetooth low energy (BLE), previously referred to as Bluetooth Smart, is a specification within Bluetooth family that focus in short and low energy communications, designed to be used by power and memory constrained devices. Originally designed by Nokia in 2006 under the name Wibree, BLE was later adopted and developed by the Bluetooth Special Interest Group and marketed with the Bluetooth version 4.0 (all the prior versions are now usually referred as Classic Bluetooth).

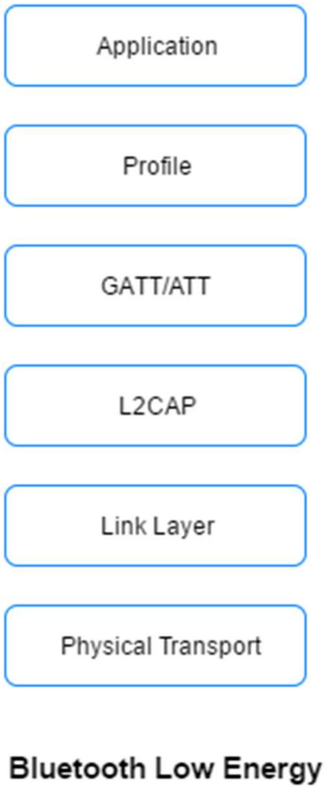

Figure 8: Bluetooth Low Energy stack [80]

A major strongpoint in this standard is the adoption rate, many mobile computing devices already support BLE. Allying the availability with the somewhat familiarity of the Bluetooth standard, the use of this standard in other peripherals also rose.

The BLE standard has an easy to understand data model and topology, Figure 8 shows the layers that comprise the BLE stack.

Physical Layer

The physical layer specifies the radio circuitry hardware, it is worth mentioning that it uses a 2.4GHz band and Gaussian Frequency Shift Keying modulation (also used in classic Bluetooth) that caps the physical throughput at 1Mbit/s. The physical throughput does not represent the actual application throughput, overhead resulting from the protocol layers limits it to around 0.27 Mbit/s. [51]

Link Layer

Directly communicating with it, is the link layer that provides a low level communication interface. It manages the timing and sequence of the transmitted and received frames. Because of its real-time requirements, it is normally implemented in a dedicated hardware chip with a Host Controller Interface (HCI) as standard to interact with the upper layers.

Device roles are defined in the link layer, if a device is the one that initiates and manages the connection it is designated as the *server,* therefore the device that accepts the connection is the *slave.* When not connected, the slave sends advertising packets and it is designated as the *advertiser,* the server scans for this packets, making it the *scanner,* these are the four device roles defined in the link layer.

The BLE protocol simplifies packet transmission by having only one format with two types, advertising and data packets, an advertiser will broadcast its basic connection information and Bluetooth device address regardless if a scanner is in the area or not. A scanner can now respond to an advertising packet with a connection request (with the connection parameters) that (if corresponded) results in an established connection.

Logical Link Control and Adaptation Protocol (L2CAP)

Separated physically and logically from the link layer, the L2CAP communicates with it by HCI and it manages the bidirectional communication channel between link layer and upper layers. It is responsible for rearranging large data into standard size data packets encapsulated with the BLE format, fitted to be transmitted. Likewise it recombines received fragmented BLE packets into a single data packet that can be sent to the upper layers.

Attribute Protocol

The attribute protocol (ATT) is a low-level communication mechanism that allows a device to transmit a set of attributes and values to a peer device, intuitively they are designated as server and client respectively. Each attribute exposed is comprised by an identification (called attribute handle), a universally unique identifier (UUID) that defines the attribute type, a set of permissions specified in the higher layers, and finally a value.

The UUID is a 128-bit number, however to reduce the data payload occupied it uses a 16 or 32-bit short value that can be combined with a base UUID to produce the complete UUID.

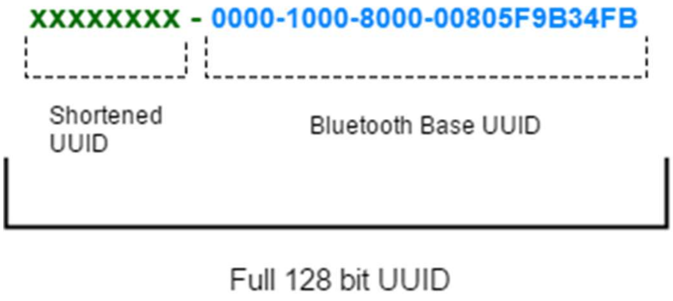

Figure 9: BLE UUID

Supposed a connection is established and the permissions set, a server will respond to a read or write request with a value or acknowledgment respectively, the information exchanged is processed in both sides assuming the type of data expressed in the UUID. [51]

Generic Attribute Profile

The Generic Attribute Profile (GATT) is a framework to design and define the data structure in which the information is transmitted. It is a high communication mechanism, built upon the ATT and meant to be used directly by the application layer or another profile, data is organized into services with their respective characteristics.

Like the other protocols, GATT also defines devices roles that implements:

Client: similar to the ATT protocols, the client sends requests and commands to the server and it receives responses, indication or notifications. Before trading information it must perform a service discovery to establish a list of the attributes made available by the server.

Server: The information is stored and structured into attributes in the server side. It then responds to client requests and commands (it can also can send information without a request if updates are enable for the connection).

Generic Access Profile

Alongside with the GATT the Generic Access Profile (GAP) is another basic framework to a BLE connection, it also connects directly to the application layer and defines multiple parameters for the advertising and establishment of BLE connections between devices. It defines the following roles that a device can perform in a network:

Broadcaster: When a device uses advertising packets to periodically send data to all available observers, it plays the role of a Broadcaster

Observer: Observer and Broadcaster are inherently bounded as the observer collects data from the advertising packets made available by any Broadcaster. These roles are built upon the *observer* and *advertiser* roles, respectively, from the link layer

Central: A central device is the initiator of a BLE connection and must be capable of establishing and managing multiple BLE connections, making up for a star topology network**.** So, being the central node it also manages the BLE network by allowing or refusing peripherals connections.

Peripheral: Compared to a Central device, peripheral devices usually have more constrains in terms of power and memory . Slaves in the central-peripheral connection announce their connection via the advertising packets and if the central device establish the BLE connection they cease to advertise and begin transmitting the respective data packets.

ZigBee

ZigBee is a wireless communication protocol developed and owned by the ZigBee Alliance, based on IEEE 8002.15.4 it is specially tailored towards low power and constrained memory devices by operating in a low duty cycle.

The IEEE 802.15.4 radio, used by Zigbee, operates in the 2.4GHz ISM band with 16 channels capable of a raw throughput of around 250 Kbits/s. It is a relatively low throughput, nonetheless, very much like BLE this technology is designed to achieve higher energy efficiency rather than transmitting large data volumes.

One major upside is the range it offers, Zigbee can arrange extensive networks with a 10 meter radio range, of course this value is highly dependent of the power used in the radio and environment characteristics.[52]

Networking is not limited by the radio range, Zigbee is capable of mesh networking and thus exchange of information between two nodes does not require a direct connection between them. Besides extending the range of the network it also adds reliability as it creates multiple redundant connections routes.

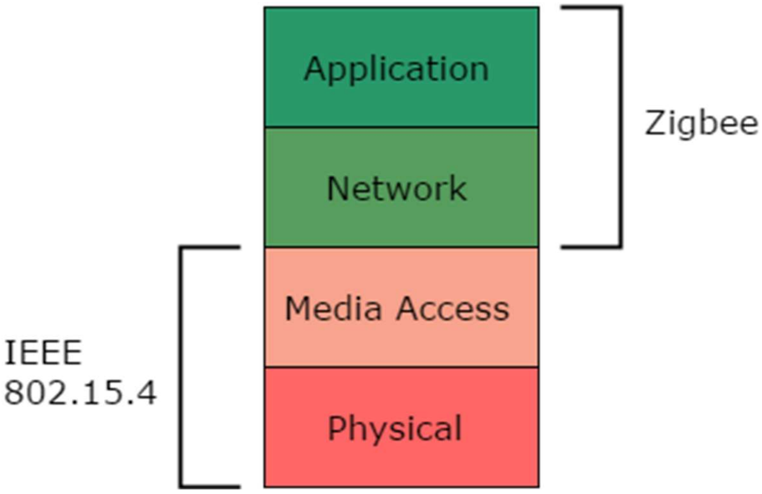

Figure 10: Zigbee stack

The Zigbee stack is comprised by four main layers as illustrated in Figure 10, the most basic layer is the physical where the translation between packets and over-the-air bits is made. Followed by the Media Access Layer (MAC layer) that sets the groundwork for networking, both these layers are inherited by the IEEE 802.15.4 standard. The actual networking is supported by the Network layer where basic functionalities like routing and broadcast are implemented, encryption and security are also handle at this stage.

A device can be seen as a node in the network as one of three types:

ZigBee Coordinator: It is a central device, usually it has more computational power and lower memory and power constraints, it manages the security in the network and acts a router for the meshes and also as a border router to outside networks

ZigBee Router: Like the Coordinator, the router can remove a node from the network or allow for a new one to join in, it also routes packets and creates redundancy in the network.

ZigBee End-Device: The low end of the Network, usually the more limited in power and memory device in the network, transmits information to the ZigBee Router and has the ability to “sleep” when it has no data to transmit in order to save energy [53].

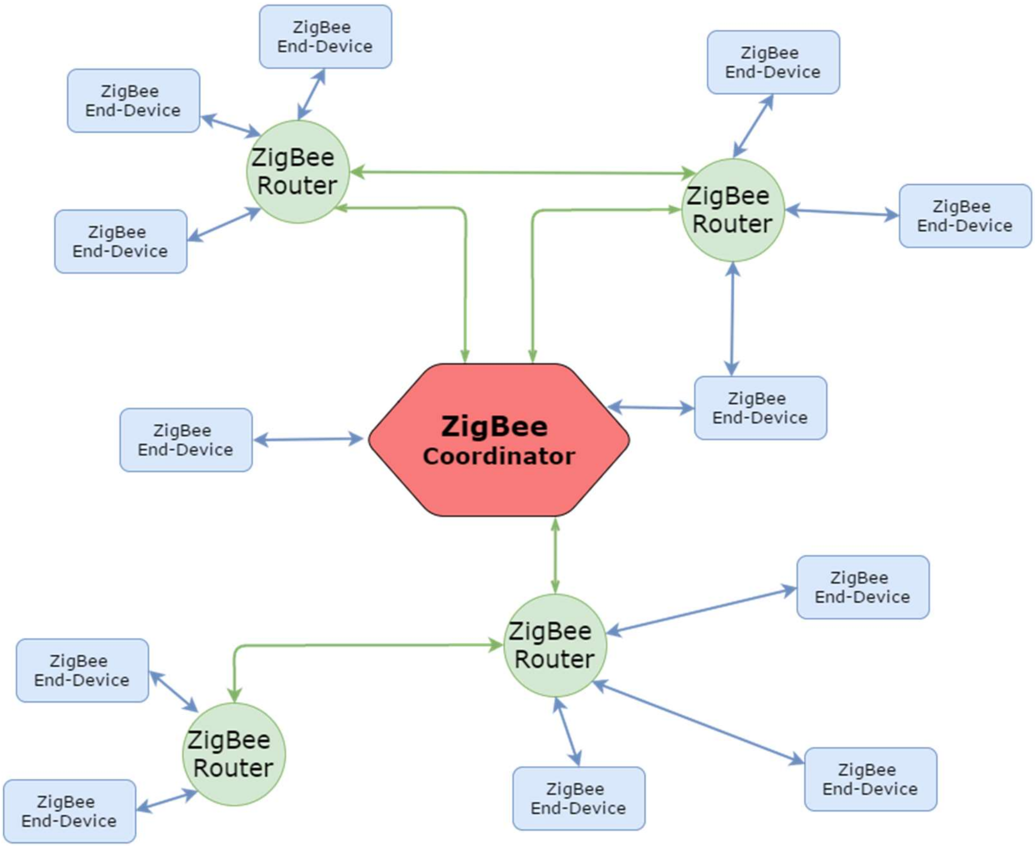

Figure 11: Zigbee network example

Finally, the application layer is the interface between user and system, it implements the ZigBee Device Object and defines device roles and management. The application layer can implement profiles, one example is the ZigBee Light Link, a lighting oriented application profile that categorizes nodes into controllers and light nodes. This profile then allows for some flexibility in the control of light sources and lighting scenarios based on information from input panels, sensors, time of day, etc.

Z-Wave

Z-Wave is another important wireless communication protocol that focus on home automation, HVAC systems, lighting control and others. It is a proprietary standard owned by Sigma Designs designed for light and short range communications and supports mesh networking.

Networking

Considering the ZigBee network topology, the Z-Wave is somewhat simpler in the sense that a network is formed by a central node and peripheral nodes. The central node, also known as controller is the root of the network and manages the peripherals nodes that can represent switches, sensors, etc. Meaning that adding a new peripheral to the network has to be done through the network controller, this simplifies the network layout but can also represent an inconvenience with extensive networks were a new peripheral has to meet the controller range at least once before joining the network. After joining the network, a peripheral node can communicate with other nodes (even out of range) over the mesh network.

The range of Z-wave communications is about 30 meters and the radio operates in the sub-GHz domain, meant to reduce interference. One potential big weakness in Z-wave is the throughput of 100 Kbit/s that actually translate in around 40 Kbits/s of data throughput, that can limit the applicability in some scenarios.

Ultimately Z-wave falls short over the other protocols mainly due to its proprietary restrains, purchasing developers kit and product certification requirements are some of the constraints allied with Z-Wave. Another potential problem is security, as stated in the paper "*Security Evaluation of the Z-Wave Wireless Protocol*" [54] by *Behrang Fouladi* and *Sahand Ghanoun*, Z-Wave still has some vulnerabilities that are being addressed.

2.5. CONCLUDING REMARKS

The technologies developed in the lighting systems business have evolve from different sources to different purposes and they all offer viable solutions to implement a smart lighting system but ultimately they fall short in interoperability due to proprietary constrictions as noticeable in DALI systems, taking LITECOM as an example, it is one of the most complete and user friendly systems in the market but it still requires a physical line of communication. A step forward can also include the connectivity with others building services, a communion of information can improve the overall energy efficiency of the building but to accomplish this it is necessary to breakthrough of the technologies typically used.

Concepts like Internet of Things (IoT) can be a viable option to rethinking the lighting system as a network of sensors and actuators that can be based on different wireless communication technology that supports the established functionalities and add new ones with an increased energy efficiency.

3. CONCEPTUAL ARCHITECTURE

This chapter describes the conceptual vision for the system architecture and all its layers, it starts by defining the scope and objectives of the Smartlighting project, the requirements and features for the systems are identified in the section 3.2 by analysing the different users and their individual interactions with the system.

The fifth section presents the proposed solution to meet the identified requirements, also in this section the layers of the system and some technologies used in them are identified. Section number six details the requirements for the lighting hardware needed to support the solution and the necessary features. Finally, the last section presents several conclusions and closing remarks relevant to this chapter.

3.1. OVERVIEW

The Smartlighting project objective is to design building management solution, particularly focused on the lighting control, on the IT2 building. The system developed aims to improve the building energy efficiency and offer greater control over building services in a simple yet powerful interface. Also important in the scope of the Smartlighting project, the system should represent an open source approach to lighting and building management systems.

Currently the IT2 building lighting system is based on traditional wall switches as controls and Linear Fluorescent Lamps (LFL). The Smartlighting system aims to use LED luminaries and offer more dynamic controls over the lighting gear such as remote control via a web interface or a smartphone app.

As stated in the first chapter, LED technology is not significantly more efficient than the LFL technology, however it offers advantages that makes it a more fitted and future proof technology. To further improve energy efficiency of the building, automation of the lighting system is indispensable e.g. a simple automatic response to a user presence or absence can weigh heavily in this matter.

As important as improving energy efficiency, user comfort should also be considered in system design. Automation can be used to actually improve user comfort and interaction, e.g. temperature and lighting can be set to meet a certain user preference even before he arrives at the room, after he leaves heating and lighting can be automatically adjusted to an unoccupied room setting. This requires information beyond simple presence, the system can benefit from the use of indoor location to harvest user-specific data and build a custom profile to each user.

3.2. SYSTEM REQUIREMENTS

The identified requirements need to be set in different system layers, i.e. features like rule management, user interaction and information display should be implemented in higher layers, while requirements like a dimming feature or presence information should be implemented in lower layers.

In the hardware layer, having a failsafe mechanism greatly improves system reliability as it can fail due to multiple reasons, e.g. the luminaires should continue to function and react to the environment.

One general functional requirement is responsiveness, if the system is too slow executing commands or responding to environmental changes, it may be off putting to users, especially in critical services like lighting where a significant delay is particularly noticeable.

Finally, the user experience with the system its crucial to its adoption and integration in their quotidian, a user-friendly front end with a clear and simple presentation is more inviting than an over complicated interface with too much information that can inhibit some users to adopt the system.

i) STAKEHOLDERS

Before designing the system a prior analysis to the set of people involved in this project was conducted (stakeholders) to understand the system impact from different perspectives.

First and foremost, the developers team that start off the project by designing the system keeping in mind all the other user's interactions with it. Probably the most important stakeholder, the IT2 building user interacts with the system on a daily basis, from the most basics operations such as switching on a light to more refine operations such as adjust his personal preferences. Regarding this user, functionality and comfort are the more important aspects in his interactions with the building services.

Another important element is the building manager that needs to access important information about the building status in an easy and fast manner. This user will take advantage of the aggregation of information concerning all building services in an easy to manage platform. He will also take advantage of features that will allow him to identify malfunctions faster and to better organize the building maintenance response to them.

The building manager is also responsible for orchestrating the building maintenance, operations of this nature are performed by the maintenance team that is the main mean of intervention in the building infrastructure. Therefore it represents another stakeholder that has a special interest in having a system that reports him information about the building infrastructure status and alerts to potential technical interventions.

ii) USE CASES

To have a better insight on how the stakeholders interact with the system, several use cases are presented in the following section. A simple and short user-story describes what the stakeholder does in the building and subsequent use cases describe the stakeholder interaction with the system from his perspective.

The use cases structure is based in the standard set by *Warren W. Tignor* in the "*System Dynamics Models and the Object-Oriented Paradigm*" [58] paper from 1999. Each use case is divided into:

Requirements: Describes the state of the system or set of conditions necessary for this particular use case to take place

Main flow: Explains what actually happens in the use case

Subflow: Breaks down the main flow into detailed Subflows, regarding the main flow activity

Alternative Flow: It describes potential disruptive events that diverge from the main flow direction, usually associated with errors or unexpected situations.

