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Adaptação da Taxa de Transmissão em Redes Veiculares

Universidade de Aveiro Departamento de Electrónica, Telecomunicações e Informática
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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requesitos necessários à obtenção do grau de Mestre em Engenharia Electrónica e Telecomunicações, realizada sob a orientação científica da Doutora Susana Isabel Barreto de Miranda Sargento e do Doutor Arnaldo Silva Rodrigues de Oliveira, professores auxiliares do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro.

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Resumo

Ao longo dos últimos anos, vários progressos em comunicações sem fios têm extendido investigações a novas áreas, onde soluções baseadas em redes com fios são impraticáveis. Neste contexto apareceram as Vehicular Ad hoc NETworks (VANETs), uma classe emergente das redes Ad Hoc, para interligação e comunicação entre veículos. Devido às suas características peculiares como alta mobilidade, topologia dinâmica, frequente perda de conectividade, as VANETs enfrentam vários desafios para definir protolocos e mecanismos fiáveis, como a adaptação da taxa de transmissão. De facto, a monitorização do tráfego das ruas através de aplicações são o núcleo das VANETs cujo desempenho depende da taxa de envio de pacotes e da taxa de sucesso que estas redes conseguem oferecer. Mecanismos de adaptação da taxa de transmissão têm como objetivo evitar a degradação do desempenho da rede devido a uma escolha muito elevada da taxa de transmissão, quando a qualidade do canal está deteorada, ou devido à utilização de uma taxa muito baixa quando as condições da qualidade do canal melhoram. Uma vez que os dispositivos que operam segundo a norma IEEE 802.11p suportam várias taxas de transmissão, é importante que estes possam adaptar a taxa de forma dinâmica de modo a obter um desempenho elevado. Assim é essencial ter um mecanismo de adaptação da taxa de transmissão que seja robusto e capaz de lidar com elevadas flutuações e assimetrias do canal, transmissões em rajada e de duração inconstante, e perda de pacotes devido às condições do meio e à existência de terminais escondidos. Assim sendo, esta dissertação permite avaliar e comparar os mecanismos existentes para redes sem fios, em ambientes veiculares usando o Network Simulator 3 (NS-3) e o Simulator of Urban Mobility (SUMO). Depois de analisar os principais mecanismos presentes na literatura, foram selecionados quatro para serem testados: Adaptive Auto Rate Fall Back-Collision Detection (AARF-CD), Collision-Aware Rate Adaptation (CARA), Minstrel e o Ideal. Serão considerados dois tipos de cenários: auto-estrada e urbano. A comparação dos algoritmos será baseada em métricas conhecidas como a taxa de envio de pacotes, taxa de sucesso e a percentagem de retransmissões para vários níveis de transmissão. Os resultados experimentais mostraram que o AARF-CD atingiu um desempenho superior, quando comparado com os restantes algoritmos. O CARA foi o segundo melhor algoritmo segundo as métricas consideradas. De realçar que o AARF-CD obteve uma taxa de sucesso superior ao do CARA, apesar deste oferecer uma taxa de envio de pacotes superior em certos cenários. Em relação ao atraso na rede, tanto o AARF-CD como o CARA alcançaram resultados similares. Foi também concluído que algoritmos com diferenciação de perdas de pacotes como o AARF-CD e o CARA oferecem uma melhor adaptação da taxa de transmissão. Por fim, é sugerido um algoritmo de adatação da taxa de transmissão que tem em conta parâmetros externos, como a velocidade, distância e a densidade de veículos. Cada parâmetro é considerado de acordo com a sua influência na transmissão de dados através de pesos. Desta forma os parâmetros que afetam mais a adaptação da taxa de transmissão serão associados a pesos maiores. A adatação da taxa de transmissão será baseada num processo de pesos, de acordo com o efeito das condições exteriores no desempenho da rede.

Abstract

Over the last years, several progresses in wireless communications have extended research in new sub-areas, where wired solutions are impracticable. In this context, VANETs arose as an emerging area of wireless ad hoc networks, which connect and allow communication between vehicles. Due to its peculiar characteristics such as high mobility, dynamic topology and frequent loss of connectivity, VANETs face many challenges to define reliable protocols and mechanisms like rate adaptation schemes. Indeed traffic querying and road sensing applications are the core of VANETs whose performance depends on the throughput and the success ratio these networks can provide. Rate adaptation mechanisms aim to avoid performance network degradation due to rate over-selection when channel quality is deteriorated or rate under-selection when channel quality improves. Since IEEE 802.11p supports multi-rate capabilities, devices must adapt their transmission rate dynamically in order to achieve a high performance. Thus it is critical to have a robust rate adaptation mechanism that can deal with high fluctuation and asymmetry of channels, bursty and infrequent duration transmissions, and loss packet own to the extreme environment conditions or hidden terminals. Thereby, this dissertation evaluates and compares the existing rate adaptation mechanisms for wireless in vehicular environments, using NS-3 and SUMO. Four mechanisms: AARF-CD, CARA, Minstrel and Ideal were selected to be compared, after analysing the main mechanisms across literature. It will be considered two types of scenarios: highway and urban scenario. The comparison between the algorithms will be based on known metrics: network throughput, success ratio, delay and percentage of retransmissions. Experimentation results showed that AARF-CD achieved higher performance when compared with the remaining algorithms in both scenarios. CARA was the second best algorithm, considering the same metrics. Although CARA provides higher throughput in certain scenarios, it is outperformed by AARF-CD in terms of rate success. Regarding delay, AARF-CD and CARA attained similar results. It was also concluded that algorithms with loss differentiation such as AARF-CD and CARA provide better rate adaptation. Finally, it is suggested a rate adaptation algorithm which considers external parameters like velocity, distance and density of nodes. Each parameter is considered according to its impact in the data transmission through weights. Parameters that affect more the rate adaptation are associated to larger weights. Thus, the rate adaptation is based on a weighted process according to the effect of external conditions in the network performance.

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Acronyms

4G Fourth Generation of cellular wireless standards

AP Access Point

AU Application Unit

AODV Ad hoc On-Demand Distance Vector

ACK ACKnowledgment

ARF Auto Rate Fallback

AARF Adaptive Auto Rate Fallback

AGILE Ack-Guide Immediate Link rate Estimation

AARF-CD Adaptive Auto Rate Fall Back-Collision Detection

AU Application Unit

AMRR Adaptive Multi Rate Retry

BER Bit Error Rate

BSS Basic Service Set

BSSID Basic Service Set Identification

C2C-CC Car-to-Car Communication Consortium

CCH Control Channel

CSMA Carrier Sense Multiple Access

CTS Clear To Send

CCA Clear Channel Assessment

CARA Collision-Aware Rate Adaptation

CARS Context-Aware Rate Selection

CCA Cooperative Collision Avoidance

CHARM Channel-Aware Rate Adaptation

DSRC Dedicated Short-Range Communications

DCF Distributed Coordination Function

DAD Duplicate Address Detection

EWMA Exponential Weighted Moving Average

EWM Emergency Warning Message

FCC Federal Communications Commision

GPS Global Positioning System

GPRS General Packet Radio Service

GSM Global System for Mobile communications

IEEE Institute of Electrical and Electronics Engineers

ITS Intelligent Transportation System

IP Internet Protocol

ID IDentifier

LTE Long-Term Evolution

LOS Line-of-Sight

LLC Logical Link Control

LWMA Linear Weighted Moving Average

MAC Medium Access Control

MANET Mobile Ad Hoc Network

NS-3 Network Simulator 3

NS-2 Network Simulator 2

NLOS Non-Line-Of-Sight

OEM Original Equipment Manufacture

OBU On-Board Unit

OLSR Optimized Link State Routing

OSI Open Systems Interconnection

OFDM Orthogonal Frequency-Division Multiplexing

PHY Physical

PDR Packet Delivered Ratio

QoS Quality of Service

RSU Road Side Unit

RTS Request To Send

RSSI Received Signal Strength Indicator

RAM Rate Adaptation in Mobile environments

RRAA Robust Rate Adaptation Algorithm

RBAR Receiver-Based AutoRate

SUMO Simulator of Urban Mobility

STDMA Self organized Time Division Multiple Access

SNR Signal-to-Noise Ratio

SSID Service Set IDentification

SCH Service Channel

TCP Transmission Control Protocol

UDP User Datagram Protocol

UMTS Universal Mobile Telecommunications System

UWB Ultra-WideBand

VANET Vehicular Ad hoc NETwork

V2V Vehicle-to-Vehicle

V2I Vehicle to Infrastructure

WAVE Wireless Access Vehicular Environments

WLAN Wireless Local Access Network

WIMAX Worldwide Interoperability for Microwave Access

Wi-Fi IEEE 802.11 a/g/n

WSMP WAVE mode Short Message Protocol

WUSB Wireless USB

WBSS WAVE Basic Service Set

ZOR Zone-Of-Relevance

Chapter 1

Introduction

This document, denoted as "rate adaptation mechanisms in vehicular networks", presents the accomplished work during the dissertation concerning to the master in Electronics and Telecommunications Engineering in the department of Electronic, Telecommunication and Informatic of university of Aveiro.

This work aims to analyse and take a step further towards rate adaptation mechanisms in vehicular networks.

In this chapter it is explained the motivation associated to this work, proposed objectives and a brief description of its structure.

1.1 Motivation

Nowadays vehicular networks have been deeply investigated by several entities. They gather efforts to build a solid network to share information between vehicles, increasing road safety. Drivers could be warned about traffic jams, accidents or other types of alerts. Therefore, it is expected that all vehicles will communicate between them, and consequently take decisions according to the received information such as security and alarm messages. Beyond security information, these networks can address other applications in which dissemination of information could be based in interactive games or social networking.

The main purpose of research in VANETs is to investigate how communication between vehicles can improve user experience, increase security and connect all the elements of a road to the same network.

These networks, known as VANETs, are formed by dynamic nodes with high and unpredictable mobility, the vehicles. VANETs experience often lack of nodes in the network, leading to periods without communication between vehicles, once they do not have vehicles in their range. All this interaction depends on the set of parameters that determine their velocity and position. Vehicles form dynamic clusters which suffers many changes in their topology according to vehicles density and mobility.

Many factors such as velocity, density, position and distance cause undesirable results which are intolerable to this type of network. For example high delays or low throughputs can compromise network performance.

Data rate adaptation is one of the key mechanism at MAC layer in order to control data communications. It evaluates and decides which rate should be applied at the physical layer for communication.

Several rate adaptation mechanisms based on different techniques have been deployed for Wi-Fi networks. However vehicular environments cannot be considered as a traditional Wi-Fi network. In those networks, devices experience high interference and channel instability and asymmetry. New standards and technologies were developed to face these new challenges, intrinsic to VANETs.

In the near future, the number of communications among vehicles will increase using WAVE and Dedicated Short-Range Communications (DSRC) infrastructures [13]. Actually, the Federal Communications Commision (FCC) has reserved a DSRC spectrum to improve bandwidth and minimize latency in Vehicle-to-Vehicle (V2V) and Vehicle to Infrastructure (V2I) communication. Many applications can be run in vehicular networks, exchanging different types of messages; however, some of them require a high level of communication reliability to succeed. Low delays and high throughputs have to be guaranteed even in hostile and dynamic environments with unstable link conditions.

Thus, devices have to react dynamically through appropriate mechanisms to establish communications in these extreme conditions. Control and record information relative to data communication is an important approach in order to take appropriate decisions. In this way, rate adaptation mechanisms perform a vital role in this thematic, where optimal system performance in terms of throughput, delay and success ratio is the main goal. In fact, data rate adaptation mechanisms are not yet defined in the new standards for VANETs. It has to select an adequate rate available in IEEE 802.11p protocol according to the real-time medium conditions. By its side, it allows eight transmission rates ranging from 3 to 27Mbps at the PHY layer. For each rate, it is used a specific modulation and coding scheme.

Higher data rates are used in high quality links, transmitting more data per unit of time, nonetheless they have a higher probability of packet loss in adverse links. Regarding low data rates, they were designed through robust modulations and are appropriate in poor quality links. However, they do not achieve high throughputs as higher rates do.

Many challenges have to be considered to evaluate and design a rate adaptation mechanism for VANETs. Rapid variations of link quality due to propagation loss and high mobility must be overcome through fast adaptation. Rate adaptation must be independent from traffic amount, in another words, it must be able to estimate link quality with low and bursty traffic. Intelligence to distinguish the reason of packet losses must also be provided.

This dissertation is inserted in this thematic, whose main idea is to study and evaluate rate adaptation mechanisms over controlled scenarios. Results must clarify which existing mechanisms for Wi-fi are suitable for vehicular networks, identifying features that leads to better results.

1.2 Objectives

This work focuses on rate adaptation schemes in vehicular networks. Its main objective is to analyse rate adaptation mechanisms designed for IEEE 802.11 a/g/n (Wi-Fi), and find out which are more suitable for VANETs. Finally, it will be concluded which mechanisms' features lead to better and worse results, to understand in which aspects a rate adaptation implementation for VANETs should be based.

It is taken this approach, once VANETs are completely different from indoor wireless networks in terms of link conditions due to high mobility of nodes. Consequently, adaptation mechanisms from these wireless networks do not achieve necessarily optimal performance in

VANETs.

After studying literature and designing scenarios, several challenges arose, supporting the objectives of this dissertation. These challenges are:

- Which features of Wi-Fi data rate adaptation mechanisms are suitable for VANETs?
- How to compare these mechanisms?
- How to design a rate adaptation mechanism for VANETs?

Now it is easy to assimilate the objectives of this dissertation, which are the following:

- Find out which algorithms could work acceptably in VANETs;
- Define which metrics should be used to compare each mechanism;
- Implement mechanisms to record information relative to traffic flow;
- Evaluate and determinate which parameters affect link quality in VANETs;
- Analyse and compare the impact of these parameters through the specified metrics;
- Analyse algorithms procedure in different scenarios;
- Design specific scenarios to evaluate the rate adaptation mechanisms;
- Compare results and identify main mechanisms' features applicable in VANETs;
- Design a rate adaptation mechanism for VANETs.

1.3 Contributions

The contributions of this dissertation are:

- A comprehensive study of rate adaptation mechanisms and VANETs simulations;
- Comparison of several rate adaptation mechanisms in VANETs scenarios;
- Influence of different parameters in rate adaptation process;
- Rate adaptation mechanism according to the conclusions of this dissertation.

The work of this dissertation is being submitted to a publication in an International Conference: Data rate adaptation mechanisms in VANETs.

1.4 Document organization

This dissertation is organized as follows:

- Chapter 1 contextualizes this dissertation, describing its motivation and main objectives to be reached.
- Chapter 2 describes the main concepts of VANETs, presenting its definitions and features. It also approaches the MAC and PHY layer of IEEE 802.11p, in which rate adaptation mechanisms operate.
- Chapter 3 describes the state of art of rate adaptation mechanisms in wireless networks. In this chapter related works of several mechanisms will be analysed in order to understand how they perform rate adaptation and differ from themselves. The network and mobility simulators will be also discussed in this chapter.
- Chapter 4 describes the implementation that was performed to evaluate different scenarios through a simulator network. It will be introduced this simulator and the modules that were used, and it will be explained all the implementation required to accomplish the initial requirements and to obtain the results.
- Chapter 5 presents results from different scenarios and their discussion. It will be explained the scenarios that will be considered, and it will be presented and discussed the obtained results. It will be also presented a general conclusion taking into account all the metric results of the simulated mechanisms. Finally, it will be proposed a rate adaptation mechanism.
- Chapter 6 presents a final conclusion of the developed work. It will be also discussed future work, proposing improvements and new functionalities relative to implementation.

1.5 Summary

This chapter described the motivation and the main objectives of this dissertation. It was also presented the structured of this document.

In the follow chapter, it will be introduced the information necessary to frame the reader in this thematic, rate adaptation in VANETs.

Chapter 2

Vehicular Networks

2.1 Introduction

This chapter provides an overview regarding VANETs and its concepts, based on the existing literature in order to frame the readers in this thematic. Thus, section 2.2 and 2.3 presents the context of VANETs, and its basic concepts followed by section 2.4 and 2.5, which approaches technical challenges and VANETs architectures. By its turn, section 2.6 describes the addressing schemes.

Section 2.7 and 2.8 present the data dissemination and network access technology respectively. Section 2.8 still explains PHY and MAC amendments relative to IEEE 802.11a standard to turn it in IEEE 802.11p.

Finally, section 2.9 focus on applications and services provided by VANETs and provides some practical examples.