IT2 user

User-story

The IT2 user routine starts with the arrival to the entrance and using is key card to log into the building security system, allowing him to enter the building. He then proceeds through the hallway towards his office, upon arriving he turns on the lights and sits down by his computer and starts working. In the end of the day he goes through the hallway to the entrance using his key card to log off from the security system and leaving the building. He latter decides to change the time of the meeting.

Use cases

Use Case 1 (UC1) - Entering the Building

1.1 Requirements:

None

1.2 Main Flow:

The user arrives at the entrance and authenticates himself [E1]. The system acknowledges the user and registers the information about his presence.

1.3 Subflows:

None

1.4 Alternative Flows:

[E1] Authentication fails

Use Case 2 (UC2) - The user travels down the hallway

2.1 Requirements:

User is in the building

Sensor information about the user movement is gathered

2.2 Main Flow:

While travelling through the hallway the luminaries in his path automatic dim up and the ones after him dim down. [S1] [E1]

2.3 Subflows:

[S1] The system acknowledges the user presence and intention to travel to his office, it starts his computer and begin adjusting the heating of the room to his preferences

2.4 Alternative Flows:

[E1] Only the luminaries above the user dim up, dimming down as he goes away.

Use Case 3 (UC3) - The user enters his office

3.1 Requirements:

User is in the building

The system has his presence and credentials information

3.2 Main Flow:

Arriving in his office the luminaries automatically turn on to his preference light level [E1] [S1]. He sits by his computer and access the web interface [E2], he decides to adjust the temperature and light level of the room before starting to work. [S2] [S3] [E2] [E3]

3.3 Subflows:

[S1] The system checks the light level to make sure that the room is not under illuminated

[S2] The system presents the user only with the hardware that he has permission to use

[S3] The system checks possible potential conflicts with other users (present in the room) preferences before perform the operations

4.4 Alternative Flows:

[E1] The luminaries turn on to a generic light level

[E2] The system detects a conflict with the preferences of other user present in the room and notifies the requester about the temperature and light level that are actually going to be implemented.

[E3] The luminaries and the heating system do not respond

Use Case 4 (UC4) - The user leaves the building

4.1 Requirements:

User is in the building

User presence information is in the system

4.2 Main Flow:

He goes down the hallway to the entrance [UC2] and uses his key card to log off the security system [S1]

4.3 Subflows:

[S1] The system acknowledges the user is leaving

[S2] The system checks the user office to make sure no electronics or heating equipment has been left on unintentionally

4.4 Alternative Flows:

None

Building manager

User-story

Just like the other IT2 users, the building manager (BM) arrives at the building, logs in to the security system and goes to his workplace. He uses his smartphone to check important notifications and when he arrives at his workplace he can visualize various information about the building (energy consumption, occupation, malfunctions, etc.). He detects a malfunction in one of the luminaries and is also notified of a hardware installation request. In the end of the day he logs off from the security system and leaves the building

Use cases

Use Case 5 (UC5) - The BM checks his notifications in the system

5.1 Requirements:

BM has entered the building [UC1]

BM is logged into the system [UC2]

5.2 Main Flow:

The system notifies the BM with more information about building status than the normal user, however no critical notifications are present [E1]

5.3 Subflows:

None

5.4 Alternative Flows:

[E1] A critical notification was generated and its visual impact stands out in the graphical interface

Use Case 6 (UC6) - The BM checks the building status

6.1 Requirements:

BM has entered the building [UC1]

BM has arrived at his workstation [UC3]

6.2 Main Flow:

The system presents the BM with dashboards that convey multiple information about building status [S1]

6.3 Subflows:

[S1] The BM can organize and choose which dashboard he wishes to see

6.4 Alternative Flow: None

Use Case 7 (UC7) - The BM is notified with a maintenance request

7.1 Requirements:

BM has access to the system interface

7.2 Main Flow:

The system notifies the BM that a user requested a hardware installation, he schedule a maintenance operation [S1]

A luminaire malfunction notification arises, he chooses an element of the building maintenance team and passes the information [S2] [E1]

7.3 Subflows:

[S1] The building maintenance team is notified with the time and information about the operation

[S2] The building maintenance element is notified with the time and information about the operation

7.4 Alternative Flows:

[E1] The element of the team is not available, the BM is notified

Building management team

User-story

The building maintenance team (BMT) proceeds similarly to the other users to enter the building, they then proceed to their daily work. One team member receives a notification on his smartphone APP requesting a luminaire replacement. He accepts the request and proceeds with the installation, he notifies the BM upon completion. Finally, he leaves the building just like other users did.

Use cases

Use Case 8 (UC8) - The BMT is notified with a maintenance request

8.1 Requirements:

BMT is in the building and logged in the system [UC1] [UC2]

8.2 Main Flow:

The BMT accepts the luminaire replacement request [S1] and proceeds with the operation. He detects a faulty luminaire and control module. He simply replaces the hardware and the new luminaires connects and operates under the system control[S2] [E1]. He notifies the BM[S3] [E2] and continues his daily work

8.3 Subflows:

[S1] The system notifies the BM

[S2] The luminaires have a standard control module that allows for easy interchange

[S3] The BM can notify the user through the system that his request is completed

8.4 Alternative Flows:

[E1] The luminaire does not connect to the system, although being functional

[E2] If operation is not successful the BM is also notified

A few more aspects need to be taken into consideration to integrate a building management system, in particular reliability, responsivity, user-interaction and scalability of the implemented solution.

From the previous section of Use Cases it is possible to identify critical features and essential requirements to address some of the potential problems stated:

UC3: Multiple user interaction methods, smartphone APP, web interface, etc.;

UC2 and UC3: Dimming feature in the luminaires;

User presence and the space illuminance level information;

Actuators capable of controlling other services like air conditioning units per example;

Rule management for decision making (e.g. deciding the illuminance level of a room);

UC5 and UC6: Customizable dashboards to display information relevant to each user;

Hardware capable sending information about it status;

UC8: A standard for the hardware module;

Ensure that basic services like lighting are not compromised in case of a connection issue;

3.3. SYSTEM TOPOLOGY

A conceptual architecture for the designed system is presented in Figure 12, it shows the physical deployment through devices that can represent sensors and actuators, all the way to the application and user endpoint.

The overall system results from the collaborative work of four dissertations projects, in this document it is described the work developed in the Field Layer, more specifically the device, luminaire, communication protocol and lighting system. This means that the work developed regarding the Gateway (partially) and the upper layers of the system is further explained and presented in its respective dissertations. There is also another dissertation that focus on the use of sensors in the building automation and therefor, work related to that matter is also further detailed in the respective document.

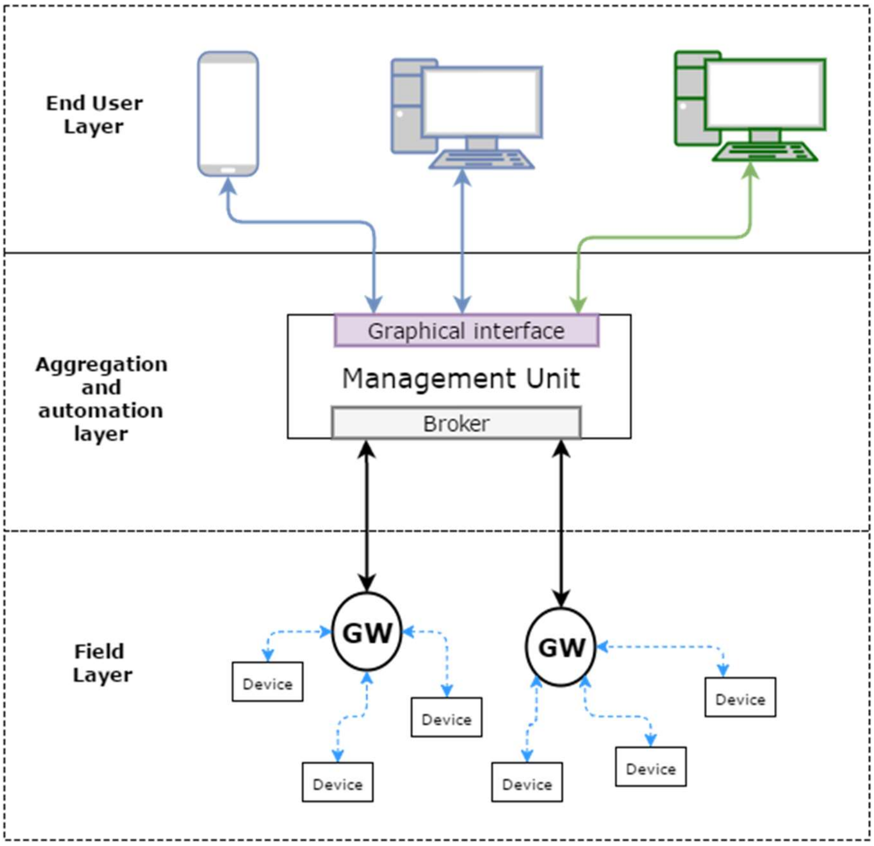

Figure 12: Proposed system topology

End user layer

The end user layer provides a graphical end-point for the user interactions, such as a mobile APP and a web interface. Figure 12 shows possible windows of interaction (web interface and APP) with both the user (blue) and the building manager. This gives user the functionality to make rules (that can go directly to the management platform or through the building manager first), it gives him control over actuators and presents him relevant information.

The building management has a more extensive control over the system and the rules in play. It also has access to more information and management options.

Aggregation and automation layer

All the information generated flows towards this management platform that analyse and processes this large volume of data to compute instructions for actuators or relevant information to the building manager or users. It must be capable of implementing a set of rules that can be managed through the building managing platform. It also creates a graphical and more perceptible environment in which the building manager can create, edit or delete rules for the system to operate accordingly. It also provides a graphical environment to display device information and location, and to perform configurations.

Bridging the gateway with other elements of the aggregation and automation layer is a broker, responsible for routing information to and from all gateways, it simplifies the process of adding more gateways and improves the scalability of the system

Field layer

The Field layer is comprised mainly by actuators and sensors present in the building infrastructure forming a wireless sensor and actuator network (WSAN). In the Figure 12 the end nodes of this network are represented as devices, one device can have one or more sensors and/or actuators. Both sensors and actuators require a certain level of computing power to exchange and process data, so each device is armed with a microprocessor.

The communication with the gateway should take advantage of current wireless technologies to avoid wiring related issues. Implementing a wireless protocol specially tailored protocols to low power devices can actually optimize the system performance.

The WSAN is responsible for gathering multiple environmental information and through the actuators react to changes or act upon instructions. The gateway, responsible for exchange information and instructions with multiple devices, needs a more extended computational power and must be able to translate data between the WSAN based on a wireless protocol (BLE, ZigBee, Z-wave, etc.) and the upper layers of the system.

In this dissertation the work described is mainly focused in the Field Layer where the lighting system is deployed, it is necessary to implement a model of interaction the upper layers of the system that facilitates the system scalability. It is also important to create a luminaire that supports the features identified in the previous section.

3.4. HARDWARE MODULE

The luminaires fit into the Field Layer (looking back at the Figure 12), more specifically at the wireless sensor and actuator network (WSAN), they communicate with the rest of the system based on the wireless communication protocol implemented. However, dedicate one microcontroller to perform communications and either control an actuator or read a single sensor information is a waste of resources, considering that one microcontroller can easily deal with multiple actuators and sensor simultaneously.

Therefor the WSAN deployment can be done by implementing multiple devices that are composed by a microcontroller and communication module, then by combining multiple sensors and actuators into this central set it is possible to create different configurations to better adapt the solution to each scenario.

The physical implementation is a central device comprise by more than a microcontroller and communication module, it also requires a power module and additional logic, inherent to the use of actuators and sensors, as showed in Figure 13. This central device must be capable of connecting to all the potential sensors and actuators available, although in practice it should only operate a few. This means that each node should have the same central device even though they might have a different set of sensors and actuators, additionally exchange components in one node should also be relatively easy and require minimal configuration. Having this flexibility allows the building manager to deploy an area specific solution that is easy to configure and install.

One important combination is the luminaire paired up with a PIR sensor, in case of the hardware module fails to communicate with the gateway, and subsequently the rest of the system, it can still operate the luminaire with the occupation information provided by the PIR sensor.

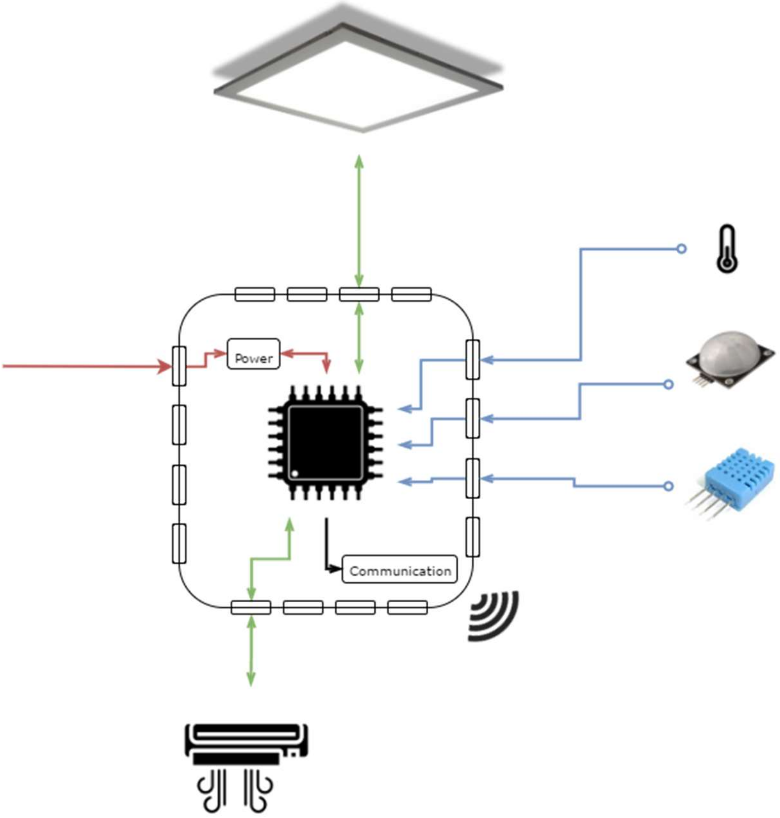

Figure 13: Hardware module

Configuring the WSAN with this architecture should also allow for a flexible deployment of sensors, e.g. some sensors that measure information like humidity, temperature or pressure, do not need multiple instances per room (dependent of the area size), and these sensors can be paired up into one sensor node, or they can have multiple instances distributed through the luminaires nodes to better characterize a larger space.

3.5. LIGHTING CONTROL

This section focusses on the lighting component and how to integrate the luminaires and lighting controls into the system. Fundamentally, each luminaire is an actuator and is seen as such by the aggregation and automation layer, i.e. it offers a set of information and functionalities. To endow the lighting gear with the capability of performing these functionalities and to communicate in a structured fashion, it is necessary to paired the LED lighting gear with a microcontroller.

To understand the process, this section stars by briefly describing the lighting gear and common techniques used to implement dimming in LED luminaires, then it explains how can this be integrated in the proposed solution.

i) LUMINAIRE

The luminaires efficiency is extremely dependent of technology that they are based upon, LED luminaires are usually comprised of light source, power supply, reflectors, frame and diffusor[59]. This configuration is not universal and different manufactures have different settings and materials.

One of the most important components after the LEDs are the power supply and diffuser as they have a significant impact in energy performance. Diffusors are a polycarbonate or polyester sheet that redirects and diffuses light, they are especially important in LED luminaires due to the directional nature of LED light, making it more application efficient light source.

The LED driver is a module that transforms power from the main power supply (usually the grid) to a power setting compatible with the light source. Usually, application efficacy of the luminaire is related to the diffuser, by shaping the light source into a direct or diffuse light. Additionally, some LED drivers offer a possible dimming implementation that also has a strong impact in the energy usage and application efficiency. [60]

ii) LED DRIVERS

LED drivers can have two distinct topologies, they can drive the LEDs by a constant current (CC LED drivers) or a constant voltage (CV LED drivers) and both have advantages and disadvantages. However for most applications, CC LED drivers are preferred due to the fact that they are more reliable.

Driving a LED luminaire with a constant voltage comes with the risk of exceeding its maximum forward current and subsequently increase the LEDs temperature (potential thermal runaway) that can reduce significantly the luminaire lifespan. This potential problem is not present in a CC LED driver because the current output is constant even when the voltage and temperature changes, preventing an over driving of the LEDs and also maintaining a more stable light intensity.

Nonetheless, CV LED drivers may offer better results when driving multiple strings of LEDs connected in parallel because it can match more precisely the current flowing through the LEDs strips.

There is also a third option that combines both CC and CV topology into a driver that uses CV regulation in lower load levels and CC in higher levels to prevent the thermal runaway problem, however, market wise they are a less common solution. [61]

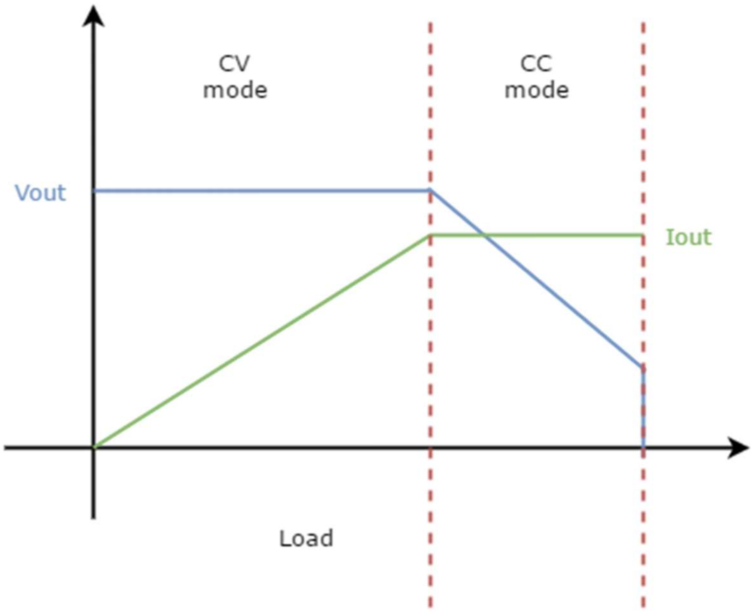

Figure 14: CV/CC LED Driver [81]

To this project the most obvious solution is a CC LED driver, using a driver capable of both operational sets is also a viable solution, however they prove to be more slightly more expensive than the CC counterparts. In a potential large scale implementation, this is an important factor considering that they do not offer a significant advantage over the CC LED Drivers.

iii) DIMMING TECHNIQUES

As stated, dimming has a strong impact on performance and efficiency on a technical perspective, but it has also advantages on the user end. Having different light settings allows the system to adapt the light system to different situations and compensate comfort factors like glare and modelling. According to Lighting Philips, optimal lighting can also have a strong impact in productivity as it helps users focus on their tasks [62].

There are different techniques to implement dimming in LED luminaires but they can be categorized in Phase-control, Analogue and Pulse-wide modulation (PWM) dimming.

Phase-Cut

Designed originally to control the light output of incandescent light sources in the 60's, this kind of techniques is based on the direct modifying of the AC voltage wave that powers the light source. The dimming results of "cutting" a phase of the sinusoidal waveform and doing so reduces the average signal delivered to the light source.

When it comes to phase-control techniques there are two main approaches, forward phase-control and reverse phase-control, they differ in the portion of the AC waveform that they cut as Figure 15 shows.

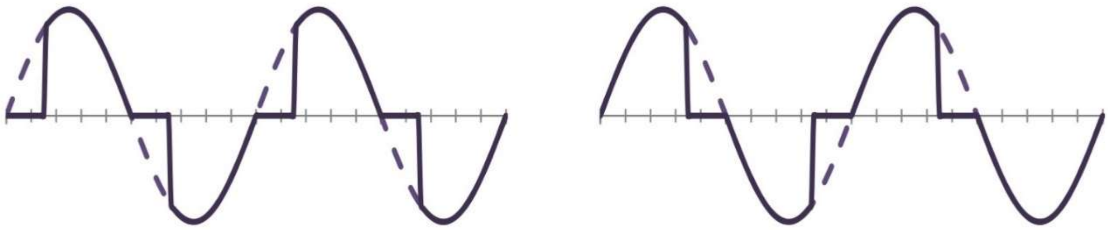

Figure 15: Forward phase-control dimming (left) and Reverse phase control dimming (right) [64]

There are LED drivers that use Phase-Control techniques to implement dimming, however this kind of technique can prove inefficient when compared to more recent developed techniques that are more focus on taking advantage of the LED technology proprieties [63,65]. These techniques were introduced as a way of controlling the first generation of LED luminaires with the dimmers installed at the time.

Analogue Dimming

Sometimes referred as 1-10v dimming, analogue dimming consists on adjusting the current level on the LED in order to change the light output. This direct relation between current and light output makes up for a simpler control overhead when compared to PWM dimming.

One of the setbacks to analogue dimming is a possible colour temperature variation resulting from the changes in the LED current. This is especially problematic in lower current settings that translate in sharper colour temperature variations. However, it can be more efficient in some cases, because it can have lower forward voltage in lower drive currents. To make use of the vantages of analogue dimming and avoid its potential problem, LED Driver manufactures have units that allow for a hybrid dimming technique that uses analogue dimming from around 10% to 100% light output and PWM dimming from 0% to 10% light output [65].

PWM Dimming

Controlling the LED light output with a PWM signal is the base of PWM dimming technique, it is especially attractive when in systems which use microcontrollers because it is easier to produce a PWN signal with a variable duty-cycle than a variable voltage signal as it is required for a 1-10V technology with analogue dimming. It is easy to assume that PWM dimming is a more compatible technique with the present trend use of microcontrollers but it is also important to keep in mind its disadvantages.

The principle behind PWM dimming is the sequential turning on and off a constant current supply to the LEDs according to a PWM duty cycle signal. From that, it is possible to iterate that it does not have the potential problem of colour temperature variation present in analogue dimming because the LEDs current flow is constant.

Varying the light output results of the adjustment of the mean current delivered, compared to analogue dimming it tends to be more precise in terms of relation of signal-light output.

However, when using this technique, it is crucial to limit the minimum frequency of the PWM signal to avoid a light flickering effect or a perceptible variation caused by the switching on-off of the LED. This effect can have adverse health consequences such as headaches, eye strain and fatigue but it can also be a safety issue considering the possibility of stroboscopic effect that strongly impact depth perception and movement notion[11].

To this project, it is possible to immediately rule out a phase-cut dimming implementation, due to its outdated nature it does not take full advantage of the LED lighting technology and it is the most inefficient technique. Choosing between analogue and PWM dimming, it might be simpler to implement PWM dimming considering that the luminaires will be paired with a microcontroller, however analogue dimming is also a very viable solution.

iv) DIMMING IMPLEMENTATION

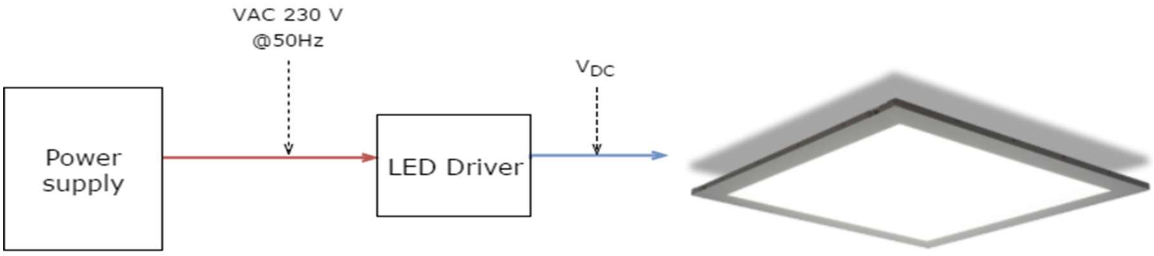

Figure 16: Lighting gear

The described techniques are implemented by manipulating the current delivered to the luminaire (more specifically, the V_{DC} section of Figure 16), Figure 17 presents a possible solution by implementing these techniques via a microcontroller.

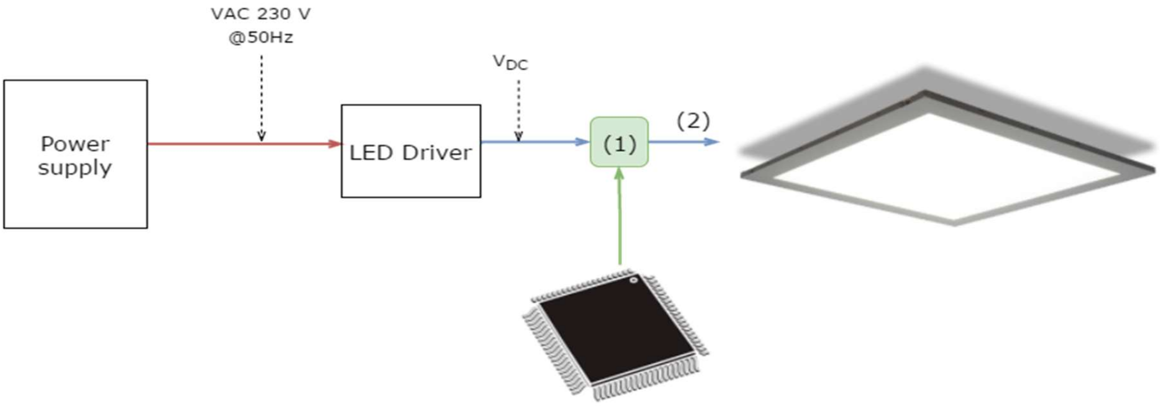

Figure 17: Potential dimming implementation

The *"(1)"* represents a regulating circuit capable of implement analogue or PWM dimming, this allows for the microcontroller to set the current delivered to the luminaire by either regulating its constant value or its mean value through a PWM signal.

Another possible solution is the use of a LED driver that supports dimming, i.e. a driver that has an input to regulate the output current delivered to the luminaire. This can be viewed as the previous solution with the regulation circuit embedded into the LED driver, it is advantageous because it represents a more robust solution and simpler to implement, especially when considering a large size implementation.

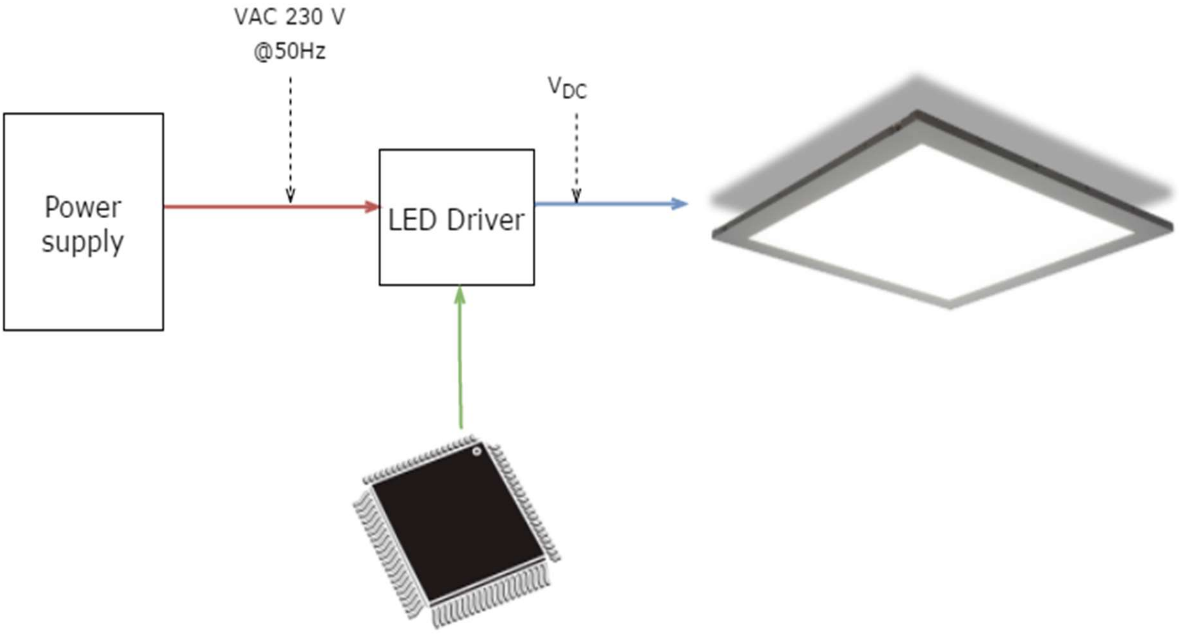

Figure 18: Dimming implementation through the LED Driver

The use of a LED driver with dimming avoids designing a dimming circuit, but requires a careful choosing of a fitting LED driver and the designing of a circuit to transform the signal from the microprocessor to LED driver. There are various manufactures and technologies but in the scope of this project the more fitted protocols are the DALI, DSI and 1-10V. [66]

It is important to note that using a LED driver to implement a dimming functionality the fundamental method of dimming is one of the described previously and still carries out their advantages and limitations.

The more viable solution is to choose a LED driver with dimming capability, it represents a more robust and efficient solution than implement a circuit operating under the power required to drive the luminaire.

Regarding the architecture of the LED Driver, a 1-10V driver would be the most fitted solution, a DALI or DSI driver implies that the microcontroller needs to mimic the frames used in these standards, this is especially problematic because they are based on Manchester Coding. Emulating this line of communication standard on a microcontroller is possible, however using it does not offer any advantage facing a simpler 1-10V implementation.

3.6. CONCLUSIONS

The proposed architecture presents an approach to building management systems based on new technologies and concepts that are beginning to gain presence and momentum into the market of lighting and building management systems. This market has been somewhat stagnated with proprietary technologies and protocols that hold back the potential interoperability of multiple building systems to achieve a higher energy efficiency.

Particularly, this system aims to correlate different types of information provided by the actuator and sensor network, it also aims to provide fast responsiveness and simple user interaction for an improved user experience. With that in mind the complexity of the system is masked by a simple yet powerful graphical interface to support the user interaction and usability of the system. All this is translated into physical action by means of actuators, one of the more important actuators is the luminaires as they represent a major part of a building energy expenses, having complete control and extended information about their status and functionalities can result in a major improvement in terms not only energy efficiency but also in user comfort.

Regarding the WSAN, sensor placement is determinant for the system performance, this is especially true for illuminance and PIR sensors, as poor placement leads to incorrect readings and therefor inappropriate responses that compromise not only the efficiency, but more importantly the functionality.

Focusing on the lighting gear**,** dimming the light output to adjust the illuminance level to each situation is an essential feature that has a major impact in the energy efficiency of the system, this can be accomplished by different methods but for the use of LED technology the more fitted methods are PWM and Analogue dimming. Considering the use of a microcontroller, the most reliable dimming solution is to implement PWM preferably through a 1-10V LED driver itself due to its simpler control.

4. DESIGNED PROTOTYPE AND LIGHTING ASSESSMENT

This chapter is divided into two main sections, the first is used to define the proposed system prototype, more specifically the topology, hardware used and the features and functionalities implemented. It follows the concept designed in the section 3.3.

The second section describes a lighting study performed via a DIALux simulation. It shows and justifies the assumptions made regarding the simulated space and gear and further explains the analysis conducted.

4.1. INTRODUCTION

The prototype needs to meet the system requirements identified in the section III.IV, so the second section of this chapter is dedicated to the selection of the used hardware, protocols and technology.

To validate the system as a viable solution for IT2 building, it is important to have a prior study supporting the use of the LED luminaires in the infrastructure. To do so, the DIALux tool is used to simulate the IT2 building and lighting installation, it serves the purpose of validating the system as a lighting solution by analysing it through the EN-12464 standards scope.

DIALux is also used to estimate the system long term energy consumption, it calculates an annual estimated energy consumption based on the infrastructure utilization and the lighting system capabilities. This provides an insight to an optimised set of supported features and configurations.

The idealized system in the previous chapter was translated into a working prototype to be subjected to tests. To consider this solution viable, the tests should be performed under conditions as close as possible to a real-world scenario.

4.2. SYSTEM OVERVIEW

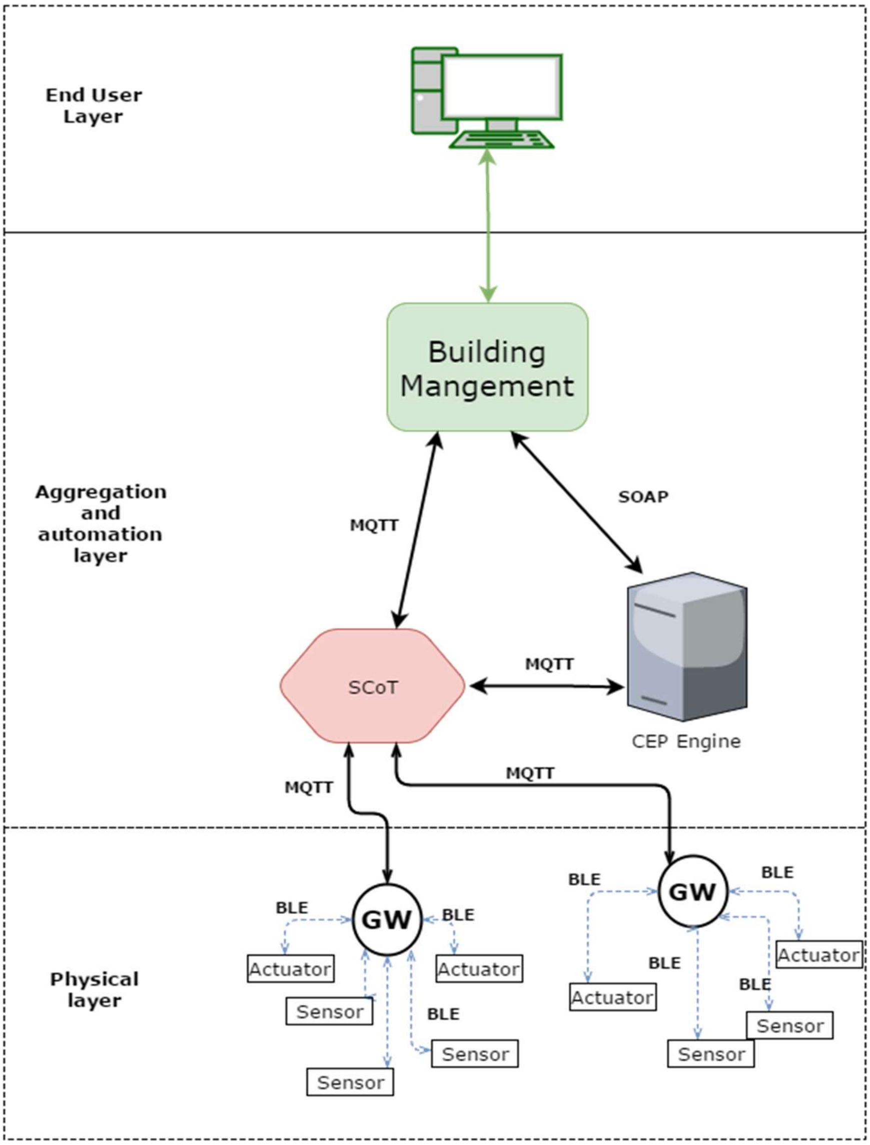

Figure 19: Prototype topology

Figure 19 shows the actual prototype configuration, compared to the ideally configuration showed in Figure 12, it is noticeable some compromises where made due to time constrains, namely the user interfaces. The aggregation and automation layer is based on the WSO2 Complex Event Processing (CEP) engine and communicates mainly by MQTT, using Simple Object Access Protocol (SOAP) only in the building management communication. Another difference is the use of the SCoT [70] (Smart Cloud of Things) platform that functions as a broker between the physical layer and the aggregation and automation layer. Extending this system to meet the demands of a large installation means expanding the WSAN with more sensors and actuators, so there is the need to have a standard model to exchange information and access the devices and to simplify the process.

It was implemented an object model based on the IP Smart Objects Alliance (IPSO) guidelines that defines the standard on which devices should be implemented and accessed.

i) OBJECT DEFINITION

An object is a standard representation of a sensor or actuator that structures its information resources. A single object can have multiple resources to be read and/or written e.g. a door lock actuator can have a resource to toggle the lock and another that shows the door's location. The first is most likely a read and write resource used to check if the door is locked (by reading its current state) and to actually lock it (by writing in its resource). The second can only be a read resource as the actuator cannot perform any action regarding its location.

A device can hold multiple objects types with their respective resources, so it is crucial that both object and resources are identified by a unique ID as presented in Figure 20 (left diagram). There can also be the case of a device with multiple objects of the same type as showed in the right diagram of Figure 20 (or an object with multiple resources of the same type). In order to coupe with this, it is associated an instantiation number with each object and resource. Therefor to access a resource it is necessary to specify the object ID and instantiation, and the resource ID and instantiation.