2.2 What are VANETS?

Intelligent Transportation Systems (ITSs), which is illustrated in figure 2.1, aims to reduce road accidents introducing several security services and afford comfortable travels allowing access to the e-mail or news.

In 1999 it was created a system of dedicated communication in north America, the DSRC with 75MHz of band spectrum in 5.9GHz by FCC, reserved for vehicle communication.

On the other hand, in Europe the Car-to-Car Communication Consortium (C2C-CC) [14] was initiated by automotive Original Equipment Manufactures (OEMs) and car manufacturers to decrease accidents through inter-vehicle communication. ITS Consortium in Japan [15], the "prevent project" [16] in Europe and the "Network on Wheels" [17] project in Germany are other examples of research projects.

In 2010 the Institute of Electrical and Electronics Engineers (IEEE) intensified research in this area, more specifically in IEEE 1609x family standards [18] designed for WAVE and IEEE 802.11p [19] to enable communication between vehicles.

Improvements in wireless technology, the popularization of Wireless Local Access Networks (WLANs) and the technological developments in automotive industry led to new research with one main purpose: connect vehicles as a single network.

VANETs emerged as a new class of Mobile Ad Hoc Network (MANET). They are formed dynamically by vehicles equipped with technology that allows communication between them.

Technically, VANETs are distributed and self-organizing. Nodes are characterized by very high speed, without a specific movement pattern, making IEEE 802.11 standards for Wi-Fi inefficient and inappropriate in VANETs.

Vehicles are equipped with On-Board Units (OBUs) which are physical units responsible for sending and receiving information across the network. VANETs allows two different schemes of communication, V2V and V2I. The last case requires a physical device placed on the roads named Road Side Unit (RSU). This device was created to overcome gaps due to low node density. They can be connected between themselves and route data from one vehicle to vehicles that are out of range. This approach can reduce packet loss, however it is sensitive to delays. Unlike OBUs, RSUs are wireless gateways which can access to OBU or external networks by itself. Therefore, after connecting to RSUs, OBUs are able to access the internet. These RSUs might belong to the local government or private telecommunication operators.

VANETs can be used by any type of vehicle: private or public transportation such as buses and public service vehicles (police).

Several challenges must be considered in vehicular networks such as high mobility, network dynamism, loss of connection during transmissions and low time of connection among nodes. In this way rate adaptation mechanisms of other wireless networks may not be suitable in this environment. In fact it is difficult to manage VANETs topology, due to its features previously referred.

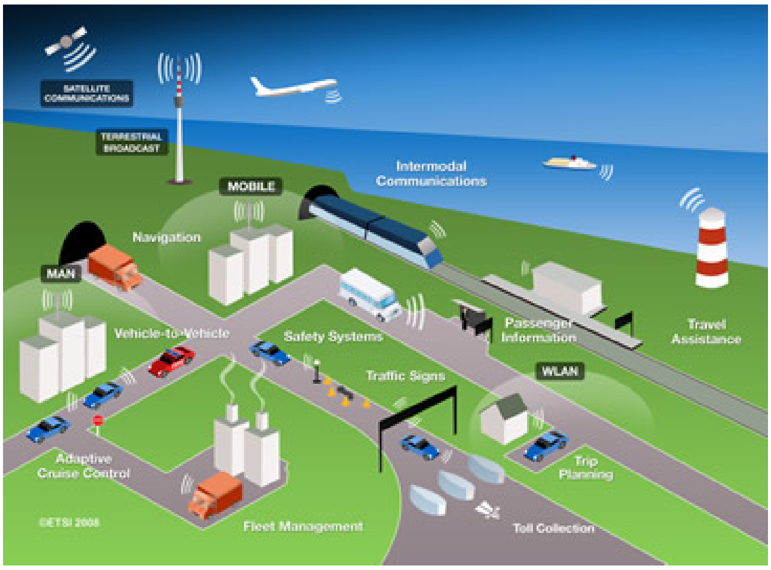


Figure 2.1: Intelligent transport system in [1]

2.3 Basic concepts

According to [4] it is necessary to familiarize readers with some concepts, in order to understand vehicular networks and its specific mechanisms.

2.3.1 Specific features

As discussed before VANETs are a type of MANETs, but with specific features as presented below [4, 20]:

- **High mobility:** The vehicles in VANETs are usually moving at high speeds along roads. Specially in urban scenarios, vehicles can take multiple directions along different roads.
- **Rapid change of network topology:** Network topology changes often due to high vehicle velocity. Then mechanisms defined for VANETs must be able to adapt quickly whenever the topology changes.
- **Partitioned network:** Due to the dynamic nature of traffic and consequently constant changing network topology, network can experience gaps. In these cases, clusters of nodes can be formed. This phenomenon can be minimized through physical infrastructure placed along the roads. Cellular network is also an option, but it entails higher costs.
- **Wide network size:** VANETs can link a large number of vehicles, from one city, or even several cities. Therefore, scalable protocols are required to practically manage dense networks.
- **Geographical communication:** beyond unicast and multicast, VANETs can address another type of communication. They can route packets to a particular geographic area, using Global Positioning System (GPS) coordinates.
- **High energy and process capacity:** Nodes does not have energy problems, once vehicles are supplied by batteries. They have high computer resources to process information, once nodes do not have limited size.
- **Latency restrictions:** Some messages such as safety messages, can not tolerate high delays, otherwise an accident can occur. They have to be received on time, to allow a reaction by the drivers.
- **Adverse environments:** Vehicles can experience two different scenarios: highway and urban. The first one implies higher velocities, lower density and one single direction, while urban environments are characterized by lower velocities, higher density and several directions.
- **Synchronization:** Nodes have to access periodically the Control Channel (CCH) which only transmits high-priority traffic safety messages. This channel is only available in intervals of 10Hz, requiring synchronization by nodes.

2.3.2 Equipment

Vehicles must be equipped with OBUs to belong to vehicular networks in order to receive, send and process information. Most of articles assume that physical devices are compound by the following list of hardware to allow communication:

- **Central processing unit:** It manages and implements applications as well as communication protocols.
- **GPS:** It allows synchronization to nodes and accurate position information.
- **Antenna:** It allows nodes to receive and send information among them.
- **Sensors:** It measures useful parameters such as vehicle location and speed for routing purposes. Information to evaluate system performance is also tracked.
- **Interface input/output:** It allows interaction between user and system.

2.4 Technical challenges

According to [21] and [22] some technical challenges of VANET can be described as:

- **Communication over link layer:** Cases of hidden and exposed nodes cause negative effects on throughput. Hidden nodes are two nodes that are out of range of each other, but communicate with nodes within the transmission range of both. They will cause a collision when the two nodes attempt a transmission simultaneously with the same node. On the other hand, exposed node problem occurs when a node does not transmit a packet, once a neighbouring transmitter is occupying the medium, but it does not interfere with the previous node communication.
- **Reliable communication at MAC layer:** Latency and association among nodes must be fast and efficient, due to its high dynamic nature and mobility. Network must provide reliability and assure quality to messages and applications, particularity the safety ones.
- **Routing and information dissemination:** At routing layer, information dissemination must be fast and efficient. Routing algorithms should adapt according to network changes such as topology, link quality and density network. They should also permit different transmission priorities according to application type: safety, real-time or not.
- **Quality of Service (QoS):** This still remains a challenge, despite of optimizing bandwidth and improve latency of transmissions. QoS routing should be dynamic enough to re-define new routes, whenever current routing paths become unavailable owing to node velocity and position and network topology.
- **Broadcast:** This is also a challenging area in VANETs. Broadcast storms are still a problem which leads to collisions and consequently to retransmissions and high delays. Indeed intelligent dissemination schemes should be performed through new broadcast algorithms.
- **Rate adaptation mechanism:** It must be efficiently implemented to provide suitable data rates to communications. This mechanism is essential to achieve higher overall system throughputs and rate success.
- **Security:** Regarding security, areas such as authentication, driver confidentiality and availability should be developed to avoid inside and outside network attacks.

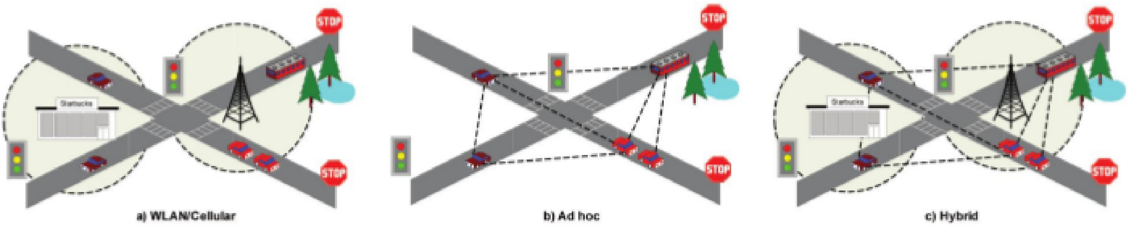
2.5 Network architecture

VANETs do not rely on fixed infrastructure to disseminate information, instead they use their highly dynamic environment to ensure communication. As shown in figure 2.2, VANETs can be classified in three architecture types [2, 23]:

- **Pure ad hoc:** Vehicles equipped with OBUs communicate among them, without infrastructure resources such as RSUs. They route information until the final receiver through either single or multiple hop. This architecture is low cost, however it relies on node density to guarantee traffic flow, being difficult to establish communication in low density scenarios. This architecture presents another drawback, once vehicles cannot access to external networks.

- **Pure WLANs/cellular:** Vehicles can use infrastructure placed along the roads connected among them to ensure V2I communication. These physical devices, which can accede to external network like internet, centralize all the network information. Despite of entailing high costs, through this architecture, vehicles can always connect to the network and even to the internet, if roads are covered by these technologies.

- **Hybrid:** This architecture joins the both referred architectures in order to minimize drawbacks from each one of them. Total coverage is not supported by infrastructures, instead they are placed strategically to increase network connectivity. Vehicles are still responsible for disseminating information in areas that are not covered. In this architecture both types of communication are possible: V2I and V2V. Finally, this approach is more viable once it reduces costs due to the low number of infrastructures, and increases connectivity among vehicles.



a) WLAN/Cellular b) Ad hoc c) Hybrid

Figure 2.2: VANETs architecture in [2]

The C2C-CC [3] proposed an architecture that divides VANETs into three distinct domains: in-vehicle, ad hoc, and infrastructure domain. Figure 2.3 shows the interaction among domains and the standard technology that is supposed to be used in each case, at a high abstraction level.

The in-vehicle domain is logically compounded by an OBU and Application Unit (AU). AU is the device that executes and manages applications and uses OBUs to communicate. It is connected to OBUs, nonetheless it can be a portable device. They are wired connected, but bluetooth, Wireless USB (WUSB) or Ultra-WideBand (UWB) connection is also possible. Finally, they can be placed in the same physical unit.

Ad hoc domain is formed by vehicles equipped with OBUs and RSUs. OBUs allow communication among vehicles without relying on physical infrastructures which centralize network information. An OBU communicate directly with other if they are in the same range, otherwise multi-hop communication can be used. In this last case, packets are forwarded until they reach the final destination.

Regarding RSUs, they can be seen as static nodes in VANETs, and their main purpose is to forward data and improve network connectivity by increasing network ad hoc coverage. As mentioned before, RSUs can be connected to an external network, enabling Internet connection. Consequently AUs can communicate with a host on the Internet. RSUs can also communicate among them, directly or via multi-hop using vehicles. As shown in figure 2.3, OBUs might communicate with other wireless networks such as public or private hotspots.

Finally infrastructure domain contains two different access domains RSUs and hotspot. Once again, both increase network connectivity and allow OBUs access to the Internet. Although expensive, OBUs can also use cellular radio networks such as Global System for Mobile communications (GSM), General Packet Radio Service (GPRS), Universal Mobile Telecommunications System (UMTS), Worldwide Interoperability for Microwave Access (WIMAX) and Fourth Generation of cellular wireless standards (4G). In terms of security, this domain is managed by an entity that issues digital certificates to OBUs and RSUs. These certificates are used to verify if security credentials belong to nodes.

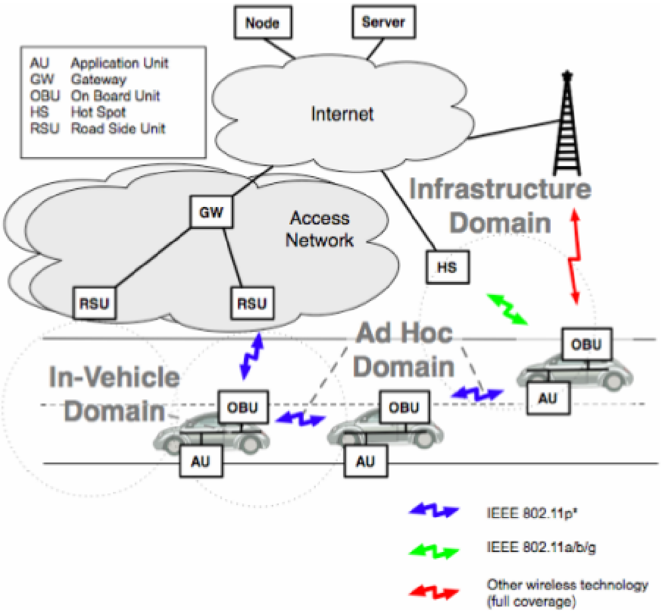


Figure 2.3: Car-to-Car Communication Consortium architecture in [3]

2.6 Data dissemination

As it was described before, vehicular environments face distinct types of scenarios in which nodes density is different. In this context, dissemination algorithms are important in order to support efficient communications among applications. Most of them have restricted requirements of latency.

According to Kumar [24], data dissemination can be divided in three approaches:

- **Opportunistic data dissemination:** Information is totally received when vehicle or infrastructure target is in their range and available to communicate.
- **Vehicle-assisted data dissemination:** Vehicles carry information with them and send it to receiver (RSU or vehicle) as soon as possible.
- **Cooperative data dissemination:** Part of information is received by vehicles and shared later to complete the transfer.

Data dissemination along VANETs can also be performed via multi-hop or single-hop as it is illustrate in figure 2.4.

Generally single-hop is implemented via broadcast over MAC layer. Through figure 2.4 in scheme (a), vehicle A disseminates data to the neighbour vehicles. Vehicles out of range such as B does not receive it. Through single-hop communication, information is only sent to all vehicles that are reachable by one hop.

On the other hand, data dissemination can be via multi-hop which is the most common in VANETs. Here, data disseminates through several vehicles from the emitter until the receiver. This case is also represented in scheme (b), shown in figure 2.4. In this case vehicle A communicates with B through C, although multi-hop can be performed by broadcast.

Another criteria to classify data dissemination is the number of receivers that should receive data information:

- **Unicast:** The message is addressed to one node. This mechanism is usually used by leisure applications such as streaming, games or access to contents in internet.
- **Multicast:** Messages are addressed to a certain network group. Through multicast it is possible to define a group of vehicles as a target to send information.
- **Broadcast:** Packets are flooded in the network to vehicles within the vicinity of the sender. These ones will relay the packet along the network. As result, packets can cross the entire network from the sender until other distant vehicles. It is used essentially by safety applications. Since vehicular network can cover large areas, broadcast is usually performed to zones where the information is relevant. Kremer [25] described a new concept called Zone-Of-Relevance (ZOR), which defines a certain zone where messages are useful, and messages are only broadcasted to vehicles that belongs to this area.

This topic has been extensively investigated and some relevant conclusions are presented in the literature.

Torrent-Moreno et al. [26] analysed the reception probability sent via broadcast. It was considered a widespread VANET scenario with saturated traffic. It was verified that messages have between 20 and 30 percent probability of being succeeded for distances of 100 m. Large distances have lower success probabilities.

In order to improve broadcast performance Alshaer e Horlait [27] proposed a mechanism where vehicles retransmit broadcast messages with a certain probability based on vehicles' density. Broadcast storms which were referred before, could be minimized by this approach.