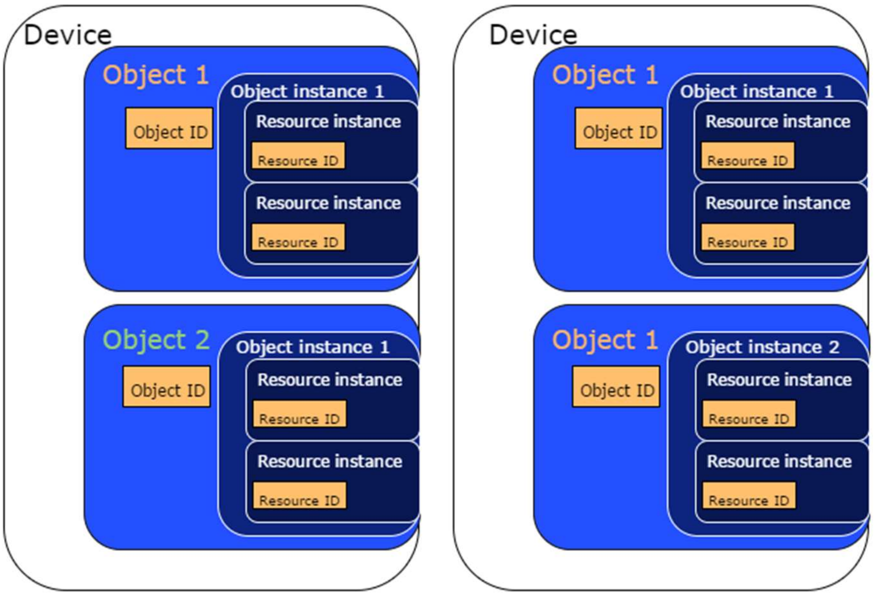

Figure 20: Object representation (left diagram represents a device with two objects of different types and the diagram on the right a device with two objects of the same type)

In a more practical sense, a device can be viewed as the hardware module idealized in the previous chapter (III.VI.V section) where different sensors and actuators can be added. Each sensor/actuator has a specific object model that is also associated with that device, e.g. adding a luminaire and a PIR sensor means that a luminaire and PIR object model with an unique ID are associated with that device. All this information is structured in a JavaScript Object Notation (JSON) for a simple and fast exchange of information.

In a first approach, the idea was to implement the object model at the device level meaning that the information would flow through the gateway to the targeted device based on the ID present in each JSON message. However, when confronted with the BLE protocol a different approach was designed.

ii) BLE IMPLEMENTATION

As stated in the second chapter, BLE is designed for short and small burst of communication, and although the JSON messages are not particularly large, the process of communication between gateway and device can be optimized. When comparing the structure of the BLE communication and the object topology, similarities are evident as showed in Figure 21, services can be compared to objects and resources to characteristics.

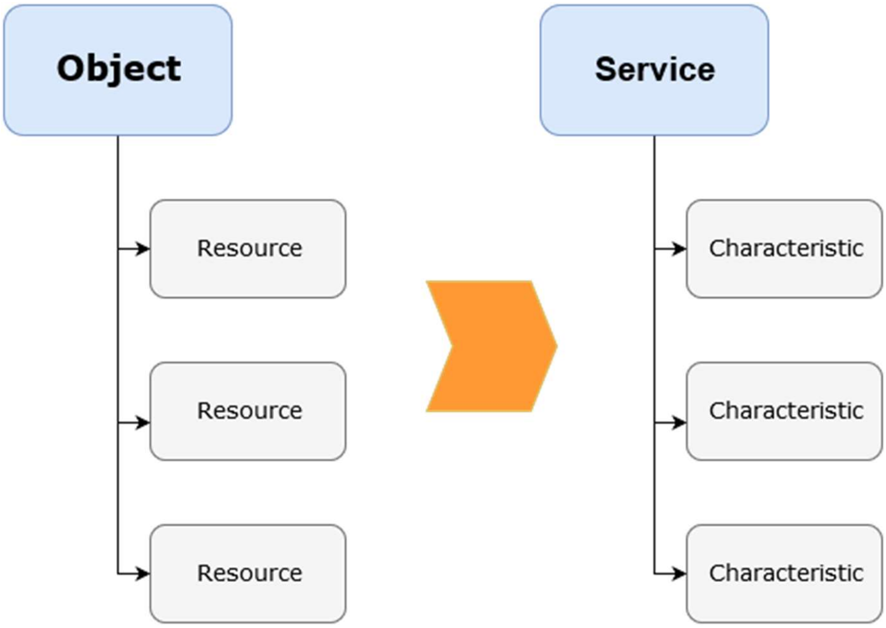

Figure 21: BLE and object model comparison

Taking as an example a light sensor with one readable resource that conveys the light level. When the system tries to read that value, it sends a JSON message with the object ID and instantiation, and the resource ID and instantiation. The gateway then parses the JSON to make sense of the operation and information required. It then accesses the required service of the specific device, serializes the gathered information into a JSON and responds to the request. This means that the object notion is implemented in the gateway that communicates with the devices through a BLE structured channel. So, one of the gateway jobs is to parse the JSON and reroute the information through each device characteristics and resources.

The first issue to be resolved is identification. Each object is linked to a specific device through the object ID, so in order for the gateway to distinguish between devices each BLE service UUID follows the principle showed in Figure 22.

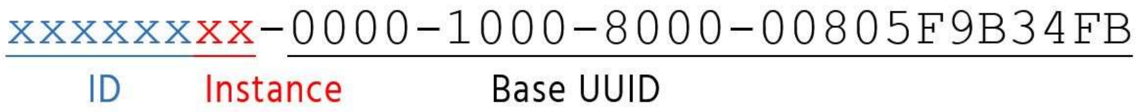

Figure 22: BLE UUID

The UUID is used to identify a resource by mapping the first 4 bytes to the resource ID and the last 2 for the instantiation. The remaining information concerns the base UUID that can be set to identity this project devices entity.

As an example, to turn on a luminaire the aggregation and automation layer would send a JSON containing information about that luminaire's specific physical device where, the object model ID and instance, the ON/OFF resource ID and instance and the value corresponding to the ON state. With this information the gateway calculates the UUID as explained, then through the BLE connection (with the specific physical device) it writes the value in the characteristic with that UUID.

Luminaire BLE Service

A device connected with the gateway through BLE, offers a set of services corresponding to the sensors and actuators that it manages. Most sensor services have just one or two characteristic (referring to the value that it reads), on the other hand a more sophisticated actuator like a luminaire offers an extensive service.

The advertised luminaire service consists of the characteristics showed in Table 3, one important detail is the use of the notify property for reporting information to the aggregation and automation layer. This means that changes in these characteristics will be reported, eliminating the need for a periodical reading.

Characteristic	Properties	Descriptor
On_Off	WRITE WITHOUT RESPONSE NOTIFY	bool
Log_dimmer	WRITE WITHOUT RESPONSE NOTIFY	uint8
Lin_dimmer	WRITE WITHOUT RESPONSE NOTIFY	uint8
On_time	NOTIFY	uint16
Dim_max_value	WRITE WITHOUT RESPONSE NOTIFY	uint8
Dim_min_value	WRITE WITHOUT RESPONSE NOTIFY	uint8
Time_high	WRITE WITHOUT RESPONSE NOTIFY	uint16
Time_low	WRITE WITHOUT RESPONSE NOTIFY	uint16
Auto_function_max_value	WRITE WITHOUT RESPONSE NOTIFY	uint8
Auto_function_min_value	WRITE WITHOUT RESPONSE NOTIFY	uint8
Dim_up_time	WRITE WITHOUT RESPONSE NOTIFY	uint16
Dim_down_time	WRITE_WITHOUT_RESPONSE NOTIFY	uint16

Table 3: Luminaire BLE service

The BLE connection was configured with an advertising interval of 1000ms, general discoverable mode and undirected connection.

These are the general and standard BLE configurations used for the tests performed, the final product may use a more optimised configuration. For example, devices can use the directed connectable mode with the address of its gateway to solely and directly connect with it instead of advertise a general connection. They can also operate with limited discoverability to avoid unnecessary advertising of their connection.

4.3. PHYSICAL LAYER SETUP

The previous section validated the system as a lighting solution and showed an estimation of the energy savings that can be achieved by implementing certain features. It is now necessary to test the system to understand if such a topology is a viable solution in terms of responsiveness and scalability.

The assembled prototype physical layer consisted of three nodes, more specifically two luminaires with PIR sensors and a sensorial node that included a light, temperature and a humidity sensor. The communication protocol used was BLE.

i) LUMINAIRE

The LED luminaire used in the prototype tested determine the basic layout and its output. The luminaire itself has 204 LEDs that are divided into 12 rows of 17 LED's (connected in series) connected in parallel, this prevents the total failure of the luminaire in case of a LED breakdown.

The 12 rows of LED make up for a square architecture. They point to the center of the luminaire through the diffuser that redirects and scatters light in a downward direction. The following figure shows the light intensity through a plane right under the luminaire at several heights.

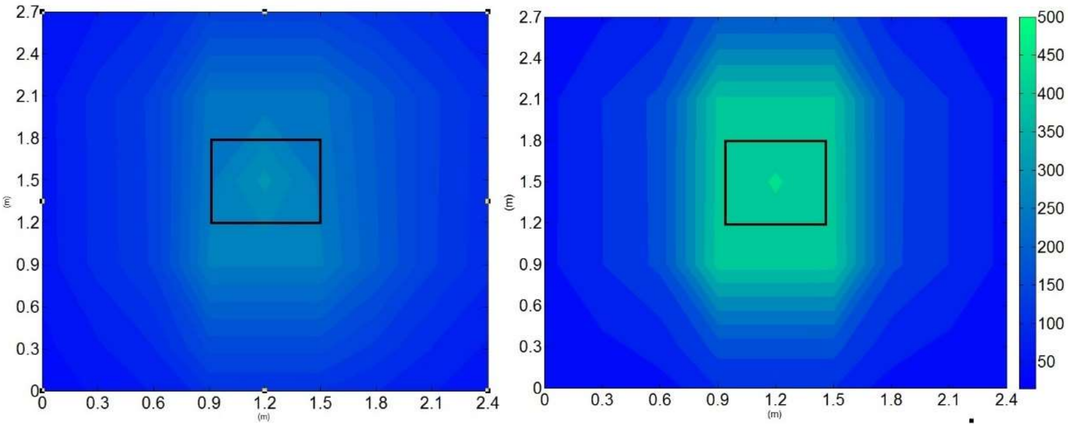

Figure 23: Light level measure at 1.4m (left) and 1m (right) from the luminaire

These measures were performed with a luxmeter at 1 and 1,4 meters from the luminaire. The points distant each other by 0.6 meters. These are useful to estimate the light level at user related planes, such as, at the eyes height or on a sit-down plane. It is important to understand that this measures are an over simplification of the process used to actually measure a luminaire light distribution curve that takes in account the luminaire's luminous intensity in different directions and planes.

Although the data in the Figure 23 is fairly simplistic: does not take in account reflections and is limited by the lux meter precision and the room dimensions, however it represents the luminaire's light output distribution that its used to define its virtual model. [70,71]

ii) LED DRIVER AND DIMMING SUPPORT

Following the conclusions set by the brief analysis of LED drivers in the section 3.5, the selected driver was a constant current RCOB-1050A by Recom Power that outputs 46W to power the luminaire. This part was chosen not only for the CC topology but also because it supports 1-10V dimming, meaning that it is possible to implement the dimming feature set in Figure 18.

Figure 24 shows the LED driver conceptual view, *DIM+* and *DIM-* represent wiring to the microcontroller that sets the dimming level proportionally to the voltage (between 0V and 10V) in these ports.

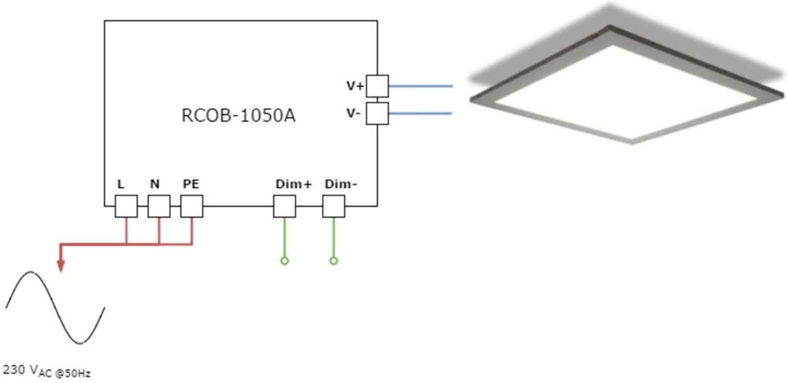

Figure 24: LED driver wiring

The output current was measured to determine its relation with the input signal. As expected, the current delivered to the luminaire is proportional to the control 0-10V control signal applied as illustrated in the Figure 25.

Initially, the concept was to convert a PWM signal from the microcontroller into a DC voltage between 0-10V using a low pass filter followed by amplification, to convert between 0V - 3.3V range to the 0V to 10V. However, upon testing the LED driver it was

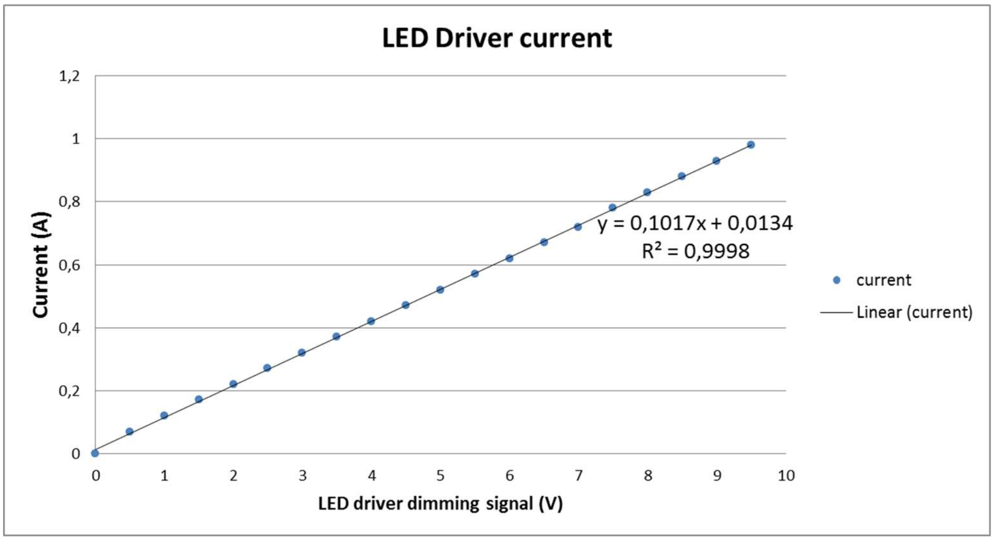

Figure 25: LED driver current output

noticeable that the *DIM+* and *DIM-* ports output 10V by default. To make up for a simpler circuit, it was used a MOSFET as a switch between this two ports, controlled by a PWM signal.

iii) MICROCONTROLLER

The microcontroller used for this project was the Nucleo-L476RG from STMicroelectronics. It is based on the ARM Cortex-M4 32-bit processor that operates at a frequency of up to 80 MHz and offers high-speed memories of 1MB Flash, 128 KB SRAM. Two major factors determined the use of this microcontroller, the first and foremost is the price hardware relation, and the mbed support, an online IoT device platform that offers several tools in the development of IoT solutions.

iv) IMPLEMENTED FEATURES

The luminaires provide an indispensable service. Interconnecting them with a building management system must not compromise its functionality in case of a system shutdown. A luminaire feature enables it to function autonomous from the rest of the system.

Dimming

One of the most important features identified in the section III.IV was dimming, it where then reviewed the main techniques used and how to implement them. The selected technique was to implement dimming through the LED driver by controlling the voltage at the 0-10V input of the driver, using a PWM signal.

The microcontroller, generated a 3kHz PWM signal, far higher than the minimum recommend to avoid flickering issues [73]. The light output measured is depicted in

Figure 26 where made with a lux meter right below the luminaire, they show that, as expected, the PWM duty cycle has a direct and linear relation with the light output, i.e. changing the control signal has a proportional response in light level.

This shows that it is now possible to control the luminaire's light level by setting the PWM duty-cycle. However, simply changing the control signal means that the light level will "jump" from the current level to the pretended. A far more user pleasant interaction would be to set a light level and have the luminaire brightness gradually changing.

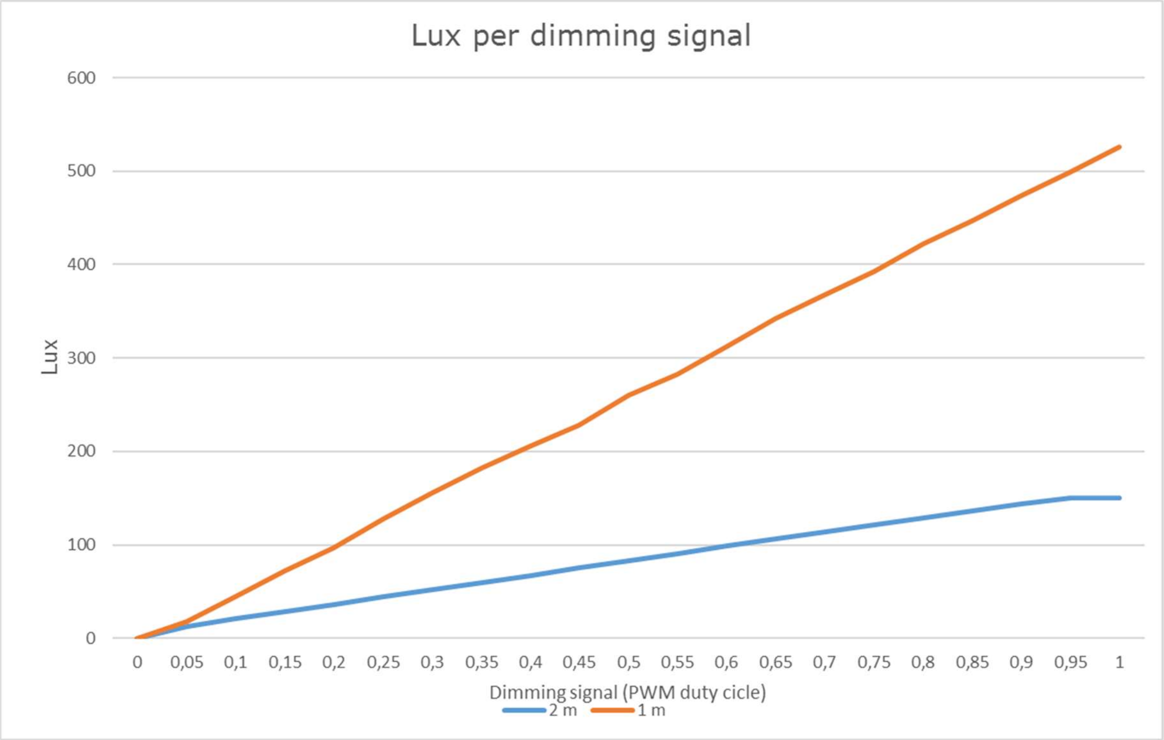

Figure 26: Light output in function of the control signal

The first and simpler approach was to implement a linear dimming curve that increased (or decreased) the light level by controlling the dimming signal with a fixed step. Altering the dimming level now implied multiple changes in the control signal. So, to make a more efficient use of the control unit, this scheduled changes are associated with a timer, leaving the processor free to other tasks. This is particularly important considering that one microprocessor unit could centralize more than one actuator and/or sensor.