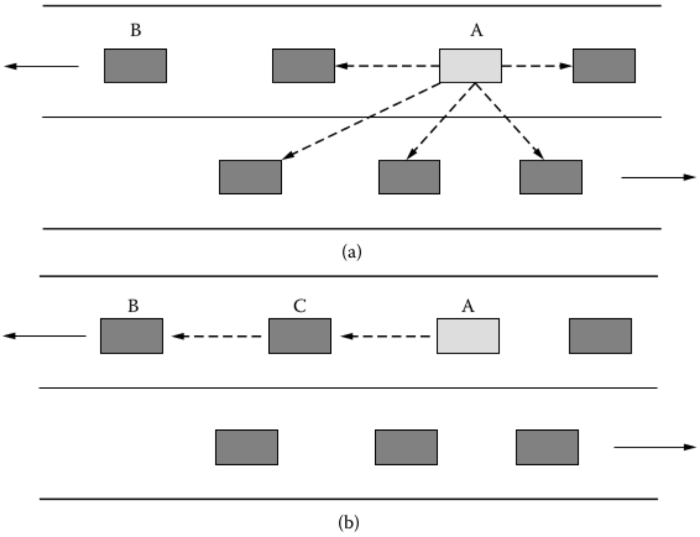


Figure 2.4: Single-hop/broadcast and multi-hop/unicast data dissemination in scheme (a) and (b) respectively [4]

Considering broadcast over V2I and V2V scenarios, Veronica Palma et al [28] investigated its performance under different network scenarios. It was verified that optimal network design can enhance dramatically system performance, once scenarios with RSUs achieved lower delays and higher throughputs when compared with V2V communications.

Resta el al. [29] used a probabilistic approach to analyse emergency message dissemination via multi-hop over V2V communications. They achieved lower bounds on the probability through which a vehicle receives a message successfully within an interval time.

Lastly Wischhof et al. [30] suggested that groups of isolated vehicles could be connected through RSUs. In this context a vehicle forwards information to the closest RSU which broadcasts the information to all the vehicles from that ZOR. Thus, broadcast storms would be minimized and consequently network overload.

2.7 Network access technology

As previously mentioned, FCC allocated 75MHz radio spectrum in the 5.9GHz band for DSRC. It is used exclusively by V2V and V2I communications. Moreover, this spectrum is divided in seven 10MHz channels: six for safety and non-safety applications and one control channel for control information and high priority messages. Safety application performance depends on the access technology that is used. Thus IEEE amended the physical and the MAC layer, and developed WAVE standard which is formed by IEEE 802.11p and a family protocol stack of 1609 protocol. The IEEE 802.11p operates over PHY and MAC, while IEEE 1609.X focuses on MAC and upper layers.

2.7.1 WAVE standard

OBUs and RSUs use WAVE standard which is composed by six sub-standards to ensure a dedicated handling on each layer. Each standard focuses on different issues over different layers. Below, figure 2.5 shows WAVE architecture and its relation at each Open Systems Interconnection (OSI) model layer. WAVE, which has several challenges that are being investigated, should be scalable, robust, low latency and cognitive [31].

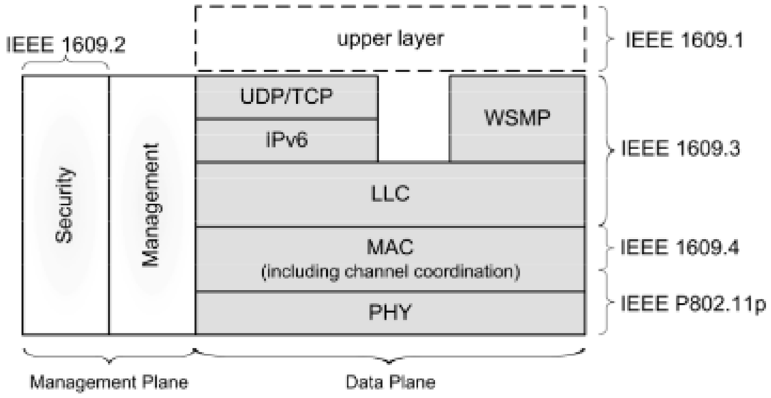


Figure 2.5: WAVE architecture in [5]

As it is illustrated in figure 2.5, it supports TCP/UDP/IP and the WAVE mode Short Message Protocol (WSMP) protocol to route priority messages with high latency restrictions.

According to [32] IEEE 109.4 allows IEEE 802.11p to operate in multi-channel over CCH and the six Service Channel (SCH) to carry the different types of messages. The IEEE 1609.3 standard specifies a set of functions that are related with Logical Link Control (LLC), network and transport layer. It handles addressing and routing within WAVE system. On the other hand, IEEE 1609.2 processes the format of security messages and perform its encryption and decryption. Finally, IEEE 1609.1 manages resources in WAVE. Thus, applications can be remotely controlled by a resource manager and a remote device.

2.7.2 IEEE 802.11p

IEEE 802.11p is an amendment of IEEE 802.11a to operate efficiently in vehicular environments.

According to Jiang e Delgrossi [19] IEEE 802.11p was designed to define the set of services and functions that are needed by WAVE stations to face independently extreme environments. It also characterizes a new set of WAVE signaling techniques, as well as interface functions that are managed by IEEE 802.11 MAC.

Regarding modifications, IEEE 802.11p operates at 5.9GHz instead of 5GHz, manages seven channels with 10MHz bandwidth each to deal with multipath environments, illustrated in figure 2.6 and uses different modulation and coding schemes. With this last amendment, data transmission range from 3 to 27Mbps. In this standard, even higher data rates can be used in high speed environments. Finally authentication is not required by nodes.

After defining 802.11p standard, several studies over different conditions were carried out to evaluate its performance.

Jafari et al [33] evaluated WAVE architecture and IEEE 802.11p standard through Network Simulator 2 (NS-2) [34] using realistic vehicular mobility models. They found out that end-to-end delay was directly related to the distance between the vehicle that broadcasts messages.

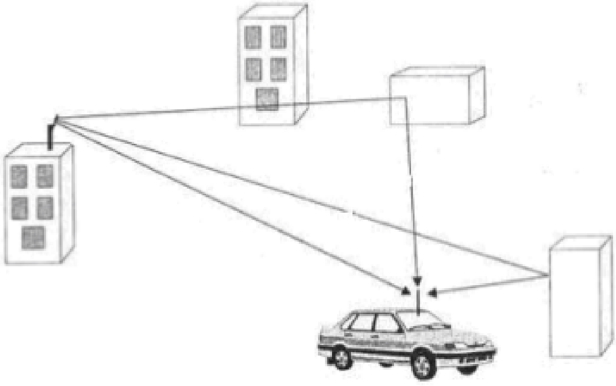


Figure 2.6: Multipah physical environments [6]

Results also revealed that end-to-end delay and average throughput increase as the message size increase. Finally it was shown that the probability of successful message reception was the same for all vehicles when the distance between transmitter and receiver was less than 138m.

Ghandour et al. [35] analysed the usage of multi-channel in tems of effective utilization of the channel resources. More specifically, it was studied the performance of safety applications over multi-channel single radio VANETs. It was shown that synchronous channel switching affects message delay and delivery ratio. Moreover, they concluded that IEEE 1609.4 WAVE has some drawbacks that can compromise vehicular applications with strict delay requirements. After investigating broadcast communication on multi-channel single-radio, they proposed a method that provides fast dissemination of safety messages in 1609.4, which is compatible with the existing WAVE. This scheme reduces delivery delay of safety messages and increase delivery ratio under different topologies and various applications.

IEEE 802.11p MAC is based on Carrier Sense Multiple Access (CSMA) where nodes listen the medium before sending. If the channel is busy, nodes have to wait a period of time which could lead to delays, specially in dense scenarios. Bilstrup et al. [36] studied MAC performance under this mechanism, and concluded that a specific node/vehicle experiences a packet loss around eighty percent. Thus Bilstrup et al. proposed to use Self organized Time Division Multiple Access (STDMA) for communication between vehicles. Initial results showed that STDMA outperformed CSMA for traffic safety applications in ad hoc vehicular networks.

Todd et al. [37] analysed the impact of speed and vehicles density and proved that speed is an insignificant parameter in vehicular communications, unlike vehicle density. For different velocities it was concluded that average throughput does not change significantly, average delay converges and packet loss increases.

Finally, Neves et al [38] evaluated the communication range in real scenarios and concluded that it is possible to perform communications with more than 1 km in Line-of-Sight (LOS) and around 100 m in Non-Line-Of-Sight (NLOS) scenarios.

2.7.2.1 MAC layer

MAC layer provides an interface and control mechanism between data link and PHY to allow efficient communication. This layer suffered several changes in order to adapt it to vehicular environments. According to [39] Basic Service Set (BSS) is a group of IEEE 802.11 stations which are connected though an Access Point (AP) via wireless. Whenever a station wants to access a BSS, it must obtain a Service Set IDentification (SSID) which is the public name of a wireless network. Furthermore, every BSS has an unique Basic Service Set Identification (BSSID) which is shared by all stations. Figure 2.7 shows a BSS interaction.

Normally, vehicular communications occur in high speed environment, requiring rapid transmissions, however BSS mechanism for IEEE 802.11 MAC consumes much time, being unsuitable for IEEE 802.11p. In [19] the term WAVE was introduced, arising a new BSS type: WAVE Basic Service Set (WBSS). This method allows a station to change data, after joining and completing a WBSS process. The BSSID is always available and authentication and association are not needed.

A WBSS is a type of BSS in which stations using WAVE mode communicate with a common BSSID. When a vehicle intends to join the WBSS, it sends a WAVE beacon with the required information. A vehicle joins a WBSS if it is configured to exchange frames with the BSSID associated to that WBSS. Additionally, a station should not be member of more than one WBSS simultaneously, neither join a BSS. Finally, WBSS is extinguished when it has no members.

Figure 2.7: Basic service set concept in [7]

2.7.2.2 PHY layer

Doppler effect caused by movement and challenging channel characteristics increase interference over vehicular environments. However, PHY layer suffered the minimum necessary changes from IEEE 802.11 PHY to allow WAVE communications.

Nonetheless a set of changes were made [19]:

- **10MHz channel:** IEEE 802.11p uses 10MHz channel with Orthogonal Frequency-Division Multiplexing (OFDM) modulation instead IEEE 802.11a, which uses OFDM over channels of 20MHz. Consequently, parameters in time domain were doubled when compared in IEEE 802.11a. Redefine bandwidth was essential to guarantee a feasible guard interval to prevent inter-symbol interference over the same radio transmission in vehicular environments. Note that live guard is an interval to ensure that distinct transmissions does not interfere among them. To sum up, a narrower bandwidth makes signal more robust against fading and multipath propagation in vehicular environments.
- **Improve receiver performance requirements:** Channel interference is a physical property which occurs to vehicles that share the same medium, as showed by V. Rai et

al. [40]. To overcome this phenomenon, IEEE 802.11p defined a standard that specifies receivers' features to avoid the adjacent channel interference.

- **Redefine transmission mask:** IEEE 802.11p uses four spectrum masks which are more accurate and reliable. Each one has a specific output power and a transmit spectrum mask.

Through [41], those referred doubled parameters in time domain reduced data rates to a half. Table 2.1 resumes IEEE 802.11p specifications.

Parameter	802.11p	802.11a	Amendments
Channel bandwidth	10MHz	20MHz	Half
Data rate	3, 4.5, 6, 9, 12, 18, 24 and 27	6, 9, 12, 18, 24, 36, 48 and 54	Half
Modulation	BPSK, QPSK, 16-QAM, 64-QAM	BPSK, QPSK, 16-QAM, 64-QAM	No change
Coding rate	1/2, 1/3, 3/4	1/2, 1/3, 3/4	No change
Guard time	1.6μs	0.8μs	Double
OFDM symbol duration	8μs	4μs	Double

Table 2.1: 80211p and 80211a PHY values, adapted from [9]

In IEEE 802.11p, the symbol time was doubled leading to the reduction of data rate to a half. Then, considering the same transmit power, one symbol is twice more powerful than in 802.11a. Accordingly, energy per symbol and per bit is doubled.

Regarding Bit Error Rate (BER), Pavel [6] studied transmissions over fading channels, comparing IEEE 802.11a and 802.11p PHY layer. It was concluded that IEEE 802.11p achieves better results since it needs less energy per bit to achieve the same BER.

In terms of data rate adaptation it is interesting to analyse table 2.2. Note that the minimum receiver sensitivity increases as the rate increases. Thus, modulations of higher rates are less resistant to environments where interference and adverse conditions are less experienced.

Such mechanisms act differently according to the decision they adopt to increase or decrease data rate. Regardless the mechanism that is used to adapt data rate, minimum receiver sensitivity is a parameter through which it is defined if the receiver is affordable or not. Consequently power threshold has a great importance in vehicular communications once sensitivity is fixed and hardware-related for all standards. This subject will be deeply exploited in the following chapter.

2.8 Applications and services

As already mentioned, VANETs were developed to increase road safety. In order to be attractive and feasible, VANETs have to provide applications and services to enhance adherence to become a desirable technology by investors.

Thus, besides safety applications, VANET can support other types of applications such as traffic monitoring and management and comfort applications.

Data Rate (Mbps)	Minimum receiver sensitivity (dBm)
3	-85
4.5	-84
6	-82
9	-80
12	-77
18	-70
24	-69
27	-67

Table 2.2: Minimum receiver sensitivity per data rate adapted from [10]

2.8.1 Safety applications

These applications focus on decreasing road accidents and the loss of life. They provide active road safety by warning drivers at real time through critical information that requires low delay. Kumar et al. [24] suggested several usages for safety applications such as:

- **Curve speed warning:** Driver is warned whenever he approaches too fast a danger curve. In this case GPS and maps are used to evaluate risk of accident.
- **Traffic signal violation warning:** Driver is warned that he is close of running the traffic signal. Message is sent after evaluating traffic signal status, timing, and vehicles' position and velocity. This warning can be broadcasted by RSUs to vehicles that are in its range.
- **Emergency electronic brake lights:** Vehicle is alerted when the preceding vehicle makes an abrupt braking maneuver. This warn is performed in cooperation by other vehicles and RSUs.
- **Collision risk warning:** In this case vehicles in cooperation with RSUs detect the chance of collision among vehicles that are not able to communicate. The system collects data about vehicles that are coming from the opposite direction and are approaching the intersection. If there is risk of accident, vehicles from ZOR will be warned.
- **Stop sign movements assistance:** This system was designed to avoid accidents at intersections. Network collects data and informs driver when it is safe to pass the intersection or not.
- **Control loss warning:** Neighbours vehicles will be warned through broadcast message if a driver had loss the vehicle's control.

Taking into account their usage, Kihl et al. [4] divided safety applications into two categories: Cooperative Collision Avoidance (CCA) and Emergency Warning Message (EWM).

2.8.1.1 Cooperative Collision Avoidance

The main purpose of CCA is to avoid all types of collision such as chain collision or frontal collision. When they receive this type of messages, vehicles can brake automatically if they support this mechanism, otherwise they can simply alerted.

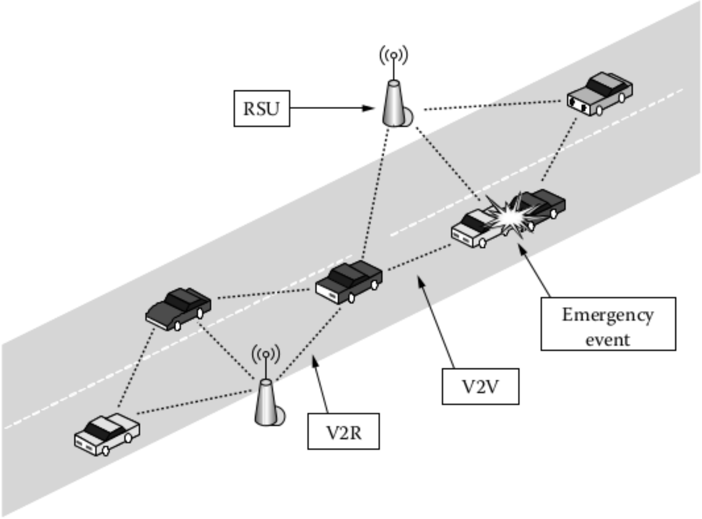


Figure 2.8: Safety application in [4]

In order to be effective, these messages have to be received on time, according to Biswas et al. [42] safety messages does not support latency time larger than 100 ms. These messages are only performed over V2V communications once V2I do not guarantee the referred delay. Figure 2.8 illustrates an accident and the safety messages flow. Safety messages are sent to vehicles and RSU which are responsible for forwarding the messages.

2.8.1.2 Emergency Warning Messages

EWM Applications consist on detecting an accident or a dangerous zone and inform all the vehicles of that ZOR.

These applications require that messages remain available for a certain amount of time [43]. They can be performed over V2I communications once they do not have high restrictions delay. RSUs have an important role for these applications, since they can maintain the messages in a certain ZOR.

EWM divides into two categories [4]:

- **instantaneous:** It informs other vehicles about an accident or anomalous situation. Once again the warning is addressed to all vehicles of that ZOR. These messages are not available for a long time.
- **permanent:** These messages aim to warn about dangerous road conditions. In order to be effective they have to be available for long time to inform approaching vehicles. EWM permanent can act in geocasting mode in which the message is sent to all vehicles in that ZOR, and then vehicles take responsibility for warning neighbour vehicles coming into that ZOR as it is illustrated in figure 2.9.

As low density scenarios have low connectivity, Maihofer [44] proposed a central server unit in charge of disseminating information in the ZOR. In this scheme vehicles would send an EWM to the responsible unit of that ZOR via cellular network.

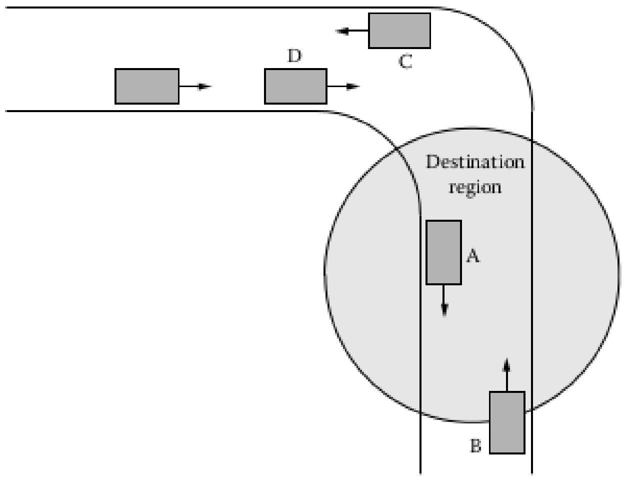


Figure 2.9: Permanent geocasting in [4]

2.8.2 Monitoring and management applications

These applications improve vehicle traffic flow, traffic coordination and assistance. Unlike safety messages, these applications do not have delay restrictions. Basically, they aim to provide an intelligent road monitoring. Monitoring and management applications can be divided into two classes [45]:

- **Speed Management applications:** These applications help drivers in managing the speed of their vehicles, leading to smoother journeys avoiding dangerous situations.
- **Co-operative navigation application:** These applications increase vehicular traffic by managing the navigation. Recommend itinerary or traffic information are examples of these applications.

2.8.3 Comfort applications

These types of applications provide entertainment and useful messages to the driver and passengers. Through vehicular network drivers can access to internet and search information like nearest coffee or cinema. It also provides video on demand and music streaming. Users can receive announcements from hotels or restaurants when cross a certain area [43].

Thus, according to [24] comfort applications can be divided into: co-operative local applications and global internet applications.

Co-operative local applications are services provided by local applications which refer something of that area while other application type focus on global services such as community's services or parking zone management.

Finally, access to the internet can be supported through cellular networks, WIMAX or Wi-Fi hotspots.

2.9 Summary

This chapter provided an overview of vehicular networks based on the information available in the literature. First, it was given a brief summary of VANETs history and definition. Then, some specific characteristics were described as well as technical challenges.

It was also presented three types of architectures for VANETs deployment: pure ad hoc, pure WLANs/cellular and hybrid. Posteriorly it was analysed the addressing and data dissemination schemes. Then, the standards developed for vehicular communications were also presented, focusing on IEEE 802.11p and 1609.x family. It was explained their purpose and characteristics. Finally, amendments in PHY and MAC layer were also discussed.

Regarding applications, it was shown that they can be divided in several categories: safety, monitoring and management and comfort applications.

Chapter 3

Data Rate Adaptation in wireless Networks

3.1 Introduction

The previous chapter introduced the main concepts and challenges of VANETs. By its side, this chapter presents the main concepts of data rate adaptation mechanisms in wireless networks.

First, section 3.2 presents the purpose of rate adaptation mechanisms and discusses their challenges. Several techniques that are used to choose the optimal rate are also described.

Afterwards, in section 3.3 it is discussed and compared some of the most important rate adaptation mechanisms for wireless networks.

Finally section 3.5 describes network and mobility simulators

3.2 What are Rate Adaptation Mechanisms?

In VANETs, vehicles are constantly moving, generating unpredictable interference caused by fading, attenuation or interference from other 802.11 devices. Even when nodes are stationary, wireless channel conditions change, due to the area around devices.

This channel instability can affect the network and application performance, the overall system performance. Thus, MAC layer performs an important role in terms of QoS that is offered through its mechanisms. One of these MAC layer mechanisms is rate adaptation.

Rate adaptation aims to select the best data rate in order to achieve the optimal throughput for specific channel conditions. Some algorithms estimate channel conditions, measuring the time-varying state of the wireless channel. These algorithms must adapt fast to minimize delay between time adaptation and packet time transmission, once predictions of future channel conditions can become outdated. Indeed, rate adaptation depends on accuracy of the channel quality estimation, otherwise inaccurate estimations will affect negatively the system performance leading to packet loss and long transmission times. The main goal is to avoid over or under selection rate.

Data rate should be chosen using appropriate metrics relative to channel quality such as SNR or BER. Other adaptation mechanisms use different parameters to chose a physical bit-rate; however, they must also provide fast adaptation, low overhead and high throughput.

A different approach is rate adaptation based on frame loss, which has been also implemented in some algorithms. Loss based approach considers that channel quality decreases if the frame loss increases; consequently, a lower data rate is chosen.

Nevertheless, frame loss can be due to interference among different transmissions instead of channel degradation. Thus, a decrease on the data rate in these cases can cause higher frame loss, because lower rates will extend frame transmission time. A reliable trade-off between physical data rate and robustness is required to maximize system performance. Higher rates lead to higher throughputs and low transmission times, although transmission range from which frames can be decoded is reduced, since RSSI and channel capacity decreases with distance. For example, cellular networks adapt data rate through feedback mechanism from the receiver to the sender. The 802.11 standards do not specify the referred feedback mechanism; instead they look for the best transmission rate by estimations using probing or other parameters, such as the number of successful or failure transmissions.

According to [46], rate adaptation algorithms face some important challenges in vehicular environments, such as:

- **High SNR variation:** Usage of metrics to measure SNR encounter some difficulties due to contentiously SNR variations over the time. In vehicular environments, RSSI spikes are larger and more inconstant then in stationary environments.
- **Delay induced by estimation window** Packet error estimation window causes delay in rate adaptation, since estimation window approach is reactive and relies on past history for future link quality evaluations. As link conditions changes rapidly in vehicular environments, estimation window could contain old and unreliable samples.
- **Idle station** Estimation windows cannot work with idle stations, since they have not participated in recent transmissions. Then, it is impossible to estimate parameters in the recent past.
- **Hidden station**: Collisions due to hidden stations are barely addressed by packet error statistics. In these cases rate is decreased by rate adaptation mechanisms which aggravates the channel collisions, since it would prolong the transmission time.

3.2.1 Techniques

As described before, rate adaptation algorithms can address different techniques to choose the optimal data rate. In fact, its adaptation varies according to the method that is adopted. Thus, such mechanisms can be designed according to the following techniques:

- **Transmission history:** Through this technique, algorithms select data rate according to patterns registered in transmission history. These informations, such as timeouts and number of retransmissions are obtained from the link and MAC layer. These techniques are less responsive and need some time to achieve the optimal data rate [47, 48].
- **Probing:** Algorithms based on probing technique sense the channel conditions using probe packets at different rates. If probe packets are well succeeded in terms of throughput, then the rate changes to the probe packet rate. Probe packets can be sent at the next higher rate or at random rates [47, 49].

- **PHY information:** This approach uses PHY layer to obtain relevant information to select a data rate. Its estimations result from metrics contained in PHY layer such as SNR or RSSI of the received frame. Through this technique, rate adaptation can be more dynamic and fast since it focuses on direct measures of channel conditions. However information from PHY layer is limited to signal strength, since wireless card interfaces were not designed to provide more information [50, 51].
- **Channel reciprocity:** This method is based on gathering information exploiting channel reciprocity. The sender obtain accurate channel information and adapts more quickly to dynamic wireless channels without including Request To Send (RTS)/Clear To Send (CTS) or probe-packets [52].
- **RTS/CTS:** This mechanism has the purpose of obtaining information from the receiver to the sender to allow better estimations by the sender. Finally, it permits loss differentiation, since packet loss could be due to channel degradation or collision (dense networks). As referred before, decrease the data rate without finding out the real reason of packet loss might lead to low systems performance. In this scheme collision probability increases as transmission time increases. As this mechanism also increases system overhead, some algorithms have been implemented with a different approach called RTS/CTS probing to evaluate whether to use it [53, 12].

Rate adaptation mechanisms can be classified differently according to the features that are considered. According to Xi Chen [50] rate adaptation mechanisms based on channel condition information can be divided into two groups:

- **Packet statistics-based:** These algorithms use consecutive frame transmission failure and success as indicators of channel quality;
- **SNR-based:** It is used RSSI values of ACKnowledgment (ACK) frames to analyse channel conditions at the receiver part, assuming a symmetric channel.

The same author classified rate adaptation mechanisms into two groups, but now basing on rate updating period:

- **Window-based:** These algorithms are reactive and depend on history to predict channel conditions. Scenarios with adverse channel conditions hampers the choice of the optimal window size.
- **Frame-based:** Algorithms use number of frame transmission failure and success to readjust the data rate. These parameters are compared with a threshold to find out when data rate should be adapted.

In the next sub-sections algorithms will be addressed considering two groups as described in Biaz et al [12]: rate adaptation algorithms with and without loss differentiation.

3.3 Algorithms without loss differentiation

This sub-section presents rate adaptation algorithms without loss differentiation, which cannot distinguish frame loss due to channel degradation from collisions. They can be divided into two groups [12]: frame loss and SNR based rate adaptation.

3.3.1 Frame loss approach

These algorithms gather information through monitoring packets over the wireless channel to select the optimal data rate. Generally, they consider metrics such as packet delivery ratio and throughput to evaluate channel conditions.

Kamerman et al. [54] proposed the first rate adaptation mechanism for IEEE 802.11 named Auto Rate Fallback (ARF). It adapts the rate comparing the number of consecutive successful transmissions with a threshold. Rate increases whether the referred threshold is reached or when a time expired. Through this algorithm, senders start a transmission using the lowest rate available in that standard. Rate decreases to the previous rate if the first transmission using the new rate fails, or when occurs two consecutive failures.

Later Lacage et al. [55] improved this algorithm and implemented the Adaptive Auto Rate Fallback (AARF). This algorithm produce less rate fluctuations than ARF, being more stable. A sender increases the rate when the consecutive successful transmissions reaches the threshold. If the first transmission with this new rate fails, the sender adapts the rate to the lower rate and doubles the threshold. If the first transmission at the new rate succeeds, then the threshold is reset.

Onoe [56] was developed by MadWifi and implemented in Linux 802.11 wireless driver. It is an algorithm that searches for the highest data rate that guarantees a loss rate lower than 50 percent. Thus it decreases data rate to the previous rate when the average number of retries per packet is larger than one, and increments a variable called credit if the number of retries per packet is lower then 10 percent, otherwise it decrements the credit. If the credit is larger than 10, then the rate is increased and the variable credit is reset. Otherwise, data rate is maintained. Data rate is only adapted at intervals of 100 ms. Lastly, it is insensitive to bursty losses and does not adapt when fast wireless channel changes occur.

Adaptive Multi Rate Retry (AMRR) [47] was, in parallel with Onoe, one of the first proposed mechanisms. It uses one probe packet to test the next higher rate after transmitting N packets. This parameter N is doubled when a probe packet fails, and it is reset when AMRR decreases the rate. If the probe packet succeeds, AMRR increases the rate. It decreases the data rate after two consecutive failed transmission.

Minstrel [57] is one of the most used algorithms. It can be found in mac80211 Linux driver framework ported from MadWifi. This algorithm [58, 59] is composed by three parts in order to chose the optimal data rate: multi-rate retry chain to chose the best data rate whenever it occurs short-term variations in channel quality; rate selection which defines the rate of normal and sampling transmission; and statistics calculation. Minstrel obtains statistics of the channel quality through sampling transmissions and takes rate selection decisions as table 3.1 illustrates. The referred table is filled periodically every 100 ms according to the measured throughput and probability of success for each rate.

Regarding ”look around rates” from table 3.1, Minstrel performs a specific strategy before trying a new rate. It does not sample slower random rates if the link is good. In this case lower rates than the current rate are not used, they are placed second in the retry chain. However, if the link is not good, then it will be tested sample frames at the random rate. When the link deteriorates, it uses sample frames at lower rates. This method, which determines if lower rates should be sampled, allows better performance than the initial approach, where it was wasted too much time sampling lower rates over good links.

Lastly, Shankar et al. [46] proposed Context-Aware Rate Selection (CARS) which is a rate adaptation mechanism for vehicular networks. This algorithm uses context information such as vehicle speed and distance from the neighbour to select the data rate. Thus, link quality is estimated using the context information and the history. CARS estimates the packet error through a weighted decision involving two functions. One of them uses context information, transmission rate and packet length to estimate the packet error rate. The other function uses Exponential Weighted Moving Average (EWMA) of the transmitted frames statistics for each rate. The weighted decision is performed by a parameter, that gives more relevance to context information or to the EWMA of the frame transmission statistics. This parameter is based on the vehicle velocity. Consequently, when the velocity is zero, context information will not be used to predict link quality. It will be given preference to EWMA. This algorithm estimates the throughput for each rate, selecting the rate that provides the higher throughput. This calculation is based on packet error rate, average and maximum number of retransmissions, and a parameter that means the weight given to unsuccessful packet transmission.

Try	Look around rates (sample frames)		Normal Rate (data frames)
	Radom<best	Radom>best	
1	Best throughput	Random rate	Best throughput
2	Random rate	Best throughput	Next best throughput
3	Best probability	Best probability	Best probability
4	Lowest base rate	Lowest base rate	Lowest base rate

Table 3.1: Multi-rate retry chain used by minstrel in [11]

3.3.2 SNR approach

These algorithms use channel reciprocity or information from the receiver to select the optimal data rate.

Holland et al. [60] developed an algorithm called Receiver-Based AutoRate (RBAR). In this approach, receivers select the appropriate transmission rate during RTS/CTS exchange, based on SNR measurements. Unlike the described algorithms so far, rate adaptation is carried out by receivers. According to the same author, this algorithm has the following advantages:

- Rate selection is more accurate since receiver performs channel quality estimation and rate selection. Channel quality can be estimated through parameters that are available at the receiver side, such as number of multipath components, symbol error rate and RSSI.
- Channel quality is estimated closely to the transmission time, since rate selection is performed during RTS/CTS exchange.
- It can be implemented in IEEE 802.11 devices.

As already mentioned, RBAR uses RTS/CTS mechanism. Depending on the SNR of the CTS frame, RBAR selects the highest rate that assures a BER lower than 10^{-5} and encodes it in the CTS frame. Then, the transmitter decodes the chosen data rate from the CTS frame. The main drawback of this mechanism is its dependency on RTS/CTS mechanism, which can lead to network overhead, especially in dense scenarios.

Judd et al. [52] proposed Channel-Aware Rate Adaptation (CHARM) which obtains channel information exploiting the channel reciprocity; it is assumed that conditions at the receiver side are identical to the sender side. The sender monitors the transmission through RSSI that is contained in ACK frames from a specific destination. Then, it estimates the path loss to the receiver based on a certain equation, using the RSSI and a Linear Weighted Moving Average (LWMA). By its turn, the path loss is used to estimate the SNR at the receiver side. The SNR is compared with a set of thresholds, which are updated according to the performance of the previous transmission. Finally, the SNR is used to check a multi-rate table in order to choose the best data rate. CHARM does not introduce network overhead, since it avoids CTS/RTS usage and is more responsive to channel fluctuations when compared with loss-based algorithms. Its main drawback is the assumption of channel symmetry. It considers that ACK frames experiences the same SNR than data frames. However, Gangwal et al. [61] showed that it is not true in mobile networks.

3.4 Algorithms with loss differentiation

A frame loss might be owing to either channel fading or collision. In fact rate adaptation can be ineffective or even harmful in some cases of loss: data rate should be only decreased due to channel degradation, not as response to collisions.

Federico Maguolo et al. [47] suggested some modifications to AARF and proposed AARF-CD. This algorithm uses probing RTS/CTS to decide when to use such mechanism. The usage of this mechanism and the redefinition of the number of consecutive transmissions attempts required to increase the rate are the main differences between AARF and AARF-CD.