It is possible to change the time interval in which the light level is changed (resolution). Although larger intervals mean less load in the microcontroller it also may translate in a transition were the user can perceive these small steps of brightness (or darkening). To give more control to the user over these transitions, this was implemented dynamically allowing the dimming time to be controlled.

Adjusting the dimming curve

A linear dimming curve also poses some issues regarding user confront, due to the fact that the human eye does not perceive changes in brightness in a linear fashion [74]. Some systems (like DALI) implement a logarithmic dimming curve to compensate the effect. The LED driver has a linear relation between the dimming signal and its light output (as seen in Figure 25), however the human eye perception does not. And so, to a lighting transition appear linear to a user, it must compensate the human eye perception.

There are two main laws that describe the human perception of physical stimulus, the *Weber-Fencher's Law* and *the Stevens' power law* [74,75], mathematically the *Weber-Fencher's law* follows a logarithmic relation between the stimulus and the perceived stimulus, as of the *Stevens' power law* it uses a power relation :

$$PS = k_w \ln S$$

Equation 2: Weber-Fencher's Law

$$PS = kS^{\alpha}$$

Equation 3: Stevens' power law

In which *PS* represents the *Perceived Stimulus*, *kw* the *Weber fraction*, *S* the *stimulus* and *k* is a proportional constant.

The α in the *Stevens' power law* is a factor used to adjust the equation to multiple physical stimulus, regarding brightness the valued used is 0.5 (usually between 0.3 and 0.5) [75].

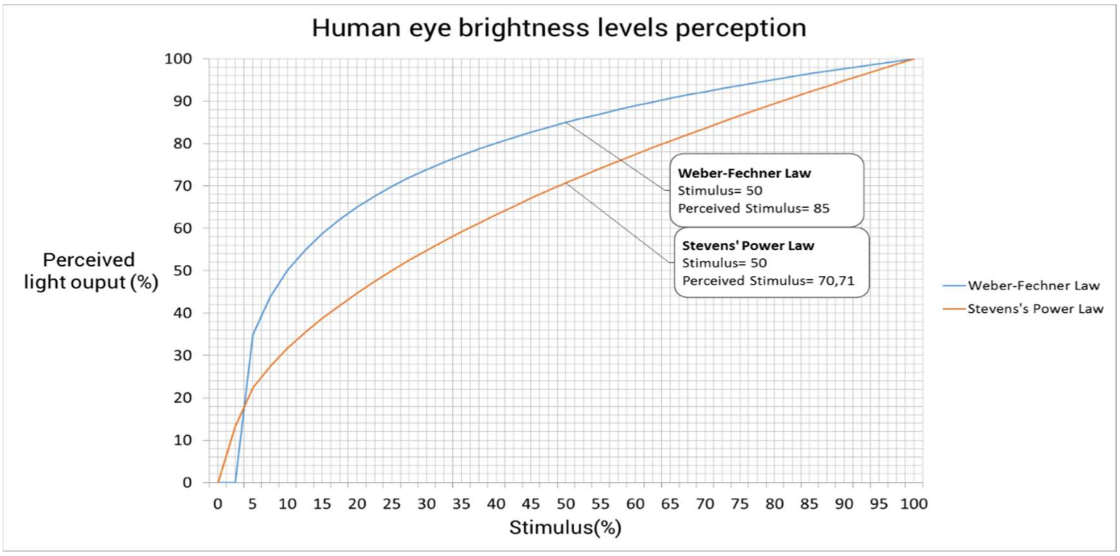

Figure 27: Human eye brightness levels perception

Both curves, represented in Figure 27, follow a similar relation between stimulus applied and the perceived light output. This two curves can match more precisely with if the Seven's Power Law uses a α of 0.3. However, *Stevens' power law* is considered to have a better and wider quantification of this relation [75]. So, on this project's work it was used *Stevens' Power* law to adjust the dimming curve with an α of 0.5. This also means that a lower brighten setting (in the user end) translate into slightly higher dimming settings in the hardware end.

Considering Stevens' power law, the dimming curve follows the equation:

$$PS = k * S^{\alpha} \Leftrightarrow \frac{PS}{k} = S^{\alpha} \Leftrightarrow \left(\frac{PS}{k}\right)^{\frac{1}{\alpha}} = S$$

As mentioned, α = 0.5:

$$\left(\frac{PS}{k}\right)^{\frac{1}{0.5}} = S \Leftrightarrow S = \left(\frac{PS}{k}\right)^{2}$$

Equation 4: Dimming curve equation

Being the stimulus the actual light output (that is linearly dependant of the PWM signal duty cycle) and the perceived stimulus the light level perceived by the user.

The dimming curve that relates user input set with the signal's duty cycle (that controls the light level), is represented in Figure 28. The duty-cycle values are normalized and *k* (the proportional constant) was set to a value of 2. This quadratic dimming relation allows to compensate the human eye perception.

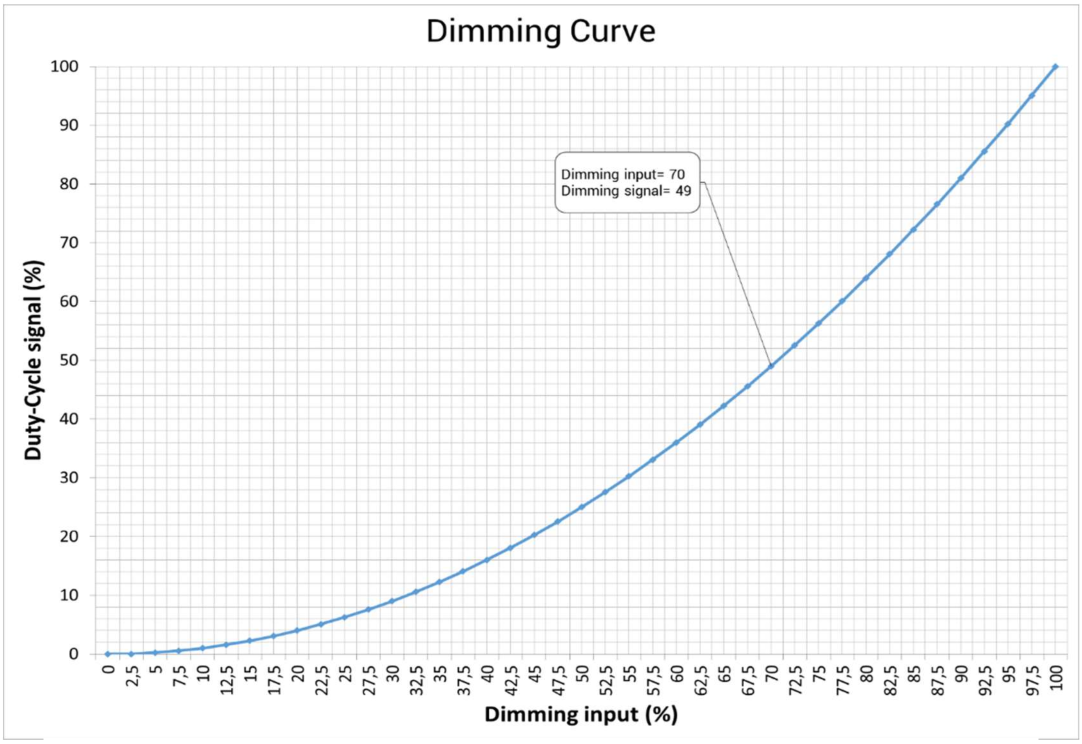

Figure 28: Dimming Curve

The parameter α can be adjusted to better suit users perception, as of default it is uses the value 0.5 [75].

Figure 29 shows an actual dimming transition where the input was changed from 0% to 20% and after 5 seconds to 100%. The quadratic nature of the PWM signal is more noticeable in lower light settings, and as expected the light output levels are also adjusted, meeting only at 100% as expected from Figure 28.

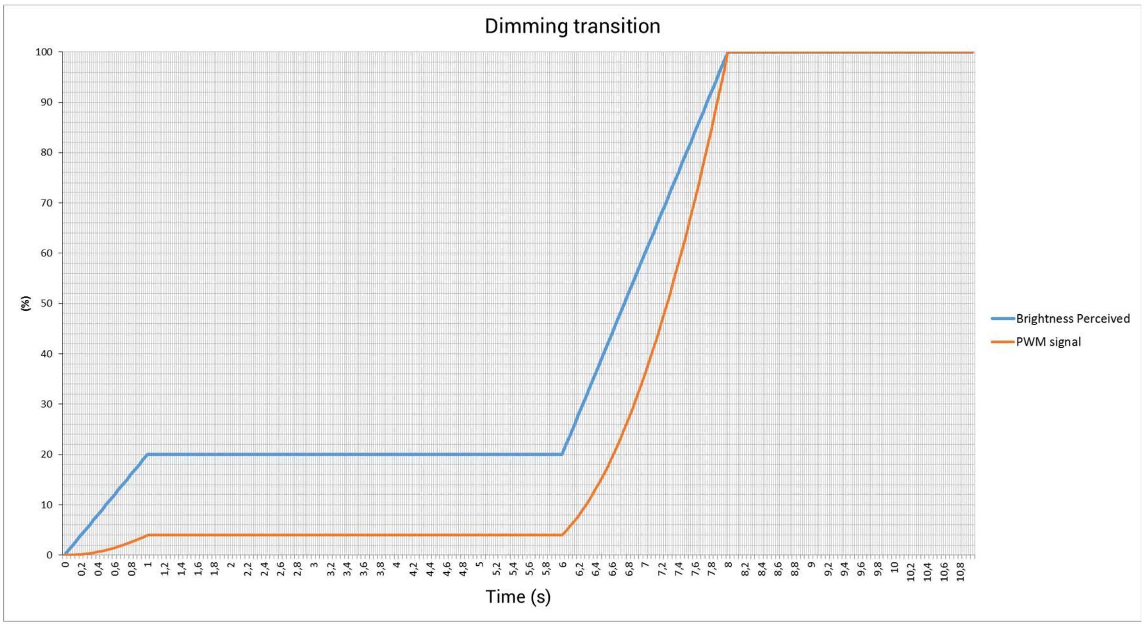

Figure 29: Dimming transition

Dimming profile

A dimming profile is programmed behaviour that defines the light output levels and the transitions of a luminaire. It is typically used as a response to a input, for example a presence sensor triggered. Using the dimming functionality, the following dimming profile showed in Figure 30 was implemented.

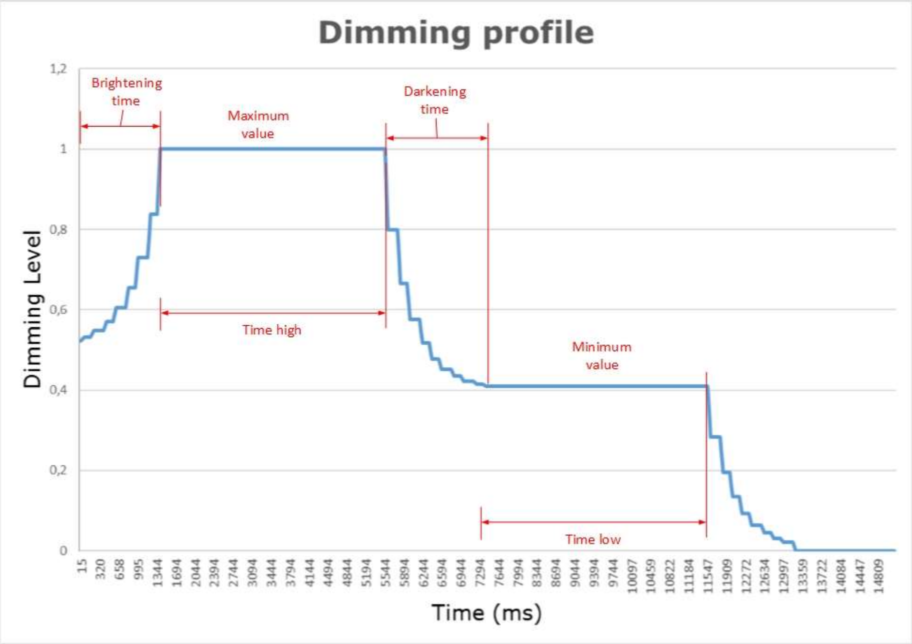

Figure 30 Dimming profile

The variables seen in Figure 30:

- ON state time
- OFF/DIM state time
- Minimum value
- Maximum value
- Fade-out time
- Fade-in time

Are all customizable, providing some freedom in adjusting the dimming profile.

This 3-stage dimming profile (high value to low, and finally to off) is quite common and often implemented in outdoor lighting systems with presence detection. It is embedded in the luminaires as a backup functionality but it can be used in non-task areas like corridors where the users usually just pass by. In a normal use situation, the system should illuminate the corridor area, meaning that a presence activation should trigger multiple luminaires.

This behaviour can also be implemented in the aggregation and automation layer. It has control of all the luminaires in corridors and the trigger of multiple luminaires is simpler. Another reason to implement it this way is the standardization of luminaires i.e. having the same behaviour and functionalities in every luminaire gives the system more flexibility to interchange and replace hardware.

Auto response mechanism

As a failsafe mechanism, an automated response of the luminaires to a presence signal is also implemented. The response follows the behaviour described in the Figure 31.

While operating under the auto response mechanism, sequential presence activations reset this behaviour. If a presence activation triggers the luminaire, it should set the high value for a certain amount of time, afterwards it should change its light level to the low value and if in this stage (or prior) another presence activation takes place, it should restart the whole behaviour.

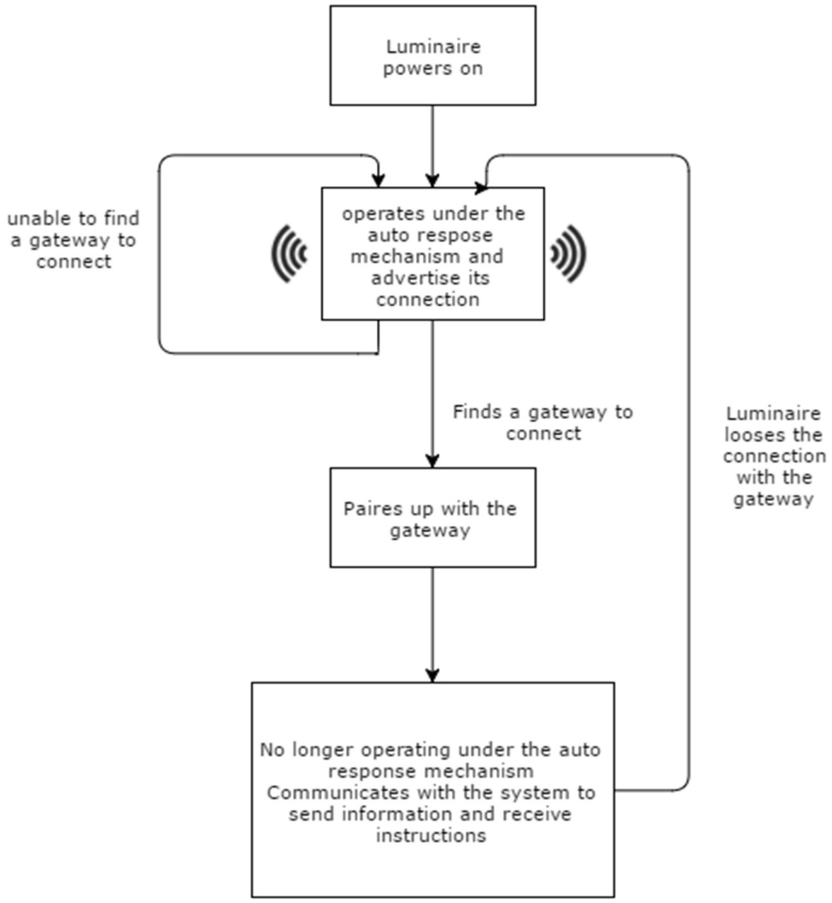

Figure 31 Auto response mechanism

When the microcontroller boots, it starts the to advertise its connection. In this stage this auto function is on and the PIR activation triggers the described behaviour in the luminaire. Normally this should be imperceptible to the user as the connection is established relativity fast. However this allows the luminaire to function normally even when it boots up and there is no gateway available.

When the microcontroller connects to the gateway, the auto response mechanism no longer responds to PIR activations and the luminaire's control is handed to the system. In case of a communication break, the auto function is reactivated and takes control, preventing its malfunction.

v) WIRELESS PROTOCOL AND GATEWAY

The decision of implementing BLE was based on many factors. There was an interest to study if BLE was a viable solution to these kind of systems. When compared to ZigBee in terms of performance and energy efficiency, BLE offers a higher performance energy wise. The fact that it is designed for periodic and small transmissions also fits the system architecture.

One point to consider when implementing the system is the fact that BLE does not have as much flexibility in networking especially when compared to ZigBee, so it important to design each WSAN within BLE physical limitations. However, BLE is a dynamic wireless protocol that is evolving and growing, with the prospect of higher communications rates and larger range in the next iterations of the protocol its adoption is validated. With this in mind, the gateway used was a Raspberry Pie 3 model B, it meets the requirements established in the section VI of the II chapter with the following features:

- 64-bit quad-core ARMv8 CPU @ 1.2GHz
- 802.11n Wireless LAN
- Bluetooth Low Energy (BLE)
- 1GB RAM
- 4 USB ports
- Ethernet port

One particularly interesting feature is the inclusion of BLE (over the previous version, Raspberry Pie 2). Having the BLE included into the board means less configuration necessary to run the protocol.

4.4. LIGHTING ASSESSMENT

To study the impact of installing this indoor lighting system in the IT2 building a simulation was performed in DIALux Evo 6.1 software. The point of the simulation was to validate the lighting system in the scope of the EN-12464 and to estimate the energy consumption improvement of features such as dimming and presence information.