CARA which was implemented by Kim et al. [53], uses Clear Channel Assessment (CCA) and RTS/CTS frames to differentiate collisions from failures due to channel quality. CARA uses RTS/CTS only when it is required, instead of the algorithms presented so far. In this context, CARA reduces collisions from hidden terminals and minimizes network overhead caused by RTS/CTS. It is easy to implement in 802.11 devices, since both mechanisms are already available in the referred standard. This algorithm will be deeply explained in chapter 4.

Robust Rate Adaptation Algorithm (RRAA) by Wong et al. [62] also uses RTS/CTS mechanism after a transmission failure to avoid further collisions own to hidden terminals. This algorithm is based on two modules:

- **Rate adaptation:** RRAA starts transmitting with the higher available rate. Then, it selects data rate according to the loss ratio, obtained from transmissions statistics of the recent history. It compares the loss ratio with two thresholds to decide whether to increase the rate.

- **Collision loss:** RRAA uses a variable RTS window to specify the number of consecutive frames proceeded by it. RRAA does not adapt fast in case of high channel fading, since it only adjusts its rate at the end of the transmission window.

Verma et al. [63] developed a rate control mechanism called Ack-Guide Immediate Link rate Estimation (AGILE) that allows the transmitter to adjust the data rate using SNR measurements from ACK frames, and estimating the maximum achievable throughput. In this algorithm SNR of a frame represents the quality of the channel at that time. It is equipped with "RTS filter" that provides intelligence to decide when to use RTS/CTS mechanism or not. In order to select the data rate, this algorithm calculates the probability of a successful frame transmission for each rate, using the SNR of a received frame. Then, basing on this probability and considering also each rate, it determines a parameter, that is called transmission time for a frame. At last it selects the rate with the minimum transmission time.

Chen et al. [50] proposed a receiver-based algorithm called Rate Adaptation in Mobile environments (RAM) which can deal with channel asymmetry, and uses a SNR prediction method that handles well with high channel fluctuation. It is based on SNR, since packet statistics might not work well in mobile environments. As SNR is a direct measurement from channel conditions, RAM adapts well when wireless conditions fluctuate. In this algorithm, the receiver selects the data rate and feeds the transmitter, setting some values in a special register using MadWifi. Note that to modifications in ACK format is impractical, once it would require amendments in 802.11 devices at the lower layers. In order to avoid hidden nodes interference, RAM uses a RTS window to control the usage of RTS frames.

Algorithm	Loss differentiation	Based Location	Condition Indicator
ARF	No	Sender	Loss Ratio
AARF	No	Sender	Loss Ratio
AARF-CD	Yes	Sender	Loss Ratio
Onoe	No	Sender	Loss Ratio
AMRR	No	Sender	Loss ratio
Minstrel	No	Sender	Loss Ratio
RBAR	No	Receiver	SNR
CHARM	No	Sender	SNR
CARA	Yes	Sender	Loss Ratio
RRAA	Yes	Sender	Loss Ratio
AGILE	Yes	Sender	SNR
RAM	Yes	Receiver	SNR
CARS	No	Sender	Loss Ratio

Table 3.2: Features of rate adaptation mechanisms adapted from [12]

To sum up, table 3.2 summarizes the main characteristics of each described algorithm.

Rate adaptation has been exhaustively investigated considering different network topologies, mobility models, standards and metrics. Below, it will be presented the main research in the performance of rate adaptation.

Yin et al. [49] compared most mechanisms available for 802.11 devices through a controllable platform. Experiments were performed using IEEE 802.11a and nodes had no mobility. It used scenarios with fixed channel conditions and different average SNR, external interference and hidden terminal interference. It was concluded that Minstrel outperforms the remaining algorithms in terms of throughput for different traffic loads, either in high or low quality links. As a final conclusion Minstrel also performs better when compared with mechanisms that are SNR or BER based.

Through simulations, Kim et al. [53] proposed and compared CARA with ARF using IEEE 802.11b. It was used different network topologies: one-to-one, star, line and random topologies; different data frame sizes; and different wireless channel models. None mobility model was used. It was shown that CARA outperforms ARF specially in scenarios with higher node density.

Regarding to RRAA, Wong et al. [62] performed extensive experiments through an indoor environment. It was considered hidden terminals and static and mobile nodes. Static nodes were placed in different locations, while mobile nodes were moving slowly inside the building. Experiments were performed using IEEE 802.11a/b. It was verified that RRAA outperforms ARF, AARF and sample rate, improving throughput up to 35.6 percent over sample rate, and by up to 143.7 percent when compared with ARF.

By its turn, Xia et al. [58] investigated Minstrel performance over three different scenarios: static channel transmission, fast and gradual variations in channel quality. Nodes had no mobility and experiences were performed using 802.11g standard. It was concluded that it provides reasonable results in static wireless channel conditions, although it has difficulty in choosing the optimal rate in dynamic channel conditions. Moreover, Minstrel performs better when channel conditions get better, than when it deteriorates from high to low. In this last case, Minstrel usually does not select the optimal rate, instead it uses rates too high. This feature is undesirable when channel conditions experience deterioration and rapid variations. It was shown that Minstrel is even outperformed by certain fixed rates.

Lacage et al. [55] simulated AARF and AMRR resorting to IEEE 802.11b/g. It was considered transmissions through one single hop with different distances between the nodes. Station A remained static while station B moved towards station A. Station B stayed static for 60 seconds before moving 5 meters. It was concluded that the referred algorithms achieve throughputs close to RBAR which is impracticable in 802.11 MAC and PHY protocols.

RBAR was implemented by Hollad et al. [60] using NS-2. It was showed its performance in scenarios with different node speed, burst length, distance and packet size. It was also used rayleigh fading channels. It was used Intersil Prism II chipsets (family of conexant chipsets used for wireless networks) with some changes in terms of modulation schemes, providing different rates. Since RBAR is more efficient to predict channel quality, its results achieved higher overall throughput in every scenario when compared with ARF.

Resorting to NS-3, Frederico Maguolo et al. [47] simulated AARF-CD comparing it with: ARF-CD, ARF, AARF, RRAA, CARA-RTS and the ideal algorithm that always chooses the best current rate, according to the channel conditions experienced in that moment. It was varied two parameters: the number of nodes and the distance among them. Velocity was not considered. All the nodes were equipped with IEEE 802.11a interfaces. Independently of the considered scenario, it was concluded that AARF-CD outperforms the mentioned algorithms in terms of throughput, and achieves a performance similar to the ideal algorithm available in NS-3.

Verma et al. [63] proposed a rate adaptation mechanism called AGILE that was implemented in their MadWifi-based testbed. It was considered scenarios with increasing path loss, contention level, varying channel quality and transmitter mobility. Experiments, which were performed using IEEE 802.11a, considered scenarios with 3, 4 and 5 stationary nodes; scenarios with hidden stations; scenarios where it was varied the medium quality; and the transmitter mobility (roughly 1m/s). In all the referred scenarios AGILE outperforms the remaining algorithms: Onoe, AMRR and Sample rate.

Chen et al. [50] suggested and tested RAM in vehicular and indoor environments. Nodes were equipped with IEEE 802.11b. In the vehicular experiments, it was used one static and one moving vehicle with the following velocities: 2, 9 and 15.6 m/s. Indoor experiments were performed in their department building. In this scenario it was considered static nodes as well as mobile nodes which had velocity of human walk. This algorithm outperformed algorithms like CARA, RRAA, ARF, CHARM and Sample rate either in indoor static and mobile environments or outdoor vehicular environments. In this last environment, performance were particularly better, once its throughput was higher than the remaining algorithms, specially for low velocities.

CHARM was analysed by Judd et al. [52] in real world and on a controlled testbed, using IEEE 802.11b/g. Both scenarios were tested with two nodes. The real tests were performed in urban environments, inside apartment and across two university campuses. Two cases of nodes were considered in these scenarios: static and mobile. In the mobile scenarios the receiver was static while the receiver moved within the range of the receiver for 40 seconds. Regarding to the controlled testbed, it was only considered mobile scenarios with IEEE 802.11b technology. Nodes moved through a predefined route in the emulated scenario at different velocities: 0.5, 1 and 2 m/s. Beyond this, it was used high and low traffic rate and considered hidden terminals. Results showed that CHARM gathers quickly and accurately channel information. Comparing with Onoe, Sample rate and AMRR, CHARM obtained better results in static and dynamic environments, outperforming the probe-based algorithms.

Lastly Shankar et al. [46] evaluated CARS using IEEE 802.11a technology, through simulations and real outdoor vehicular environments. The outdoor experiences considered different mobility scenarios: two stationary nodes; two nodes following each other at 11.2 m/s; two vehicles moving at 31 m/s in a highway with traffic jam; intermittent scenario, where vehicles are mostly out of range. This algorithm was also tested for scenarios with different vehicles' density. In the simulated scenarios it was considered typical cities and highways with RSUs. In these scenarios, highways had 5000m and several lanes. It was also tested scenarios without RSUs through highways with 10km of length. Vehicles from one direction were clients, while vehicles moving in the opposite direction acted as servers. CARS was compared with AARF and Sample rate algorithm using the referred scenarios. It was verified that CARS adapts faster to channel variations when it experiences high vehicular speed than the existing algorithms. It was concluded that CARS achieves higher throughput up to 79 percent in the considered scenarios. Moreover, it is more resistant to collisions due to hidden stations, once it was achieved an improvement up to 256 percent. The results from simulation were in agreement with the experimental evaluation.

At this moment, it was depicted the main literature in this area. Algorithms have different behaviour in different scenarios, under different conditions. The objective of this dissertation is rate adaptation evaluation in VANETs using IEEE 802.11p standard.

Some of the presented algorithms in this chapter cannot be evaluated and compared due to either lack of information regarding their design and implementation or problems in NS-3. Beyond this, all of these algorithms were implemented and tested by their authors in the Madwifi device driver, complicating their integration in a simulator environment. CHARM uses a technique called time-aware weighted moving averaging that reduces the inaccuracy introduced by old channel information. This approach uses a linearly decreasing function of the time interval between the new packet and the previous one, starting at 1 and decreasing to 0, when the time between the new packet and the last one exceeds the window time. However, this function was not provided by the authors, and consequently it was not possible to implement this algorithm. RAM was also not implemented, since this algorithm requires some changes in ACK frames, which are not supported by NS-3. In order to perform its rate adaptation, CHARM needs to set periodically some registers of the ACK frame. However, these registers cannot be handled dynamically as attributes in NS-3. By its turn, the authors of CARS did not provided the mathematic models that support this algorithm. It uses two empirical models, which were obtained through outdoor vehicular experiments, to calculate the packet error ratio: a liner regression model of error rate as a function of distance, speed, bitrate and packet length and a model based on a sliding window statistics algorithm. Finally, AGILE requires some driver modifications in order to fill a table with attributes from each transmission/reception frame, complicating its implementation in simulator environment. Note that simulators are structured and implemented as the actual technology and standards, without considering these changes.

Therefore, rather than test every available algorithm, it was analysed which one of them has more potential to obtain good performance in VANETs:

- **AARF-CD [47]:** This algorithm was compared with ARF, ARF-CD, RRAA and Ideal in NS-3. It was varied the number of nodes and distance between them. In every scenario, AARF-CD outperformed the remaining algorithms. Its performance was close to the Ideal algorithm. Thus, it was considered that it could be a good term of comparison in vehicular environments.

- **CARA [50]:** Although CARA is not the purpose of this research, it achieved a consistent performance in mobile environments. For example, in scenarios with hidden nodes, it was the second best algorithm in terms of throughput. It also obtained good results over outdoor scenarios for slow drives. Only RAM and CHARM lightly outperformed CARA in this case. RRAA never obtained better results than CARA.

- **Minstrel[49]:** This algorithm was simulated under scenarios with external interference, hidden terminals and different averages SNR over the channel. It was shown that Minstrel got a higher performance then Onoe and AMRR. Thus, Minstrel could provide better results then the other two algorithms in vehicular environments.

To sum up, for these reasons AARF-CD, CARA and Minstrel will be tested in NS-3. The Ideal algorithm, available in the same simulator, will be also used.

Indeed, there is not any conclusion relative to this subject. This dissertation brings new evaluations and conclusions to scientific community, since it has not been tested yet in literature, under the following specifications:

- IEEE 802.11p standard;

- Varying density nodes in highway scenario;

- Varying nodes velocity in highway scenario;

- Varying distance between nodes in highway scenario;

- Urban scenario.

3.5 VANET simulation

Simulation tools are essential for researchers to develop and analyse new mechanisms and protocols for VANETs. Designing virtual networks, which behave like real networks is the main goal of simulators. Thus, they must be accurate [64, 65] in order to achieve reliable results. In this sub-section, it will be analysed several network and mobility simulators.

3.5.1 Network simulators

Below, it will be described the main network simulators to design virtual VANETs. Each one has its own features that can be more suitable for certain simulations.

- **QualNET [66]:** It was created at University of California and is maintained by scalable network technologies. Its wireless simulation models are based on BER. It also provides many propagation models like Corner [67] implemented for VANETs. It is a discrete event simulator, written in C++. Finally it is open source and has a graphical user interface.

- **NetSim [68]:** It was developed in 2002 by Tetcos and Indian Institute of Science. It is a stochastic discrete event simulator and open source software. In terms of simulation, it provides many metrics to evaluate a network at different abstraction levels like network, node and packet traces. It supports many protocols and network technologies such as MANETs, Wi-Fi, IP, QoS and VoIP. The interface environment between users, NetSim libraries and simulation kernel is made through an in-built environment. Its modules are written in C++.

- **OMNet++ [69]:** It is a modular simulator whose frameworks and libraries were written in C++. It is a discrete event simulator and open source. It provides graphical runtime environment, network emulation, database integration and other tools.

- **GNS3 [70]:** It is an open source software that simulates complex networks very close to reality. It supports a graphical user interface to design the network.

- **NS-2 [34]:** It is a discrete event simulator targeted for network simulation. It was the most preferable simulator by academic researchers for a long time. It is open-source and implemented in C++ and tool command language (Tcl). It is also important to refer that Gukhol et al. [71] implemented the IEEE 802.11p standard for VANETs. However, it became in disuse, since its wireless model was not completely accurate and due to its high complex structure. It does not support graphical user interface.

- **NS-3 [72]:** This simulator is an evolution of NS-2 and the most used by researchers. Due to its modular implementation, it is easy to design and add new modules written in C++ or python. It is an open source software, however it does not support graphical user interface. According to [73], this discrete event simulator is the best simulator, presenting the highest overall performance.

Taking into account the features of each simulator and the specifications required by this dissertation, NS-3 was selected as the most suitable. It is the simulator that supports more rate adaptation mechanisms, providing an easy integration of these mechanisms in the devices. The following points also supported this decision:

- Scalable and modular;

- Well documented;

- Reliable once protocols and mechanisms are close to reality;

- Suitable for wireless communication, supporting a wireless model based on BER;

- Easy network configuration;
- Fast execution time;
- Easy to integrate frameworks from other simulators;
- Widely used by research community;
- Easy to debug.

3.5.2 Mobility simulator

As already described, VANETs experience high mobility through its nodes. In this context, it is needed an appropriate mobility model in order to obtain accurate simulations. Vehicular mobility simulators can be divided into two classes [74, 75]: microscopic and macroscopic. Microscopic models each single vehicle, and each vehicle is considered as a distinct element where its behaviour depends on its neighbours vehicles as well as the driver [76]. Macroscopic models refer to all aspects that influence vehicular traffic such as road topology, traffic jam, speed and number of lanes.

Therefore mobility simulators provide traces that can be applied over a network. The main mobility simulators are:

- **CORSIM [77]:** Developed by US federal highway administration. It uses urban and highway microscopic mobility models.
- **DIVERT [78]:** Microscopic simulator which deals with real maps. It is maintained by University of Porto.
- **SUMO [79]:**It is an open source simulator, portable which uses microscopic mobility models. It is prepared to handle large road networks with continuous road traffic. It is one of the most popular simulators for VANET.
- **VISSIM [80]:** It provides a graphical user interface and uses microscopic model to characterize vehicles.
- **FreeSim [81]:** It is a macroscopic and microscopic simulator. FreeSim is ideal for ITS simulation, since vehicles are able to communicate with the system and monitoring the traffic.
- **Paramics [82]:** It is a microscopic traffic generator designed to simulate real world traffic, providing real working solutions. It enables traffic management and strategic road schemes to be evaluated in economic and environmental terms. It is used by transportation researchers and government agencies.
- **VanetMobiSim [83]:** It is an open-source simulator based on CanuMobiSim [84] architecture. It was conceived to be integrated in telecommunication network simulators. It supports macroscopic and microscopic mobility models and simulates different traffic scenarios according to user preferences.

It was chosen SUMO to obtain realistic traces of mobility, considering simulation requirements and its features:

- Include all the tools required to perform traffic simulation;
- Provides realistic simulations in terms of speed, priorities and car following model;
- Scenarios are easy to configure;
- Manages networks with several 10.000 edges (streets);
- Easy to integrate in NS-3;
- Fast execution speed up to 100.000 vehicle updates/s on a 1GHz machine;
- Dynamic routing;
- Collision free vehicle movement;
- High portability.

3.6 Summary

This chapter provided an overview of rate adaptation mechanisms, presenting several related works and comparisons between their performance. First, it was explained the purpose of rate adaptation mechanisms and their challenges in VANETs: high SNR variation, delay induced by estimation window and idle and hidden station. Then, it described the techniques that are used by rate adaptation algorithms in order to choose the optimal rate. Several mechanisms for wireless networks were also described and divided into two main groups: algorithms without and with loss differentiation. After comparing them, it was concluded that AARF-CD, CARA and Minstrel are the most appropriate algorithms to be analysed and compared. Indeed, rate adaptation research in VANETs is not yet deeply discussed, since there are few investigations and comparisons in this field, unlike for Wi-Fi networks, which have many available algorithms. More parameters and scenarios need to be considered in order to implement a solid algorithm for VANETs. Finally it was presented the network and mobility simulators that were chosen to perform the simulations.

Chapter 4

Scenario implementation

4.1 Introduction

As previously mentioned, NS-3 was chosen to simulate a vehicular network in order to analyse data rate adaptation algorithms. The changes in NS-3 modules that were made to perform all the goals initially proposed in this dissertation are focused along this chapter. First this platform will be presented in section 3.2, referring the reasons which make it the most suitable simulator for this type of network. Section 3.3 explains the Wi-Fi model implementation, presenting its sub-models. Then, in section 3.4 the architecture and characteristics of scenarios will be deeply described, justifying the role of each module. In this section, it will be also explained all the procedures that were used to achieve the metrics to evaluate each data rate mechanism.

Finally section 3.5 presents the challenges that were overcome to achieve the final results.

4.2 Simulation platform

Before addressing NS-3 modules, it is needed to analyse its features and capabilities to perform the simulation of vehicular networks. NS-3 is a discrete-event network simulator, written in C++ and Python for research and educational usage. This simulator is more reliable and accurate than NS-2, specially in wireless communication which is the core of all implementations. The existing enlightening documentation facilitates its usage and debug, showing how the network flux interacts with all the modules. Therefore, NS-3 project built a solid real-time network simulator with an easy network configuration, trace collection and data analysis. Beyond these features, NS-3 supports IEEE 802.11p standard and several data rate adaptation mechanisms, which can be handled with the standard previously referred. NS-3 offers many mobility models; however, none of them is suitable to simulate a real vehicular network scenario. In a real scenario other vehicles and road and weather conditions affect vehicles' mobility. To overcome this lack of reality in NS-3, it was decided to use a trace file from a simulator of urban mobility (SUMO). Afterwards, these trace files are imported and integrated in NS-3. The NS-3 also supports research on IP and non-IP based networks. However the large majority of its users focuses on wireless/IP simulations which involve models for Wi-Fi, WIMAX or Long-Term Evolution (LTE) for PHY and MAC layer, and a variety of static or dynamic routing protocols such as Optimized Link State Routing (OLSR) [85] and Ad hoc On-Demand Distance Vector (AODV) [86] for IP based applications. Ultimately

NS-3 supports a real-time scheduler that facilitates a number of "simulation-in-the-loop" use cases for interacting with real systems. Users can emit and receive packets on real network devices, and NS-3 can act as an interconnection framework to add link effects between virtual machines.

4.3 Wifi model

The main components of NS-3 are illustrated in figure 4.1.

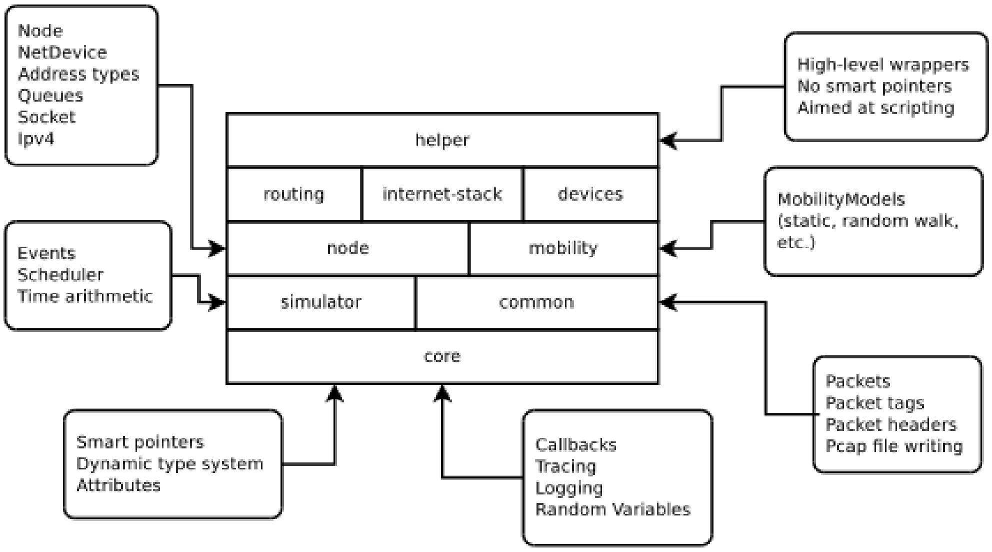


Figure 4.1: NS-3 architecture - [8]

A simulation can be run after setting nodes, device, protocol stack, applications and a channel to establish a communication. These nodes, devices and applications can be created through containers. Each common group can be configured at once. For example a "NodeContainer" is created with several nodes that belong to a device, connected to a shared channel. Protocol stack and application are installed in the same way. Finally a node can be in multiple "NodeContainers" and have multiple devices, allowing several connections. The referred devices available in NS-3 are:

- PointToPoint device;
- CSMA device;
- Bridge device;
- Tap device;
- Wi-Fi device;

It was used Wi-Fi device and IEEE 802.11p technology for all simulations; consequently, this device will be better described below.

4.3.1 MAC model

In this section, it will be introduced the basic modules of 802.11 implemented in NS-3 and their relation. Indeed, it is necessary to understand how they are structured and connected, to facilitate the comprehension of some adopted methodologies in the developed work.

According to figure 4.2, which shows ”Wifi” module architecture, ”WifiNetDevice” class holds together the following ”Wifi” related objects:

- ”WifiChannel”;
- ”WifiPhy”;
- ”WifiMac”;
- ”WifiRemoteStationManager”;

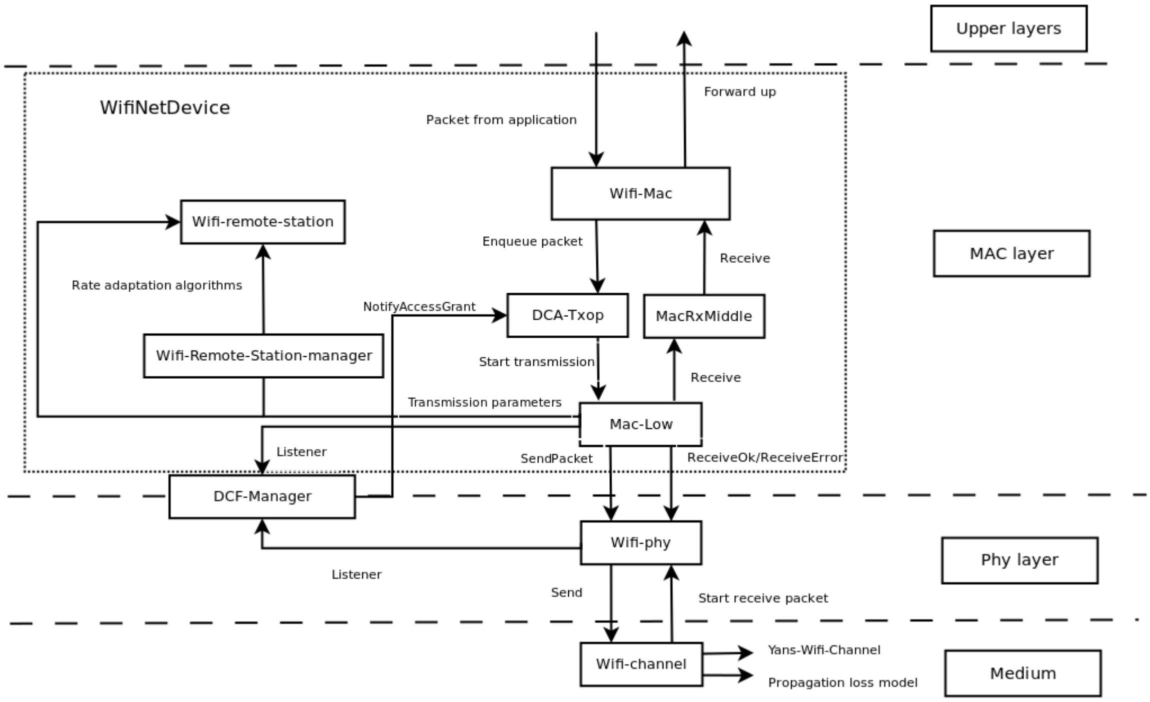


Figure 4.2: 802.11 implementation in NS-3

MAC model is divided into two main models, MAC low which is associated to Distributed Coordination Function (DCF), and MAC high which is responsible for high level MAC management.

As it is shown in figure 4.2 MAC Low is splitted in four main classes to perform its functionalities:

- ”MacLow”: It deals with transmission control RTS/CTS and ACK and data frames. According to the transmission parameters, ”MacLow” initiates RTS/CTS transmission or waits for the reception of an ACK frame. According to the host destination, it obtains the transmission mode for the next transmission from "WifiRemoteStation". "MacLow" signals "WifiRemoteStation" if a transmission was successful or failed. In case of success, the received packet is forward to "MacRxMiddle".

- "DcfManager": It handles the physical carrier sense from "WifiPhy" and decides if the access is granted or not.
- "DcaTxop": This class works with frames queuing, holding the current frame until it is acknowledged, handles frames from upper layers in "WifiMacQueue", fragmentation and retransmission.
- "MacTxMiddle" and "MacRxMiddle": "MacTxMiddle" processes frame fragmentation and appends sequence numbers to the frames, before being transmitted, while "MacRxMiddle" assembles them. It can also discard duplicate frames taking into account their sequence number.

On other hand, "MAC High" works with "WifiMac", which processes beacon generation, probing and association establishment. There are six classes of "WifiMac":

- "**AdhocWifiMac**"**:** It simulates stations that does not handle management coordination for Ad-Hoc networks.
- "**NqstaWifiMac**"**:** makes association with an access point in range and re-association if many beacons are missed.
- "**NqapWifiMac**"**:** allows active beacon generation and records the non-AP associated station state.
- "**QadhocWifiMac**"**:** provides QoS traffic for four access categories for "AdhocWifiMac".
- "**QstaWifiMac**"**:** offers QoS traffic for four access categories for "NqsWifiMac".
- "**QapWifiMac**"**:** provides QoS traffic for four access categories for "NqapWifiMac".

Only "AdhocWifiMac" will be used to implement a VANET. A "WifiNetDevice" also contains "WifiRemoteStationManager", which holds a list of per-remote-station state, "WifiRemoteStation" classes. "WifiNetDevice" controls all the underlying transmission parameters, like data rate, RTS/CTS exchange threshold, rate control, short and long retransmission and retransmission counters. Thus, it is easy to understand, that data rate algorithms are implemented in an instance of "WifiRemoteStationManager", since it defines data transmission features such as bit-rate according to channel conditions. In "WifiRemoteStation", for each destination a new station is created. This model provides an interface for "MacLow" class, to find out when a successful or a lost transmission occurs, in order to define the data rate for the next transmission. By its side, data rate is selected using rate adaptation classes from "WifiRemoteStationManager", which contain each of the algorithms described before:

- ArfWifiManager;
- AarfWifiManager;
- IdealWifiManager;

- OnoeWifiManager;
- AmrrWifiManager;
- CaraWifiManager;
- AarfcdWifiManager;
- MinstrelWifiManager;
- ConstantWifiManager;
- RraaWifiManager.

4.3.2 Phy model

PHY layer is implemented in "YansWifiPhy" class, taking *Yans* model [87] as reference. PHY model operates using one radio interface with half-duplex communication. It provides the simulation of wireless reception and propagation, deciding if a frame can be received and decoded or not. It is closely related with wireless channel model and mobility model for the nodes. Every physical data rate presented in IEEE standard, such as 802.11p, is defined in an instance of "WifiMode" class. In accordance with *Yans* model reference, a physical layer might be in one of these states:

- IDLE - physical layer is IDLE;
- CCA BUSY - Physical layer sensed the medium as busy through CCA mechanism;
- TX - Physical layer is sending a packet;
- RX - Physical layer is receiving a packet;
- SWITCHING - Physical layer is switching to another channel.

4.3.3 Channel Model

Channel models are essential elements to model a real network. A Wireless channel is simulated through a propagation loss model, which performs propagation loss in the transmission medium. It adds the effect of the configured "PropagationLossModel" on the transmission power. Thus, the reception power is accurately calculated and conveyed to the "WifiPhy".

4.4 Scenario architecture

To develop all the tested scenarios, it was necessary to analyse and interpret the interaction between models in order to understand how the traffic flow is processed. Thereafter some changes were made in NS-3 models to achieve the desired results. This phase was the most complex and time consuming of all work, since it was required to define the parameters that should be used and how to handle them in each model. After that, it was possible to adapt the simulation platform aiming to trace the right data, taking into account the dissertation requirements. To simulate a vehicular network it was necessary to define a specific packet traffic flow between nodes, and some attributes of MAC and PHY layer. Thereby, to create a VANET, it was considered this set of steps:

- Create dynamic variables to define the number of running nodes, duration of the simulation and UDP session;
- Create a container that aggregates these nodes. Containers are structures that store nodes, which will be set with a certain mobility, application, loss and "Wifi" models. Note that "Wifi" model includes all the data rate adaptation mechanism that will be used during simulations;
- Configure a mobility model and a loss model in the referred nodes;
- Configure the interface of each node with a "Wifi" model, Internet stack and IP address;
- Define an UDP echo session to allow communication between nodes.

All these modules are defined independently; however they are linked between them, allowing packet traffic flow from application layer up to the physical layer. Figure 4.2 depicts how these models are related and how data packets cross each layer. As it can be noticed, each square on the right represents one layer from Transmission Control Protocol (TCP)/IP model. The remaining refers to models that belong to each layer.

Thus, the following sub-sections explain the models that were used and the changes that were performed, in order to build the final scenario and get reliable results. Note that each sub-section is only related with one NS-3 model.

4.4.1 UDP sessions

Two simple application classes are used just to generate traffic flow between nodes: "UdpEchoServerApplication" and "UdpEchoClientApplication". Each client starts a communication with its server and waits for the echo message. These classes provide two assistants to facilitate client's and server's configuration named "UdpEchoServerHelper" and "UdpEchoClientHelper". All the UDP sessions are configured with the same maximum number of packets, interval time between packets and packet size for each performed scenario. These attributes are carefully chosen to guarantee packet loss and retransmissions only due to network intrinsic features, avoiding buffer queue or channel saturation effects. It was performed tests using three rates of packets for different cases of nodes' density and found out which traffic data flow should be applied to all scenarios. It was considered scenarios with high density of nodes as a critical case, once they are sensitive to channel saturation. Therefore, results from low and high dense scenarios would not be affected by inappropriate traffic data flow. It was taken this procedure to set the same amount of exchanged data in each scenario, and allow a fair comparison among results. Thus, it was considered 1,1 Mb/s of traffic flow per UDP session, that is approximately a half of the lowest data rate available in IEEE 802.11p. Consequently, it was configured sessions that send 133.3 packets of 1024 bytes per second. This approach leads to better results, reducing network overload especially in scenarios with many nodes in the same range.

4.4.2 Address IP and protocol stack

The assistent "InternetStackHelper" is used to install a stack protocol applying its method "Install" in "NodeContainer". This last assistant creates and manages any object "Node" over which the simulations are run. Then, the object "Ipv4Interface" assigns an IP address to each node. Finally, it is configured an application to generate traffic into the network.