The first step was to design the IT2 building model, to do so, the building plant was used to replicate the structure. Then the lighting infrastructure was recreated with the luminaire's virtual model. A set of calculations were performed in each space to check if its lighting components comply with the minimums set by the EN-12464. An energy consumption analyses was also performed considering the features implemented.

i) BUILDING PLANT

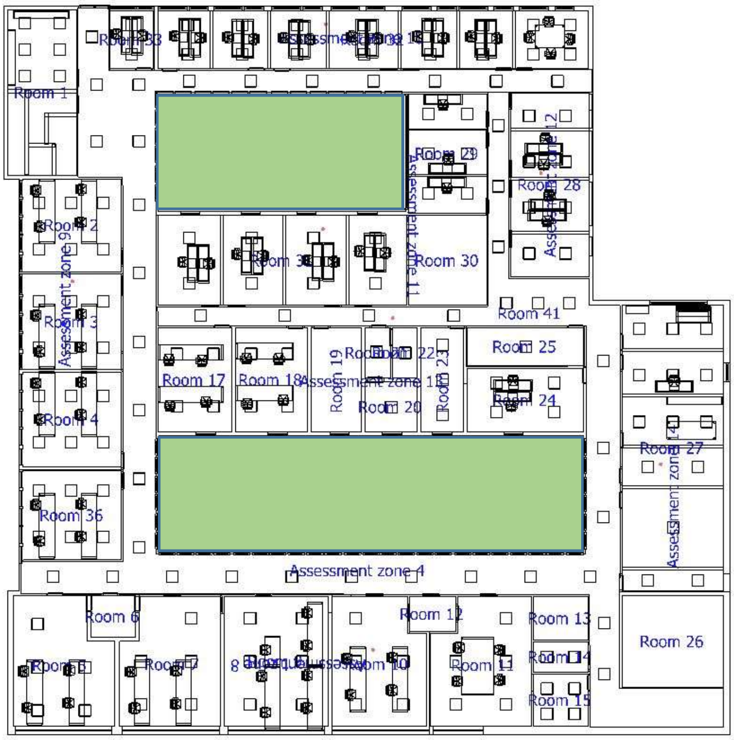

Figure 32: Simulated plant

Figure 32 represents the model overview, it was designed based on the building plant, luminaires positioning is based in the actual lighting infrastructure. Relevant to the simulation, it was also considered the building orientation and the placement of windows and doors.

Regarding lighting, the simulation focuses on office, meeting rooms and corridors, these comprise the majority of the space. The areas represented in green are in fact open spaces that transmit natural light into the adjacent spaces.

ii) LUMINAIRE MODEL

Usually these simulations are performed using the luminaire specific model, however in this case due to the lack of manufacturer information, the simulation used a generic LED luminaire model with the same topology, consumption and light output of the physical one.

Figure 33 shows the isolux diagram from the DIALux model (left) and the one measured from the physical luminaire (right). They were both taken at 1 meter form the luminaire, it is important to acknowledge the physical measurements limitations, more specifically the reflections contribution (from walls for the most part), the uncertainty inherited from the lux meter reading and the lack of resolution and space for a more precise diagram. However, it is possible to notice a similar lux distribution in function of the distance from the luminaire between both diagrams, specially right below the luminaire.

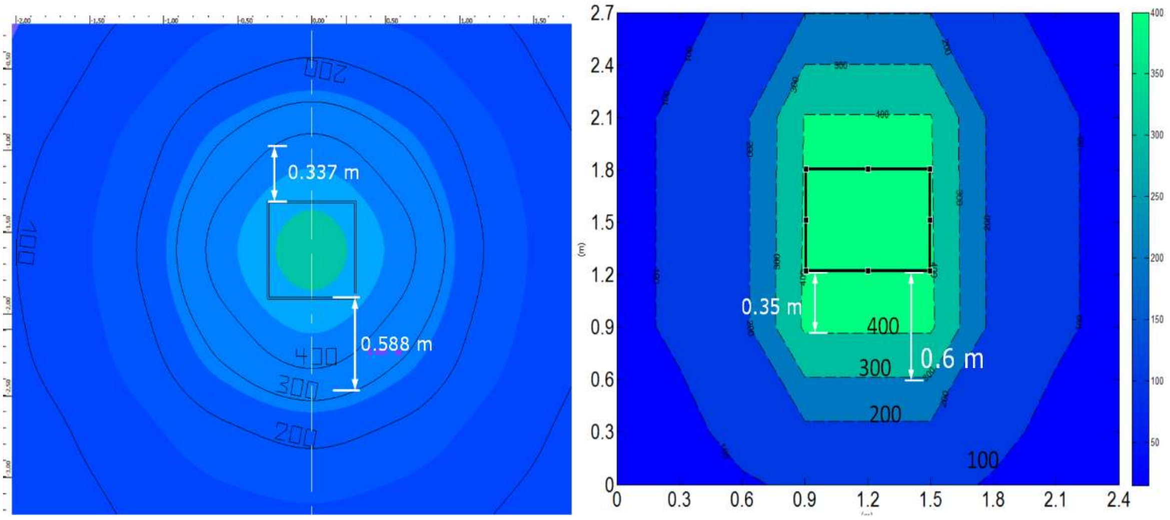

Figure 33: Luminaire isotropic lines, on the left the virtual model and on the right the measured data from the physical luminaire

The simulation model shows slightly higher lux levels in the luminaire's periphery, this difference is more notorious further away from the center. The isolux diagram from the physical luminaire also shows less light distribution in the horizontal perspective. Beyond that, the diagrams show a similar light intensity output pattern that validates the DIALux model.

The light distribution curve for the luminaire's virtual model is showed in the Figure 34, as expected both the curves (from perpendicular planes) match because of circular distribution.

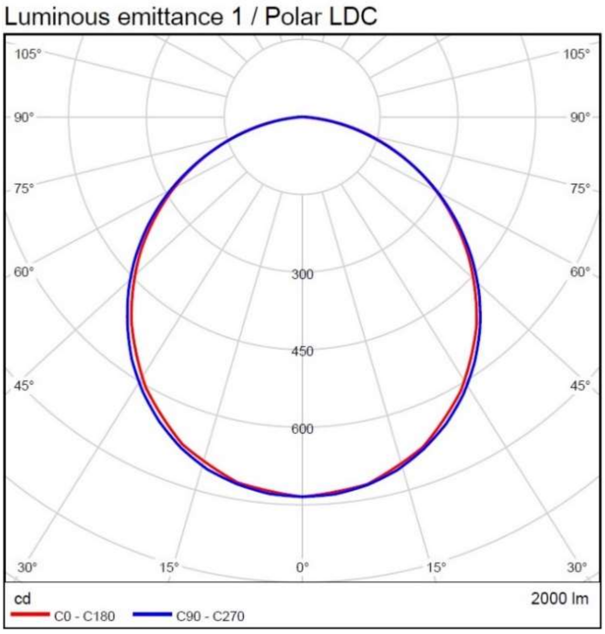

Figure 34: Luminaire actual light distribution curve

iii) LIGHTING STANDARD ANALYSIS

One of the goals for this simulation is to assure that each room follows standards set by the EN-12464-1. More precisely the lighting requirements in an office space and corridors. The simulation was performed in 3 different scenarios, low, high and no daylight, in order to check the lighting requirements with different light contributions.

As explained in the section i), the areas seen in red and white from Figure 35 correspond to internal gardens, that allow a significant use of natural light. The figure is from the DIALux simulation with the luminaires turned off to show the impact of natural light (around 12am). The natural light influence is mostly located in corridors and a number of small offices.

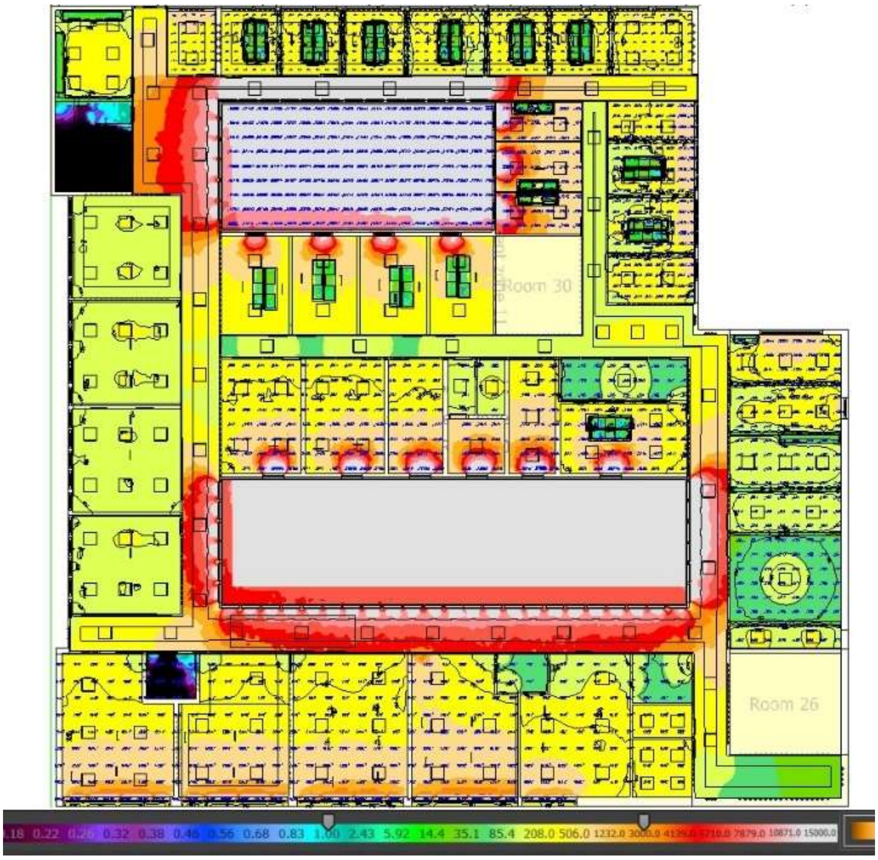

Figure 35: DIALUX simulation with daylight

Obviously, natural light distribution changes dynamically in the course of a day and to maximize its use the lighting system should adapt gradually. Taking the corridors in Figure 35 as an example, individual control could help avoid situations where multiple luminaires are turned on when in fact there is only need to illuminate the space with less daylight contribution.

Lighting standards

The building can be divided in corridors and office rooms due to their considerable different lighting needs. Other spaces like bathrooms and storage rooms are not taken into consideration because they have different lighting requirements.

It is crucial that the system guarantees at least the minimum lighting levels established by the EN-12464. The analysis focus in cylindrical and vertical illumination, task areas and other lighting components (modelling, lighting uniformity, etc.). Due to the considerable number of offices, only one example is showed, as the procedure and requirements are the same for the other offices even without natural light.

Office 9 room

The office room is facing the building's southeast side and the simulation was performed under a low daylight scenario.

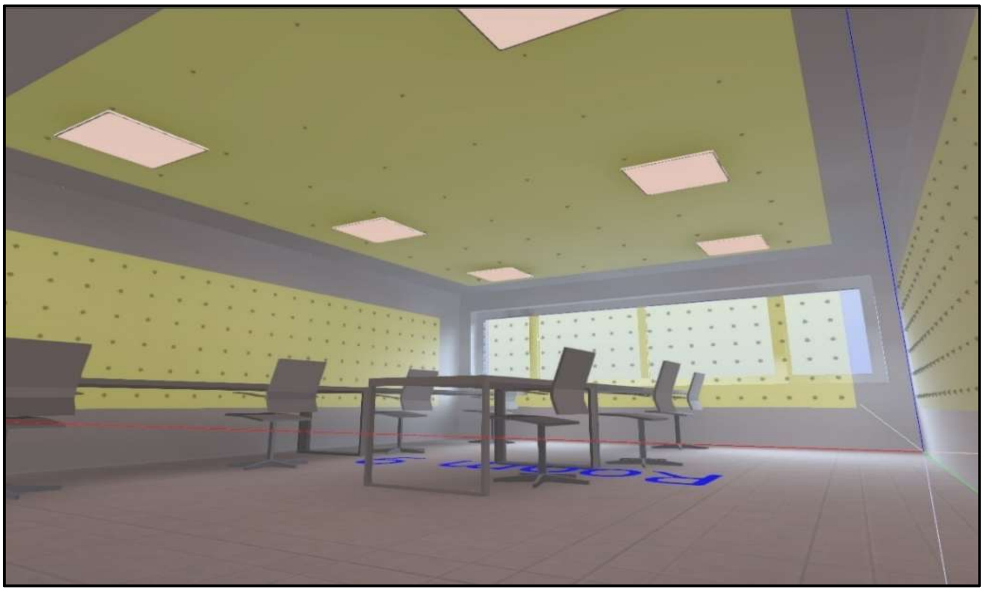

Figure 36: Office 9 view

Figure 36 shows a rendered view of the space, the yellow rectangles represent calculation surfaces (although being present, not all calculation surface for this space are represented in this perspective), the walls and ceiling surface calculations are used to compute the vertical illumination. Another important measure is the workplane lighting because it directly affects the user comfort and his ability to perform certain tasks, Figure 37 details this measure.

Figure 37: Office 9 Workplane area

Task Areas

As reviewed in the EN-12464, it is possible to create individual tasks areas in workspaces, maintaining the task area lighting requirements means that the rest of the workspace can have an overall lower illuminance. This is particularly advantageous for larger spaces where having a lower illuminance in the general workspace can prove to be a significant energy consumption cut. Even though that this is not the case for this room, this implementation is simulated in the Figure 38 to show that, if necessary, it is possible to extend this mechanism to larger rooms.

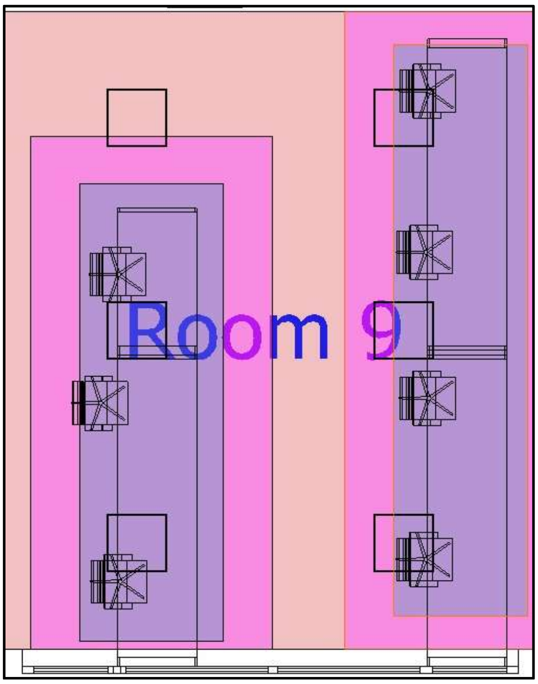

Figure 38: Office 9 task area

Both task areas have 3 main components, the actual visual task area represented in darker purple, the surrounding area represented in pink and the background are that refers to the remaining space. Instead of having a uniform workspace with the required 500lx, it is possible to focus these standards in the specific area where the task will be performed.

Corridors, hallways and other general areas have significantly lower standards, and require only that a minimum vertical illumination, modeling and cylindrical illumination values as showed in Figure 39.

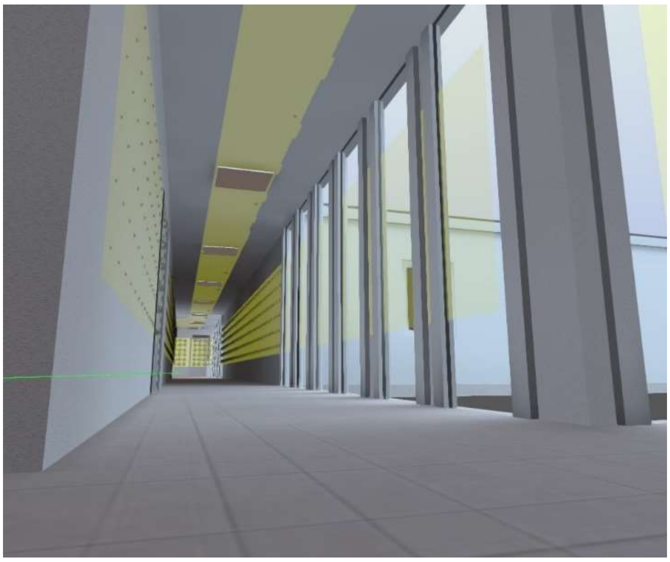

Figure 39: Corridor

Energy consumption

The energy consumption calculations are made in conformity with the EN-15193. For this simulation the main goal is to understand the energy efficiency impact of adding lighting features to the system. With this in mind the simulation was performed considering key factors like natural light availability and building orientation, other factors like occupancy dependency and usage time where estimated due to the time spawn required to measured them [77].

Simulation parameters

The idealized system operates by automatically turning on a luminaire in the presence of a user, in office spaces the luminaire is turned off when a user leaves the area, however in the corridors they dim down (following the behaviour described in the section 4.3), so both of these situations must be considered independently.

According to the EN-15193 the most efficient mode of operating is when the luminaries are turned on manually and off automatically, this assures that the luminaires only turn on when user's intents to do so. Ruling out situations where luminaires are turned on without actually being needed to, may prove a small increase in energy performance, however they also require user interaction.

The simulation was then performed with the following parameters:

Corridors:	auto on /dim
Offices:	auto on / auto off
Absence factor for corridors:	0.5
Absence factor for offices:	0.2
Hours of day operation:	3500 per year
Hours of night operation:	240 per year

This set of parameters means that a user spends around 9,6 hours a day in the building (3500 hours yearly), he is absent from his office roughly 2h. The same principle is applied in the corridors, half the daily hours that the building is in use no one is passing through the corridors. The number of night time hours that the building is being used, considers 4 months (between November and February) of less daylight time. For that period the estimation was of 2 daily hours in which the building is used normally and there is no daylight.

These assumptions overestimate the building use, considering that the normal user works around 9 daily hours weekly, this means that at least in the weekends the building use should be minimal, driving down the total of use hours per year. Overestimate this factors may lead to energy consumptions higher than the real building would present. However, it is important to stress out that the point of the simulation is to analyze the impact of implementing some lighting features, instead of precisely estimate the value of the building energy consumption (that will be available when the system is implemented.

4.5. CONCLUSION

The assembled prototype stands as the groundwork for the following iterations of the system, it does not include all the features and functionalities idealized but it operates under the selected technologies as intended and it has the potential to growth and include the missing features. It covers the main requirements identified in the section 3.2.

The simulation models were designed in line with the physical models (the luminaire and the building). A set of parameters had to be estimated for the energy consumption analyses that will show the impact of the features endow to the lighting system.

5. RESULTS AND FUTURE WORK

The following chapter shows the results from the prototype evaluation and the simulation, this data is used to validate the proposed solution in a practical and performance perspectives, i.e. to decide if the use of technologies like BLE and CEP are an added value to this kind of systems without compromising the user experience.

5.1. PROTOTYPE

The assembled prototype was based on the configuration showed in Figure 19. It was comprised by three physical devices, a gateway, a device simulator, a broker (SCoT platform) and the CEP engine. This last three elements resulted from two other dissertations work.

The device simulator was used to emulate a number of devices with the purpose of increasing the load in the platform, this way the results measured with the physical devices should be closer to a real scenario. The three physical devices were comprised by two nodes with a luminaire and a PIR sensor, and a third node with temperature, humidity and illuminance sensors (also developed in another dissertation work).

i) TESTS PERFORMED

It is possible to change the resolution in a dimming transition, increasing this parameter means that the microcontroller calculates more points when dimming to present a smother dimming curve. However, this also means more load in the microprocessor. This was tested by setting a dimming transition and collect data using two different resolutions. For this tests, the microcontroller returned every control signal value to a terminal. The same procedure was used to registered the PWM control signal in a dimming transition referring to the dimming profile behaviour.