4.4.3 Routing protocol

AODV is chosen to determinate the appropriate path over which data should be transmitted. This protocol is responsible for specifying how nodes forward information in a network and how they report network changes. According to Haerri [88], who evaluated AODV and OLSR in vehicular environments under realistic mobility patterns for different densities of nodes, concluded that OLSR outperforms AODV in terms of routing overhead, end-to-end delay and route length. However, AODV provides better Packet Delivered Ratio (PDR), specially when the network is dense, after a certain threshold. Consequently, it has fewer interference on the used metrics to evaluate rate adaptation mechanisms, since most of them rely on the success of delivered packets. Regarding vehicles' velocity, it is shown in this article, that it does not affect routing protocols performance.

In fact, routing protocol does not interfere with data rate adaptation mechanisms performance, but it improves in terms of dynamism, efficiency and fastness of information flow. Thus, through other nodes, it is possible to establish a communication between nodes that are not in the range of each other.

4.4.4 Mobility

As it was referred above, NS-3 does not support a real mobility model to implement in nodes. A mobility model involves high complexity in which many parameters have to be considered. In this way, it is imported a set of trace files from SUMO to the scenarios.

After importing these traces to NS-3, it is needed to perform a correspondence between NS-3 nodes and SUMO vehicles, because this association is random by default each time a trace file is imported. For each vehicle from each trace it is set the same node through its IDentifier (ID). This procedure is needed to guarantee that all nodes have the same features (route, maximum velocity, direction, acceleration and length) in all simulations when it is being varied a parameter. In this manner, it is easy to understand that node 1 always has an UDP echo session with node 2 in any implemented trace, if it is supposed to. More, they also have the same direction, maximum velocity, acceleration and route in any implemented trace file, for a certain evaluated parameter. To sum up, all nodes are under the same vehicular conditions in all simulations for a certain tested parameter, that influence data rate adaptation performance. Then, comparisons will bring more accurate results.

4.4.5 Propagation Loss model

It is chosen two-ray ground [89] as the propagation loss model to approach simulation conditions to reality. This model, which is more realistic than Free-Space model [90], addresses ground-reflected propagation path between transmitter and receiver, in addition to the direct line of sight path. On other hand, Free-Space model only considers that transmitter and receiver have a clear, unobstructed line-of-sight path between them.

This model uses a certain distance as threshold, called "crossover", to decide which model should be used. Free-space model is used for distances between transmitter and receiver below "crossover", while two-ray model is performed for distances above the referred threshold. This threshold is calculated using equation 4.1. Variable h_t and h_r are transmitter and receiver height, respectively, while λ is the wave length. This last parameter is obtained through light speed and operation frequency ratio.

$$C_x = \frac{4\pi h_t h_r}{\lambda} \tag{4.1}$$

To use these models, receiver and transmitter need to be distanced at least their far field, which is calculated according to the following equation 4.2, in which D is the largest antenna physical dimension and λ is the wave length.

$$D_f = 2\frac{D^2}{\lambda} \tag{4.2}$$

It is obtained $d_f = 2.57m$ considering $D = 0.256$, and $\lambda = 0.051m$ the operation frequency used by IEEE 802.11p ($5.9Ghz$). The crossover distance is $C_x = 650.97$, considering $h_t = 1.515 + 0.128 = 1.643m$ and $h_r = 1.48 + 0.128 = 1.608m$. Taking into account Friis formula [91] and using two ray model, the receiver power can be written according to equation 4.3, since transmitters and receivers normally have a distance higher than their far field, $d_f >> D$ and $d_f >> \lambda$.

$$P_r = P_t - (40\log(R) - (G_t + G_r + 20\log(h_t) + 20\log(h_r)))(dB) \tag{4.3}$$

In the previous equation, P_t and P_r are the transmitted and received power respectively, G_t and G_r are antennas gain, R is the distance between transmitter and receiver, λ is the wave length. Thus, with the previous results, it is used a loss model that simulates with a significant accuracy the real propagation model.

4.4.6 Rate adaptation

The physical rate adaptation in 802.11 is deeply investigated in Wi-Fi networks; however, research of rate adaptation in vehicular networks is very scarce. IEEE 802.11p provides a set of specification for the MAC layer and for the PHY layer. It works in non-static environments; hence, the standard provides a set of mechanisms to adapt the transmission to the system variations. For example, PHY allows a set of transmission modes that can be used to adapt to network changes. As it is known, each PHY mode uses a specific modulation and channel coding scheme, offering different performance in terms of throughput and robustness against reception noise and other types of interference.

The standard IEEE 802.11p, which is considered in this dissertation, provides eight PHY modes: eight different data rates which are selected by data rate adaptation algorithms. Data rate adaptation mechanisms are the core of this dissertation, which should be tested, analysed and compared through different metrics. Chapter 3 described the existing algorithms in the literature and evaluated their possible implementation in vehicular networks.

Thus, according to the presented related work, some algorithms can be initially discarded from simulations due to their weak performance against other algorithms, or because their usage is inappropriate in vehicular networks. Others were not evaluated due to lack of information regarding their implementation as described in the previous chapter. Thus, only four rate adaptation mechanisms will be evaluated:

- AARF-CD [47];
- CARA [53];

- Ideal [92];
- Minstrel [93];

4.4.6.1 AARF-CD

AARF-CD uses RTS/CTS mechanism, but only in certain circumstances. This rate adaptation mechanism is able to check whether to activate RTS/CTS mechanism or not. It is used whenever the counter of consecutive RTS is larger than zero. This variable is decremented if the corresponding CTS is successfully received. Otherwise, AARF-CD retries to attempt RTS transmission after a backoff period.

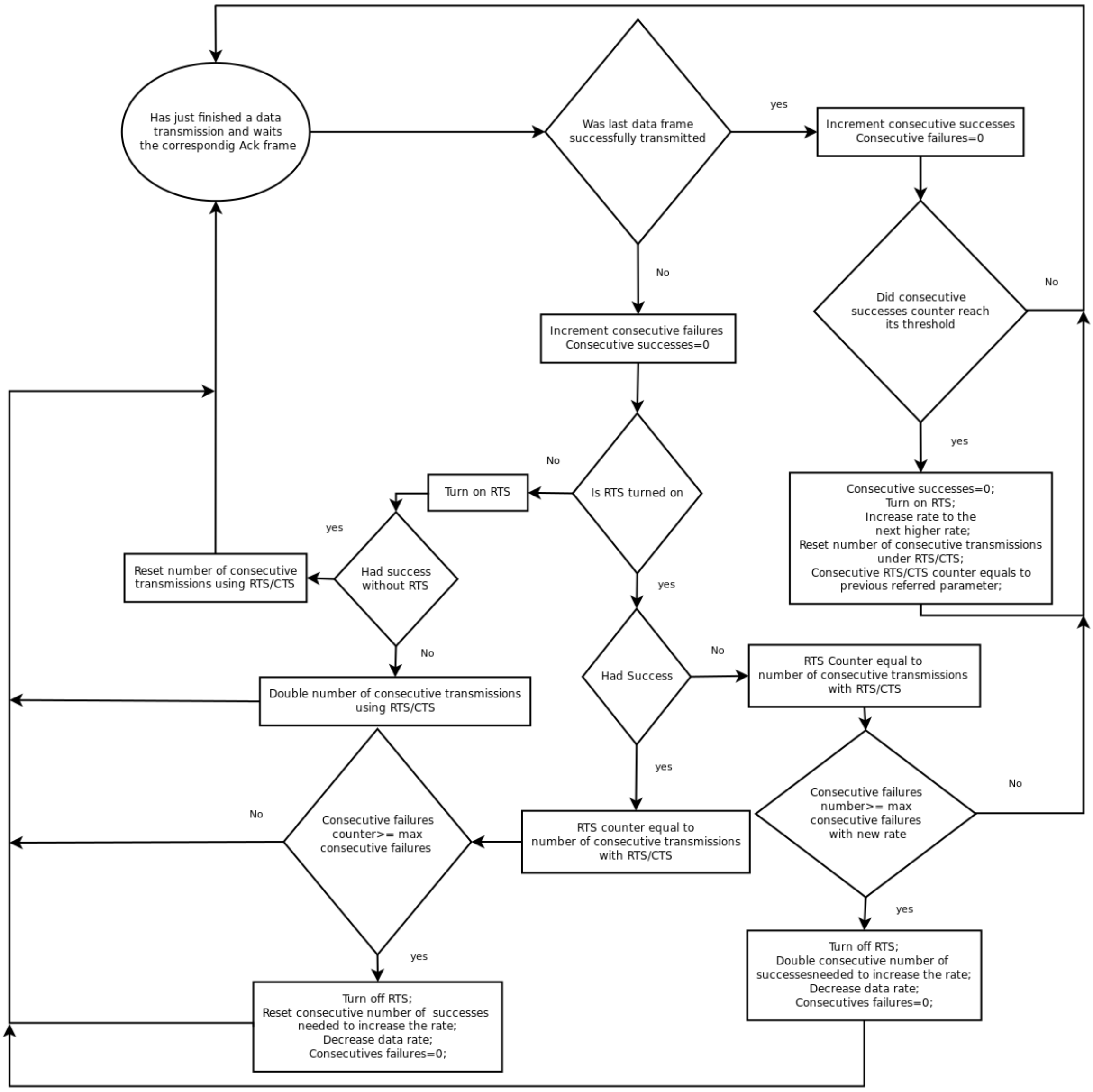


Figure 4.3: AARF-CD algorithm flowchart

Table 4.1 lists the parameters that were used in this algorithm.

Comment	Value
Maximum success threshold	60
Minimum success threshold	10
Minimum value for RTS window of AARF-CD	1
Maximum value for RTS window of AARF-CD	40
Consecutive failures needed, when a new rate is tried, to decrease the rate	1
Consecutive failures needed to decrease the rate	2

Table 4.1: Parameters used in AARF-CD

According to figure 4.3 AARF-CD can act differently depending on the last data frame transmission:

- **Data frame was successfully transmitted:** Failures counter is set to zero while consecutive successes counter is incremented by one until its threshold. At this time the next higher rate is selected, RTS/CTS is activated and the counter of consecutive RTS is equalized to the number of consecutive transmissions under RTS/CTS mechanism.

- **Data frame was unsuccessfully transmitted:** Consecutive failures counter is incremented by one and successes counter is set to zero. When RTS/CTS mechanism is disabled, the number of consecutive transmissions using RTS/CTS is doubled, if data rate has not been modified, otherwise it is reset. If a new rate is selected and the maximum number of consecutive failures after trying a new rate is reached, the rate decreases immediately, RTS is turned off and the number of consecutive successes to increase rate is doubled. On the other hand, the rate can decrease, RTS turned off and the number of consecutive transmissions required to increase the rate is reset, if consecutive failures counter reaches its threshold when there is success with RTS mechanism. To sum up RTS/CTS mechanism is turned on whenever the rate is increased or a data transmission fails. Note that parameters can be reset and limited according to user requirements, since they are attributes of the AARF-CD model.

4.4.6.2 CARA

Rate adaptation mechanisms which use RTS/CTS mechanism are able to distinguish failures due to collision or channel error, since RTS/CTS exchange reserves the channel for the following transmission. Consequently, failures associated to collisions can be disregarded.

CARA also uses RTS/CTS mechanism before sending data packets. However, to avoid network overload, this algorithm only exchanges RTS/CTS when it is required. In figure 4.4 it is illustrated a method that is implemented in Cara model. It is called RTS/CTS probing which activate this mechanism if a data transmission failure occurs; it evaluates whether to use RTS/CTS.

As shown in figure 4.4, if a transmission succeeds, then consecutive success counter is incremented up to its threshold, while the failure counter resets. Data rate increments when consecutive success threshold is reached. For unsuccessful transmissions another methodology takes place in which consecutive failure counter is compared twice. When it is larger than the

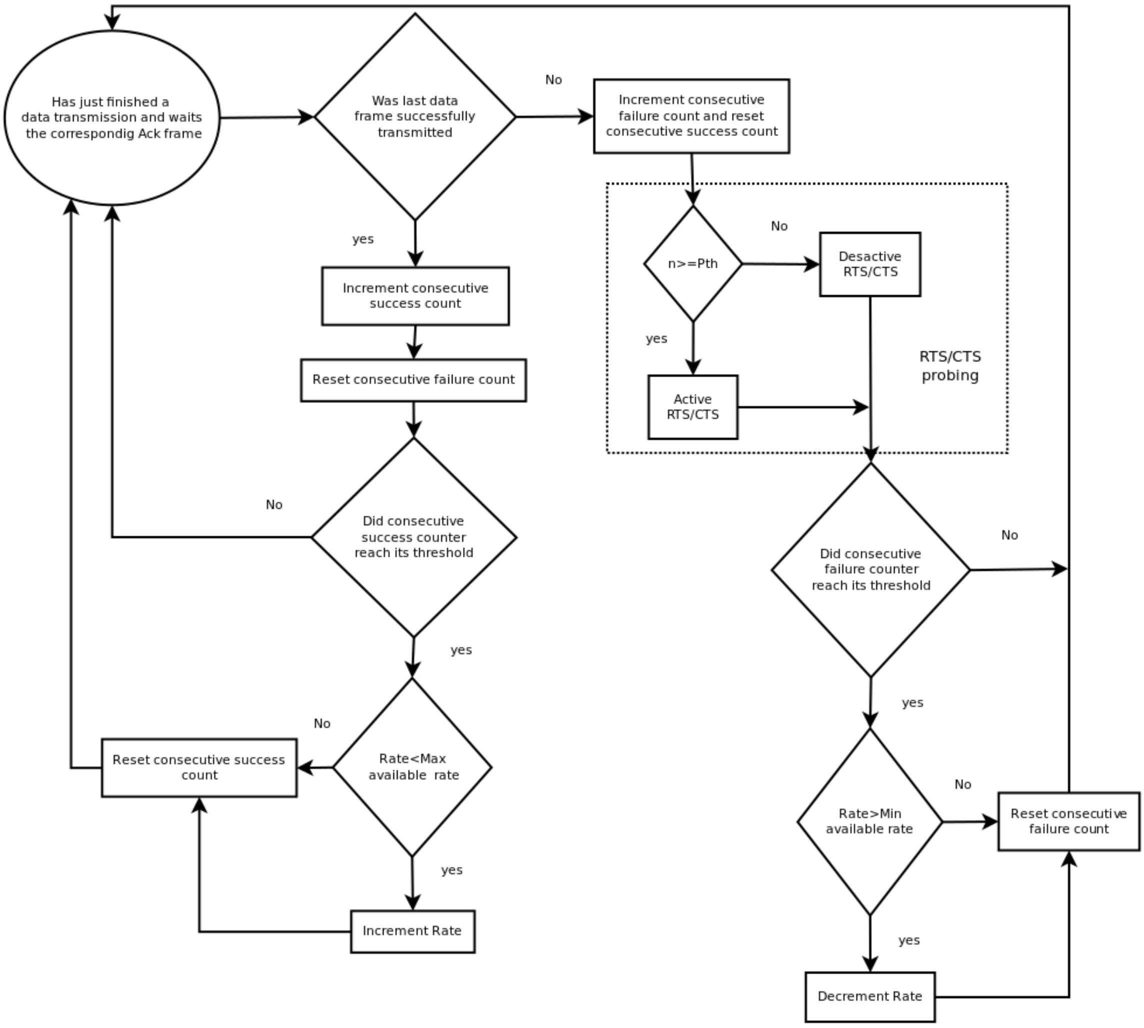


Figure 4.4: Cara algorithm flowchart

probe activation threshold, RTS/CTS mechanism is turned on. Finally it is compared with its threshold to find out if data rate should decrease or not.

This algorithm can approach different RTS/CTS probing schemes according to consecutive failure and probe activation threshold. For example, when probe activation threshold is equal to zero, RTS/CTS mechanism is used for every transmission. If probe activation threshold is larger than consecutive failure threshold, RTS/CTS mechanism is not used.

Table 4.2 shows the default values used by NS-3. In this scheme RTS/CTS mechanism is activated after one transmission failure, and the rate decreases if the correspondent retransmission fails too.

Comment	Value
Probe threshold	1
Consecutive failure threshold	2
Consecutive success threshold	10

Table 4.2: Parameters used in CARA

4.4.6.3 Ideal

This algorithm implements an ideal rate adaptation mechanism in which receivers record received packet SNR and send it back to the transmitter. There, a transmission mode is selected depending on the received SNR.