Latency

The prototype was also evaluated in terms of latency, a fast response time is one of the most important factors performance wise. Being able to respond to a user request or presence detection with a sub second time period is imperative to the system integration. Not all information requires a fast response or reaction (like the temperature or humidity data), but it is necessary to measure the latency of the *action to reaction* when the system is under a normal load.

To simulate the load in the system, the device simulator emulated 679 simulated devices that generate the following set of information:

- Temperature and humidity sensors generate events every 10 seconds
- Illuminance sensors generate events every 5 seconds
- Motion sensors generate events with a random periodicity between 1 and 10 seconds

The overall delay of the system was measured as the time between a PIR activation and the luminaire reaction. The activated PIR generates an event and an impulse at microcontroller's port, when the command for the luminaire activation arrives at the same physical device it also generates an impulse. The time gap between them represent the system delay. It was also possible to measure the BLE communication delay using the same principle between the microcontroller and the gateway, the time gap between those two devices was measured with an oscilloscope.

ii) RESULTS

Figure 40 shows a dimming transition with 0.2 and 0.05 seconds of resolution, even though the transition with 0.2 seconds resolution might be acceptable and perceived as linear by the user, if the transition time is configured to a longer setting that may not be the case. Because each step is further from the next, the user may perceive a "bumpy" transition.

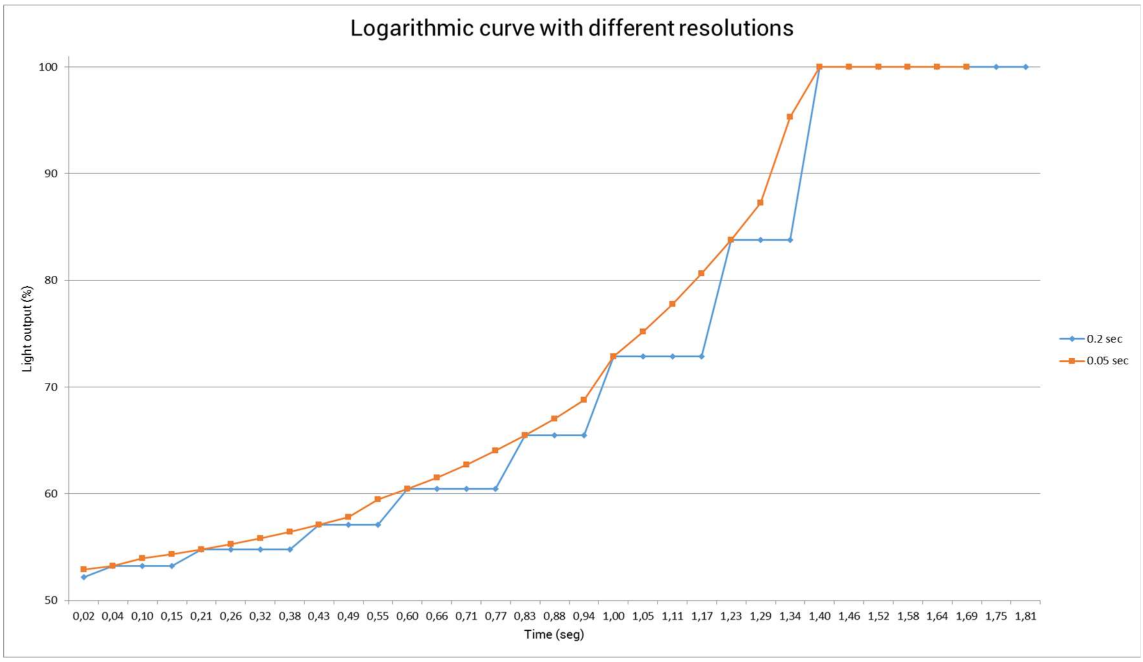

Figure 40: Logarithmic curve with different resolutions

Adding more points to each dimming transition fixes this issue but it also requires more calculations. In the tests conducted, having a resolution of 0.05 seconds presented smooth dimming transitions over different transitions times without compromising other microcontroller tasks.

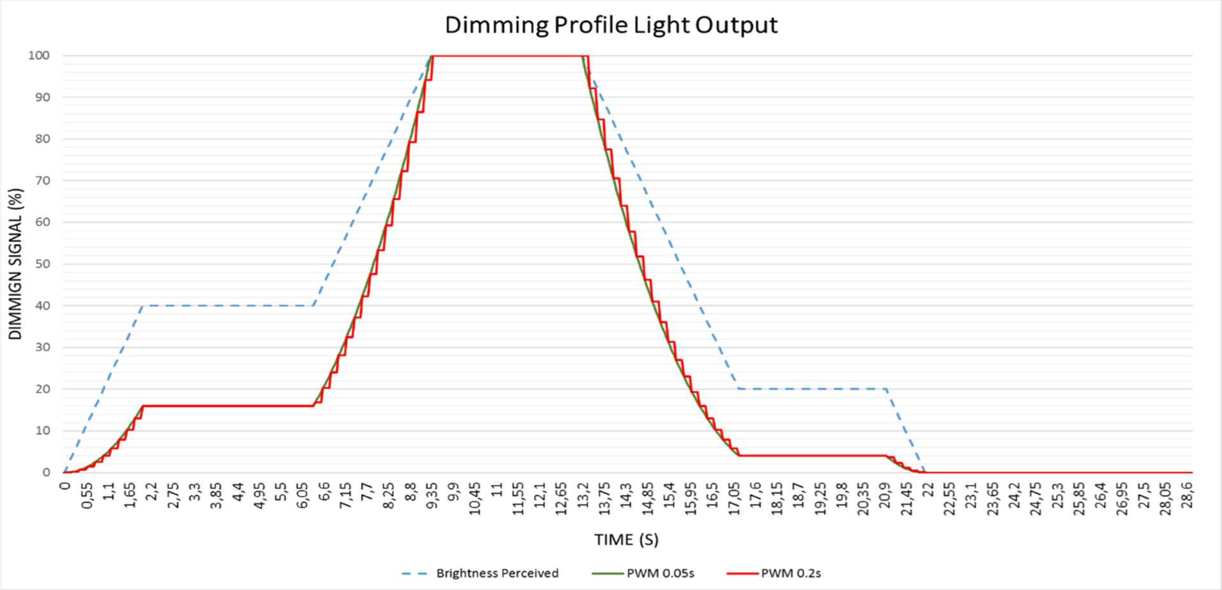

Figure 41: Dimming profile Output

This is further illustrated in the Figure 41 that shows a dimming transition were it is noticeable the effect of the dimming curve used to compensate the user perception.

Response time

This measure was performed 86 times, the average delay of the system presented in the *Table 4* :

Average Latency	149,27 ms
Minimum Latency	68,12 ms
Maximum Latency	379,52 ms
Standard Deviation	55,95 ms

Table 4: System responsiveness

In the same manner, the BLE communication delay was measured as 79 ms. The general latency of the system is around 150 ms, it is a good reaction time for a lighting system considering that response times around 0,1 seconds result in a feel of instant reaction to most human users [77].

5.2. SIMULATION RESULTS

Lighting components evaluation

The DIALux simulation results referring to the EN-12464, are presented in the Table 5 and Table 6, they measure the room 9 lighting components in three natural light settings.

	Average illuminance			**Illuminance Uniformity (Uo)**		
	No daylight	**Low daylight**	**High daylight**	**No daylight**	**Low daylight**	**High daylight**
Ceiling	172 lx	388 lx	748 lx	0.20	0.23	0.17
Wall	249 lx	471 lx	687 lx	0.77	0.61	0.5
Wall	264 lx	572 lx	1502 lx	0.35	0.54	0.68
Wall	261 lx	492 lx	1126 lx	0.81	0.66	0.56
Wall	284 lx	408 lx	839 lx	0.74	0.80	0.77

Table 5: Room 9 Vertical illumination

	Average value		
	No daylight	**Low daylight**	**High daylight**
Modelling	0.55	0.73	0.93
Cylindrical illumination	329 lx	541 lx	1348 lx
Workplane	392 lx	846 lx	1542 lx

Table 6: Room 9 lighting components

This measures where performed with the luminaires turned on at 100%, meaning that the exceedingly high values present in the simulations with daylight can be adjusted with the dimming functionality and the use of blinders and window shutters.

The only value that does not comply with the minimum standard from the EN-12464 is the workplane average illuminance with no daylight. It has a value of 392 lx when it should be at least 500 lx, it is not a significant difference and this can be resolved with complementary light sources.

Task area evaluation

The results from the task area set in the room 9 are presented in the Table 7:

	Average illuminance			**Illuminance Uniformity (Uo)**		
	No daylight	**Low daylight**	**High daylight**	**No daylight**	**Low daylight**	**High daylight**
Task area	413 lx	748 lx	954 lx	0.61	0.44	0.37
Surrounding area	371 lx	561 lx	712 lx	0.67	0.5	0.48
Background area	245 lx	326 lx	548 lx	0.44	0.33	0.11

Table 7: Room 9 task area lighting measures

Instead of having a uniform workspace with the required 500lx, it is possible to focus these standards in the specific area where the task will be performed. In this particular case, the average illuminance is well over the required mainly because of the daylight contribution. It also affects the illuminance uniformity (minimum divided by maximum illuminance) by contrasting the strongly lit windows side with the opposite side of the room. This can easily be adjusted by using the window shutters to partly block the daylight contribution. In this particular case, setting one of the task areas represented in Figure 38 in a typical low daylight scenario, means that the luminaires from the opposite side of the room can be turned off because they have a low impact in this task area lighting.

Energy evaluation Results

With the simulation parameters described in the previous chapter, the annual energy consumption of the building is estimated to be:

	kWh/year	**LENI (kWh/m²/year)**	**Costs (EUR/year)**
LED consumption	26750-33900	11-14	2967 - 3766
LED with auto control on	25150-32000	11-14	2892 - 3678
LED with constant light adjust	23100-29450	10-13	2676 - 3386
LED with constant light adjust and “manual on”	22050-27900	10-12	2534 - 3208

Table 8 : Consumptions with different configurations

The *LED consumption* measurement represents the annual energy consumption with the luminaires operating with the traditional on/off controls. The "LED with auto control on" considers the same LED luminaires but with presence control, operating accordingly to the parameters presented. Operating under the idealized system, the "LED with constant light adjust" uses the presence and light level control. A final consideration was made using the manual on/auto off setting in the luminaires to contemplate the impact of this implementation upon the idealized system.

It was also analysed the building energy costs in a year span just with lighting, this was calculated based on the last year price of kWh in Portugal [78].

6. CONCLUSIONS

Applying the IoT concept into a building management system allowed an unprecedented level of freedom regarding operability between services, technology and hardware used, potential interfaces and supported features.

Although systems based on older protocols and technologies can have a sophisticated level of interaction, they are still limited by the hardware supporting them. These constrains can exist at different levels, from the number of devices and system responsiveness to the actual physical installation. Developing a system that is, at its core, supported by open source technologies provides the freedom to combine different technologies and protocols to overcome these limitations. The use of IoT technologies also integrates the system in a concept that it is growing and evolving to potentially set a new standard of device integration and interaction.

The new functionalities endowed to the lighting system serve both the purpose of energy efficiency and user interaction, controlling and customizing the luminaires can be done by communicating through the system or even directly to the hardware via BLE, present in most smartphones and tablets. As seen through the simulation, functionalities like dimming allied with sensorial information proves to be a significant factor in increasing energy efficiency. The same logic can be applied to other services like HVAC (heating ventilation and air conditioning), extending the system control was also a design concern, the purpose of object models and a hardware module was not only to cope with a large number of devices but also with different types.

From the evaluation conducted it is possible to note four major points:

- The lighting deployment in the IT2 building is a viable solution as it meets the EN-12464 lighting requirement;
- The energy consumption simulation showed that daylight harvesting can improve the building’s energy efficiency by 20%;
- The system can handle a considerable number of devices simultaneously;
- And it is capable of responding with an average latency of 150ms, being the worst-case scenario under half a second;

Regarding the future work for the project, the most urging point would be to address security issues, ranging from the adjustment of the BLE advertising connections, to the validation of users and devices in the system. Another major improvement would be evolving from the prototype hardware into a more dedicated platform, trading the Nucleo development board with a more solution specific hardware.

Finally, a potential improvement point can result from the BLE protocol evolution, the Bluetooth Smart Mesh Group is working to include mesh functionalities into the BLE protocol (some proprietary solutions are already in place). This means that the BLE network can be evolved into a more reliable and dynamic BLE network. The commitment in evolving BLE as a IoT wireless communication protocol is quite present in the Bluetooth SIG, this is one example of how the use of these technologies supports the system evolution into a more reliable, efficient and a modern solution.

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8. ATTACHMENTS

SmartLighting - A platform for intelligent building management

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Abstract. This work proposes a solution to endow buildings with efficiency and intelligence, exploiting the advantages of Complex Event Processing (CEP) techniques and Internet of Things (IoT) principles. This combination allows efficient management of the entire infrastructure, and in particular enabling lighting to be tailored to users' needs. We validate this solution through a prototype implementation, based on wireless sensors and actuator networks that interact with the environment, using standard lightweight protocols designed for IoT. The prototype is based on high performance and real time platforms, and complex methods for analysis of large streams of data. The implementation is applied to a real world scenario, and will be used as the standard solution for management and automation of an existing building.

Keywords: Internet of Things, Complex Event Processing, Wireless Sensor Networks, Building Automation

1 Introduction

A large share of the global energy usage is taken by buildings, whose number and size keeps growing. This creates a need for energy efficient solutions which led to the growthof Building Automation Systems (BAS), whose primary goal is to achieve significant energy savings. This is done by efficiently automating the differentsystems inherent to a building, such as lighting, Heating, Ventilation and Air Conditioning (HVAC), and CCTV to name a few. Current solutions focus in full integration, where the automation rules cover multiple subsystems, providing a unified management solution.

In order to allow the integration of the different systems, and interoperability between different devices, several standards have emerged, such as BACnet, LonWorks and KNX, among others, and also DALI as the most used standard for lighting control [1].

With the Internet of Things (IoT) revolution, new solutions have been presented, specially designed for constrained devices. IEEE 802.15.4 was one of the first standards targeting Low Rate WPANs (LR-WPANs), but it only specifies the physical and MAC layers. Thus, 6LoWPAN was standardized to carry IPv6 packets within small link layer frames [2]. Taking advantage of these two standards, other communication technologies have emerged, which is the case of ZigBee and Bluetooth Smart (BtS), and in a near future the Wi-Fi HaLow [3].

Regarding higher layer protocols, MQTT and CoAP are the most commonly adopted for constrained devices. They offer extraordinary performance and various features, while working at minimum bandwidth. Moreover, despite not being designed targeting the IoT, AMQP and XMPP have been evolving towards it, and now play an important role on it.

Furthermore, the number of devices used in IoT solutions, namely in smart buildings, are increasing rapidly. This increase creates many issues related to device management, which must be solved considering a vision of autonomous behaviour. For this reason, several standards were created for dealing with device management in IoT systems. The most known device management solutions include TR-069, a technical specification that defines an application layer protocol for remote management of end-user devices which was published by the Broadband Forum entitled CPE WAN Management Protocol. The Open Mobile Alliance (OMA) Device Management (DM) Working Group also specified a device management protocol, OMA-DM. The OMA-DM specifications defines the protocols and the mechanisms allowing a server to deliver configuration parameters to a client, by using a defined set of Device Management Commands for various management procedures to be executed inside a well-defined and secure environment (DM Session). Furthermore, there is also Lightweight M2M, a standard that defines the application layer communications between an LWM2M Client (located in a device or gateway) and an LWM2M Server.

The problem with the first two solutions is that they were created to work in Telco environments, not considering constrained devices, thus the need for other more lightweight solutions. Moreover, having a device management standard does not magically enables device operation, in other words, a standard only helps us to define the interactions between devices and service applications. To be able to properly operate millions of devices, a proper object representation is required. This will map devices into objects, enabling rich interactions with many, heterogeneous devices. In this area, the most accepted are the ones specified by ETSI M2M, which tend to be complex, and the ones specified by IPSO, that proposes the LWM2M object specification and is tailored to constrained devices.

Regarding the automation logic that operates over the sensor objects, this requires mechanisms for analyzing and processing heterogeneous sources, issuing commands with very low latency. Examples of low latency processing systems are open-source Apache projects, such as Apache Storm and Apache Spark for, respectively, stream processing and batch processing. An alternative approach, more suited to this environment, considers solutions from the area of Complex Event Processing (CEP), which is the process of analyzing large streams of information from multiple sources and, by detecting patterns and identifying meaningful complex events, quickly infer a conclusion from them and possibly generate an action. This can be very useful in a large variety of applications, by allowing to predict situations and thus avoiding issues or seizing opportunities [4]. Representative CEP systems are Esper, Drools Fusion and Siddhi, which has evolved to the WSO2 CEP.

Taking in consideration all these technologies and the context of building automation, this work presents a solution for an effective, low latency automation solution, considering most software aspects, as well as sensors and actuators. Due to context of the pilot considered, and the low latency challenges presented, there is a focus in lighting systems.

This work is organized in 6 sections. Section 2 presents the system overview architecture, giving a description of each of the composing elements. Section 3 explains the design principles and implementation details about the presented work. Section 4 describes a test scenario, the results obtained and an analysis of those results. Section 5 presents future work that can be made to improve our work. Finally, section 6 supplies the final conclusions about the developed work.

2 System Conceptual Overview

Solutions for effective automation must consider a multitude of components, at different layers and provide different functionality. The aggregate of these components composes the management platform, which operates in a coordinated manner. A particular difficulty of such systems is that different knowledge areas should be present, ranging from electronics, to communications, data processing and visualization. Standards provide a great advantage as they allow companies to focus in specific areas, as long as the solutions developed use the communication protocols and operational primitives. As the focus of our work was the the development of innovative solutions at multiple layers, we consider the use of standard Machine to Machine protocols and solutions, but developed a conceptual solution thatencompasses multiple layers. The resulting conceptual system architecture is depicted in Fig.1, and it considers the following layers: Field, Network, Aggregation and Automation, and Services and Applications.

The Field layer considers the devices located in the building and through which most users interact with the system. These devices can be categorized as sensors, actuators or as hybrid devices that do both sensing and actuation. From a conceptual point of view, this will include any HVAC equipment, electric door locks, lighting fixtures, switches, as well as other environmental and presence sensors, current sensors or even other devices used for indoor location. It should be considered that devices are composed by some processing component (usually a microprocessor), a communication interface and then the actual sensor or actuator. This processing power can also be used to endow each device with some intelligence, enabling autonomous decision making as failsafe mechanisms.

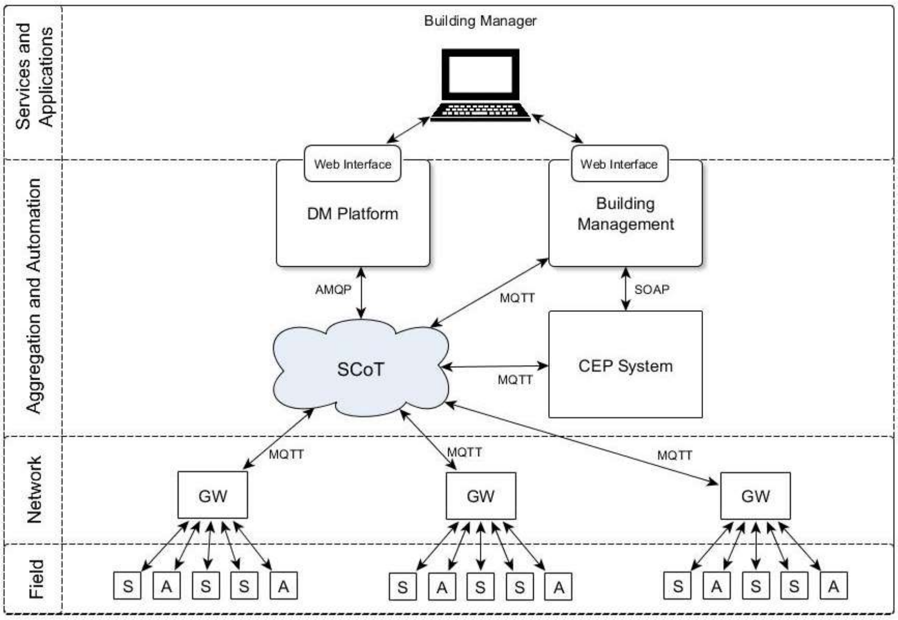


Fig. 1. Architecture diagram.

This topology can be extrapolated to other actuators that may not require such a sophisticated control over its functionalities but nevertheless can have a significant impact in energy efficiency, and operation of a building. For example, having control over windows' blinds can be used to compensate a space lighting with natural light, additionally, managing air condition units and windows can translate in lower heating costs.

The Network layer considers the communication interfaces of each Field device, and aggregator nodes named as gateways. These aggregator nodes are more powerful than the Field devices, and will have the capability of interfacing devices with higher layer platform components, in particular the IoT platform. Moreover, they can closely monitor Field devices, discovering new devices or detecting failures. In both cases, they can issue notifications for the higher layers. An important aspect of these components is that they adapt the object oriented automation orders into specific commands tailored to the communication technology. In particular, communication to lower layers can use non-IP protocols, or domain specific protocols, which may be more suited to a particular scenario. Moreover, gateways can host and execute automation rules, as delegates from the automation layer. The interest is to keep automation rules in the absence of higher layers or for emergency and failsafe scenarios. Communication is done through standard M2M/IoT protocols and technologies, such as MQTT, CoAP, Wifi, BtS, ZWave and ZigBee as deemed appropriate.

The Aggregation and Automation layer hosts the components that are capable of receiving IoT data from sensors and actuators, providing mechanisms for storing, distributing and adapting data as needed. In our vision, in particular because we consider a common object representation model, all information at this layer is homogeneous and follows a common structure, even if the specific concent of each data unit can be widely different. Still, all data units are represented by a timestamp and an identifier, which can be used both for purposes of auditing past behavior as for identifying the context of each data.

At its core we consider the existence of the Smart Cloud of Things (SCoT) IoT platform that implements a Machine-To-Machine (M2M) solution, with the goal to connect devices to the cloud. The data sent by the gateways can be retrieved and analyzed by third parties, for example, services, applications, in order to create dashboards with that information [10]. The main purpose of this platform is to provide a standardized, broker-based, communication channel, with persistence and standardized APIs, which could be provided by many other solutions.

One of the main components is the Device Management, which tracks all objects (devices) connected to the platform, its status and its properties. In our approach, we have a standardized vision over all connected objects, with a strict structure based on the work from IPSO. Therefore, it is possible to enumerate objects (e.g., a luminary), and interact with it (e.g., turning its light on), in a programmatic manner.

Another main component, and a core aspect of this work, is the CEP engine. This platform is responsible for processing every event generated by sensors (e.g., a switched was activated), and using Complex Event Processing infer actions in real time. Here, an action is not necessarily an action on the environment using actuators. It can also be an alert that can be pushed to another component or directly sent to the building manager. Also, the action can actually be no action, as in the case of turning on an air conditioning in a room already very cold.

Finally, the building management component is responsible for providing a web interface for the building administrator to create, edit or delete rules dynamically. Based on these rules it generates the complex code that forms a rule to be applied on the CEP system. Additionally, it is also in this component that the user creates the virtual representation of the building, and distributes the devices by areas in rooms. Thus, this component is also responsible for providing the information about a device's location, i.e. to what building, floor, room and area it belongs, and configure the devices accordingly.

The Application and Services layer is the final layer in our architecture, providing programmatic interfaces to other higher layers services, dashboards for users to interact with the building, and analytical tools for alarmistic, management and forensic analysis.

3 Design and Implementation Considerations

Taking in consideration our conceptual architecture, we created a real world implementation, comprising the case of a building with smart lighting. This scenario was chosen due to the focus of our research groups, automation requirements from actual building owners, allied to the fact that lighting presents a near perfect testcase for validating real time, low latency, heterogeneous systems. Moreover, it can provide real energy savings benefits for building owners, which we also wished to explore. In particular, if we consider a scenario with full softwarization of all existing devices, including the traditional light switches and PIR motion detectors, in order to keep high levels of acceptance, it is vital to deploy solutions able to react with very low latency. Even in the condition where rules are complex and a multitude of parameters is evaluated before a luminary is activated after the user presses the switch. Also, we consider advanced lighting features such as controllable dimming and fade in/fade out.

3.1 Lighting management and actuators

Combining the LED luminaires with a microcontroller serves many purposes, communication and control are the most fundamental but other features may prove useful in integration with the system.

Dimming can be implemented by the microcontroller and it has significant impact in energy saving, LEDs allows multiple dimming techniques but the most popular and efficient ones are definitely analog dimming and pulse width modulation (PWM) dimming and both have advantages and disadvantages that need to be considered when designing an application. Ultimately, choosing one type of technique requires an assessment of the application demands without compromising user comfort.

The microcontroller can be also used to implement logarithmic dimming, accordingly to the Weber–Fechner law [11], the human eye perceives a linear transition in brightness levels when the change follows a logarithmic logic due to the fact that the eye is more sensitive to changes in lower brightness levels, so the user perceives a linear transition in light levels when the dimming curve is actually logarithmic instead of linear.

Other factors can be customizable, for example a maximum dimming level can be established and adjusted over time to compensate the decay of performance in LED over time.

3.2 Sensor systems

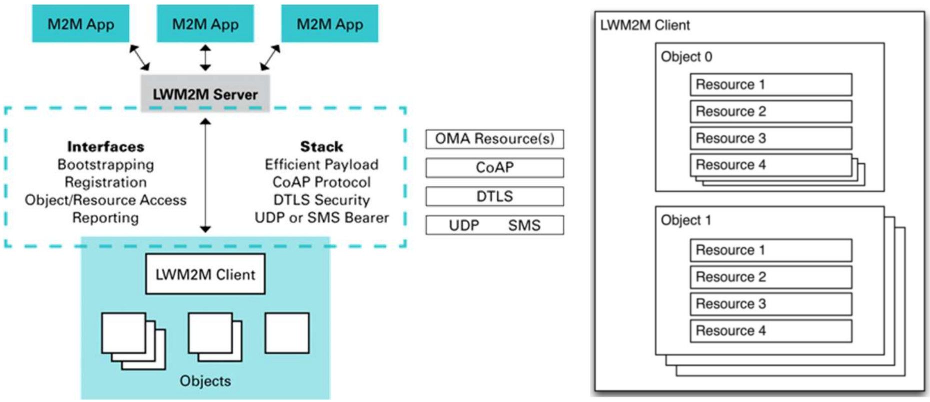
Designing a sensor system requires a full recognition of the building. Division and corridors are individually analyzed and customized according to their needs and characteristics.

Each luminaire or a small group has a presence sensor, which in case of sensing the presence of a person will turn them on and keep that way for some time depending on its location. An example of different behaviors, after sensing presence in corridors, a request is sent to the luminaires around the sensor to turn on for a short time, and therefore predict the movement of the person with other presence sensors to follow his path. In offices, laboratories and workshops where presence is more extended and a different behavior of the luminaires is required, the light should never turn off while users are still in. In our approach this all software driven by automation rules.

Laboratories, workshops or even warehouses that have a high potential of accidents need a group of sensors that can detect and timely signal those accidents. Sensors like gas, flame, temperature, noise should monitor in real time the division and alarm the gateway in case of any anomaly in the sensors levels.

3.3 Device Management

The implementation for this work imposed the existence of a simple and lightweight object model to be used in the platform's constrained devices. For this reason, we selected LWM2M from OMA.



(a) **(b)**

Fig. 2. (a) Lightweight M2M Overall Architecture with Protocol Stack.
(b) IPSO Object Representation.

The OMA Lightweight M2M architecture is composed by a LWM2M Client (M2M device/Gateway) and a LWM2M Server (M2M service/platform/application) using CoAP as the communication protocol. LWM2M provides light and compact interfaces along with an efficient data model, which together enables device management and service enablement for M2M devices. Fig. 2(a) illustrates the Lightweight M2M architecture.

LWM2M defines the interactions between a client and a server. An object model is required to manage the LWM2M client. Regarding this subject, the IPSO Alliance created an object model based on the Lightweight M2M specification from the Open Mobile Alliance dedicated to work on constrained devices. This object model is a solution for creating interoperability between connected devices and objects. The structure of this model is represented in Fig. 2(b). The Figures also show the simple addressing strategy of IPSO (object/instance/resource).

The LWM2M object specification states that an object can be a type of device and his resources are the properties that the device has.

The number of objects that IPSO defined did not include some scenarios present in the SCoT Platform. Due to this, we extended the platform with several new objects using the LWM2M format and IPSO addressing strategy. The objects created and used for this work include the objects that are found in a smart building, specifically smart lightning associated objects (Luminaire object e.g.), and now any other object can be created in order to enable orchestration of a new device.

The proposed device management solution addresses a scenario where the Gateway Domain will hold the LWM2M Client logic and the Data Domain the LWM2M Server logic, due to the existence of legacy devices in the platform. The Gateway will connect several sensors and actuators, mapping them into objects in the LWM2M logic, thus enabling interaction with COTS devices.

The Device Management Component in the Data Domain will have the LWM2M Server that will be responsible for client registration and to perform management operations on the clients.

The client side of solution can be divided in two parts, MQTT/HTTP solution and OM2M solution. The MQTT/HTTP solution consists in having a LWM2M Client in the Gateway Domain, that is responsible for creating the objects and registering himself in the server. This client will also receive management actions from the server and receive real time information from the sensors/devices and update the objects automatically.

3.4 Gateways

The key point of the gateway, is to transport data between devices and the IoT platform, in our case using a MQTT connection. For that, we developed an agent that maps the services/characteristics from BtS into the objects/resources representation specified by the device management platform. To achieve this, considering that BtS uses UUIDs to identify each service/characteristic, the ID and the instance of both the objects and resources must be included in the UUID, which is done as follows:

UUID: xxxxxxxx-0000-1000-8000-00805F9B34FB
↓ ↓ ↓
ID **Instance** **Base UUID**

Furthermore, in order to ensure the trustworthy of the devices and that only them are able to connect to the platform, both the gateway and devices can implement a challenge–response authentication, using a special characteristic for that purpose. This both enables the gateway to discover new devices automatically, and to only process authorized devices.

3.5 Automation Rules

Fig. 3. CEP flow diagram example.

For making complex processing of large streams of events, WSO2 CEP was the platform chosen for this implementation. It uses Siddhi as its CEP system, Apache Storm for creating an high performance distributed platform, and provides support for several technologies and formats for data transport, including MQTT, E-mail and SMS. The processing flow for each rule is divided in 4 main elements as shown in Fig. 3. The event streams, which are the definition of the format and the fields of the events, are used as tables by the execution plans where queries can be made using Siddhi QL, which is similar to SQL. The receivers and publishers are responsible for, respectively, receive events and inserting them into event streams and publish events from event streams. All these elements can be controlled in a web interface provided by WSO2, but also using a SOAP interface, which is the one used by the platform described in the next section.

3.6 Building Management

The building management platform, comprises two main applications as shown in Fig. 4. The structure manager application, is the part of the system that holds a virtual representation of the building, in order to allow more complex selection of data in the rules. For instance, a rule can be applied to a set of specific sensor types in all the bathrooms of a specific floor in a specific building.

It is managed through an intuitive Web interface, where the manager can easily create, edit or delete buildings, floors, room types and rooms. Moreover, in each room, the manager can dynamically create areas, to which he can associate devices, with a drag-and-drop interface.

Appended to the structure manager application, there is the device manager module which is responsible for discovering and configuring devices. Internally, for each device, based on the virtual representation, it generates the topics necessary for enabling the device to publish and receive events, making sure it subscribes not only its individual topic but also the topics of the structure elements it belongs to.

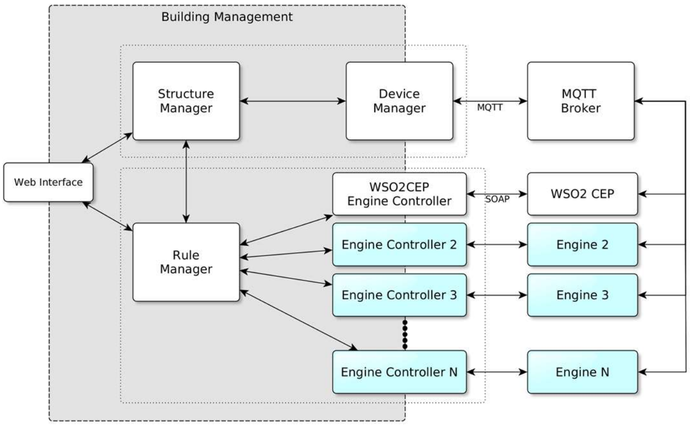


Fig. 4. Building Management Platform

Regarding to the rule manager application, although WSO2 CEP provides a lot of possibilities for creating complex queries with its powerful language, Siddhi, they are difficult to map to a Graphical User Interface. With this in mind, one of the first principles in consideration when starting this implementation, was to design a solution that would be highly extensible, with pluggable new modules. In order to achieve that, the database was implemented in a way that new modules could be added just by dropping them on a specific directory of the application. These modules just need to inherit one of the defined entities and enrich them with extended features.

All these modules can be used in a web interface for creating complex rules, for being then applied by the system on the CEP engine. However, instead of directly creating the Siddhi code for being sent to the WS02 CEP, the system first represents the whole rule in a JSON object. The reason that lead to this was, again, to allow an high extensibility of the system. By creating JSON rules in a specific format, the system is not obligated to use WSO2 CEP specifically, and thus other CEP engines can be used and even coexist. To achieve this, an engine controller must be implemented for supporting a different CEP engine, as shown in Fig. 4. The primary task of an engine controller is to parse the JSON rule and convert it to code supported by its engine.

4 Experimental Validation

Since this implementation is being applied in a real-world scenario, the evaluation focused in the proper functioning of a real-world prototype, considering the development of both software and hardware. The underlying hardware was composed by a quad-core server with 4 gigabytes of RAM hosting the WSO2 CEP, a Raspberry Pi 3 with the gateway agent and, finally devices consisting of two luminaires and multiple PIR sensors.

The developed prototype uses a LED luminaire powered by a RCOB-1050 LED driver by Recom, it is a constant current LED driver that outputs 1050 mA with 0-10V dimming signal input, enabling dynamic control of the brightness level.

The Nucleo-L476RG development board by STM, based on the ARM® Cortex®-M4 32-bit RISC paired up with the X-NUCLEO-IDB04A1 Bluetooth 4.0 provided integration of the multiple devices. For this purpose we developed several devices: two of them controlling one luminaire each, one controlling a passive infrared sensor (PIR) for detecting presence, and one module with several environmental sensors. The environmental sensors report information periodically, and are able to measure: ambient light level, a temperature, humidity, contaminant gases, accustic noise and atmospheric pressure.

Each luminaire allows configuration of the dimming type (Analog or PWM), Maximum and minimum light level, dimming up and dimming down slope time, logarithmic dimming resolution (softer or sharper light level transitions), and failsafe behavior that prevents the inoperability of the luminaire in case of a communication breach by enabling luminaire to react to a PIR activation without the need for the remaining components.

With the aim of testing the performance of the whole system, we measured the response time between a motion detection and the corresponding action on the luminaire, to have a precise average of the time-to-light, 124 measurements were performed, the results are presented in the table 1.

Response time	Minimum	Maximum	Average	Std. deviation
Round-trip time	68 ms	380 ms	149 ms	56 ms

Table. 1. System response time in real-world prototype.

Using an oscilloscope, we have estimated the delay in the BtS connection to be aproximatelly of 79 ms, obtained by measuring an impulse delay between the Nucleo and the gateway. The values obtained were also compared against a simulation (see Table 2) performed on a custom made simulator that emulates the devices by software. Therefore, the latency imposed by the physical communication channel will not be present. These results are important because they represent a system with a much higher number of devices (671 devices) and because they are able to characterize the performance of the software components, and in particular the CEP system and IoT platform.

Response time	Minimum	Maximum	Average	Std. deviation
Round-trip time	5 ms	233 ms	54 ms	39.32

Table. 2. System response time without physical devices.

The results prove the system's high performance, showing that even considering the latency from both the network and the Bluetooth connection, it is able to respond with a sub-second latency. The simulation scenarios also demonstrate the scalability of the system, up to 600 actuating and sensing devices.

6 Conclusions

We demonstrated a solution for easy creation of complex and fast automation in, among others, the lighting infrastructure of a building. Through an interactive web portal, a user can create complex rules that are dynamically added to a CEP system.

With the implementation and evaluation described in this paper, we have shown that the system is able to respond with a sub-second latency and thus most users have no perception of any delay, as stated in the book *Usability Engineering*[12] by Jakob Nielsen, response times around 0,1 seconds result in a feel of instant reaction to human users. The current implementation provides the basis for creating a full featured system capable of automating efficiently and intelligently the several infrastructures of a building. For demonstration purposes it was only endowed with basic modules for creating rules for lighting control. Thus, as future work, more modules shall be added to the system for allowing the creation of more complex rules.

Additionally, manual control of devices by the user with its smartphone is also a very interesting feature, and is easily integrable in the system by requesting the building management application for temporarily disabling the automation for a specific device. Moreover, lightweight CEP engines could be implemented at the gateways in order to allow local automation and thus better failure handling.

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