Transmission modes are defined through a set of SNR thresholds which are built from a target BER, initially set as 10^{-6}, and transmission modes are based on specific SNR/BER curves. Therefore, this mechanism works differently from others. Transmission modes are constructed dynamically for each packet, instead of choosing it according to its SNR threshold and SNR packet.

Figure 4.5 explains how the ideal rate is chosen.

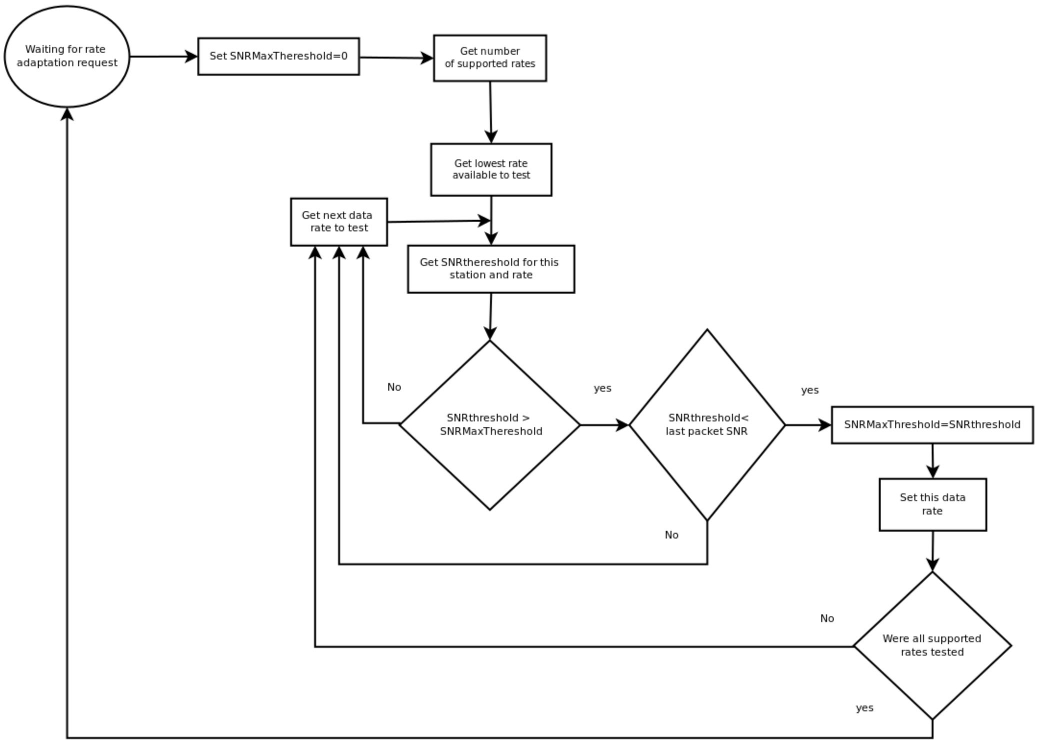


Figure 4.5: Ideal algorithm flowchart

After getting an available rate, a function called "GetSnrThreshold" returns the minimum SNR required to successfully transmit data using this mode at the specified BER. A data rate is used if its SNR threshold is lower than the last packet SNR and larger than the maximum SNR threshold at that time. This procedure is performed for all available rates.

Finally, the maximum SNR threshold is initially set to zero and updated each time the data rate changes.

4.4.6.4 Minstrel

Minstrel sends 10 percent of frames, known as sample frames, at a random rate to collect information about the respective success and throughput. The remaining 90 percent are data frames.

Consequently, its retry chain is organized according to the type of transmitted frame: sample or data frame. Figure 4.6 shows how Minstrel works to choose rates from its multi-rate retry chain, presented in table 4.6. For data frames, the rate that offers the best throughput is firstly selected. Then it is used the rate with the next best throughput, best probability, and finally the lowest available base rate.

According to its rates, sample frames have different retries in the chain as displayed in table 4.6. In high quality links, in which sampling lower rates is a waste of time, the random selected rate is placed second in the chain, if it is slower than the current best throughput.

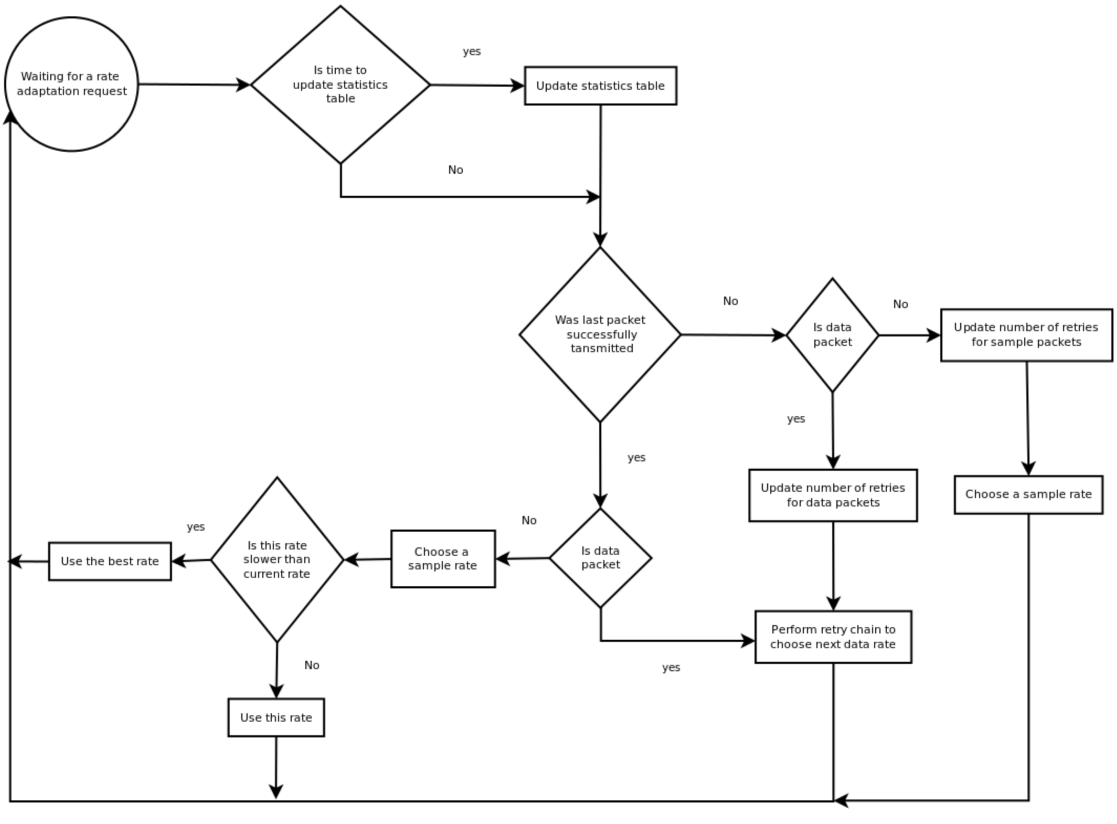


Figure 4.6: Minstrel algorithm flowchart

The random selected rate is only sampled to collect information when the link experiences low quality. Lower rates can be also sampled if a transmission fails over a high rate. Finally, retry chain statistics are updated ten times per second through a timer.

EWMA is an important feature of Minstrel algorithm. It allows to give more relevance on recent results rather than older results. It defines the history weight on the data rate choice. Note that recent results have more emphasis for higher EWMA's; NS-3 uses an EWMA of 75.

From figure 4.6, the retry chain for data is performed to choose which rate should be used for data packets.

4.4.7 Transmission parameters

MAC and PHY layers are responsible for transmitting packets over links. MAC layer controls communication with other host in the network, as well as data rates and other specifications in PHY layer. It also deals with many parameters that provide information about transmission quality. Therefore, at MAC layer it is analysed and decided which parameters should be traced and how to relate them.

Another point that was taken into account was the importance of attaching the current transmission parameters to the packet that is being handled, from a certain UDP session, to parse separately each UDP session. Then, it will be performed an average of all sessions to obtain an overall network evaluation. To describe each UDP session, it is necessary to define "Wifi-mac" as rendezvous point, in which it is possible to join its relevant parameters from different models. "Wifi-mac" is chosen, since this model can access to all transmission parameters in the receiver and sender side. So, it is able to recognize when a retransmission or a successful transmission occurs, identify the UDP session that is being processed, and handle packets in order to read contained information from others models. The following information is retrieved from this model:

- Current data rate from rate adaptation models;
- Rssi set by "PropagationLossModel";
- Transmitted packet number from "WifiMac";
- Received packet number in MAC layer from "WifiMac";
- Retransmissions number from "DcaTxop";
- Node ID from "YansWifiChannel".

It is very important to aggregate these parameters to describe each UDP session and then the entire network in terms of transmitted packet number, received packet number and retransmissions. In the same way, it is also possible to characterize each packet from a certain UDP session with the current data rate, RSSI and the node ID from the transmitter node.

4.4.7.1 Data packet identification

Data rate adaptation algorithms can be evaluated and compared through specific metrics, based on data traffic flow behaviour. Before recording any parameter, it is necessary to differentiate the data packets from all the traffic flows. In other words only packets from source application should be considered in the MAC layer, unlike packets from others layers like routing or transport, which should be discarded. Thereby, data packets are tagged in the source application to allow their identification in the MAC layer ("WifiMac"), since this layer can not distinguish types of packets.

Therefore, it is created a function, whose flowchart is shown in figure 4.7. Through the referred figure, it is possible to conclude that the initial state remains active while a packet does not arrive to be processed. When a packet arrives, its flags are checked. If this packet is not already tagged, then it will be marked as data. Beyond this, it is also tagged with its sending time to determine the delay at the receiver application. Finally, the initial state returns to active.

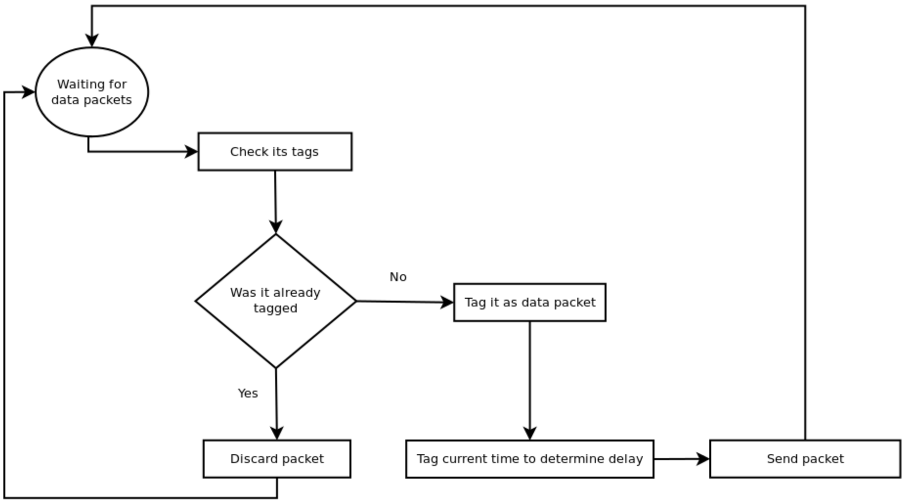


Figure 4.7: Tag data packets

4.4.7.2 Current data rate

To understand in which function and how it is selected the current data rate, it is analysed the referred data rate adaptation models. The next step is to associate to each packet the current data rate.

The purpose is to attach it in each packet to make it available in the "Wifi-mac" class. In "Mac-low" it is possible to tag each packet with the current data rate, to read it later in "Wifi-mac" model, since only in that model data packets are available to be handled. According to figure 4.2 the current data rate has to cross "WifiRemoteStationManager" to be tagged in the packet, in "MacLow". After this, the data rate that was tagged in each packet is accessible in the "WifiMac" model. In this model, it is executed the developed function described in figure 4.8.

When the MAC layer receives a packet, it is checked the packet type and its transmitter ID. Note that all handled packets in this layer were already tagged at application layer. If it is a data packet and its transmitter ID is equal to 1, then its informations about transmission capabilities are recorded. Otherwise, the packet is discarded.

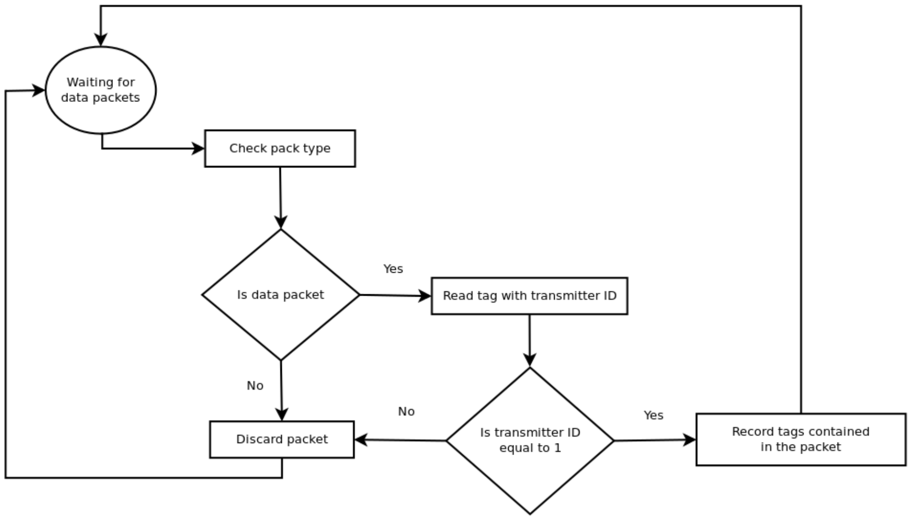


Figure 4.8: Record information in data packets

4.4.7.3 RSSI and Node ID

In "YansWifiChannel" model, it is possible to identify the RSSI and the transmitter's ID relative to a packet from an UDP session. This model calls "PropagationLossModel" to determine which RSSI shall be applied to a certain transmission. Analogous with what has been described before, each packet is also tagged with its RSSI and transmitter's ID.

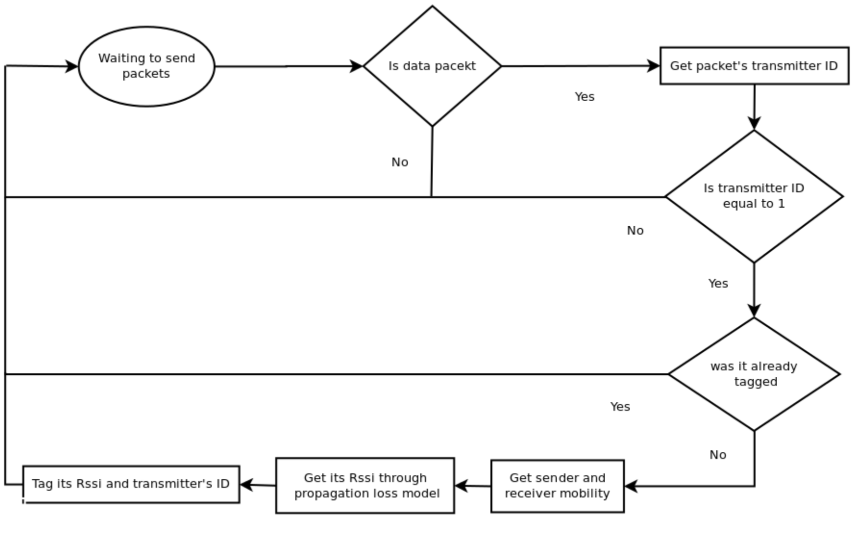


Figure 4.9: Tag RSSI and transmiter's ID

Indeed, the transmitter's ID is used only to distinguish each UDP session. Following what has been explained, it is clear that until now each packet contains the data rate and RSSI correspondent to the moment in which it was sent and its transmitter's ID. Figure 4.9

depicts the created function, which tests the conditions that must be overcome to tag RSSI and transmitter's ID in each packet.

The sender and receiver mobility have to be considered in order to get RSSI. The value of this parameter, which is calculated in the propagation loss model, depends on nodes' mobility.

4.4.7.4 Transmitted and received packets

The transmitted and the received packet number in MAC layer are counted in "WifiMac". Thereby, two simple functions are created, which are invoked to increment these parameters whenever a node starts a transmission or receives a data packet.

4.4.7.5 Retransmissions

Data packet retransmissions are identified through missed acknowledges. The transmitter must receive one acknowledge for each transmitted data packet. Therefore, for each missed acknowledge, the counter of retransmission number is increased in one unit. One data packet has seven retries to achieve a successful transmission.

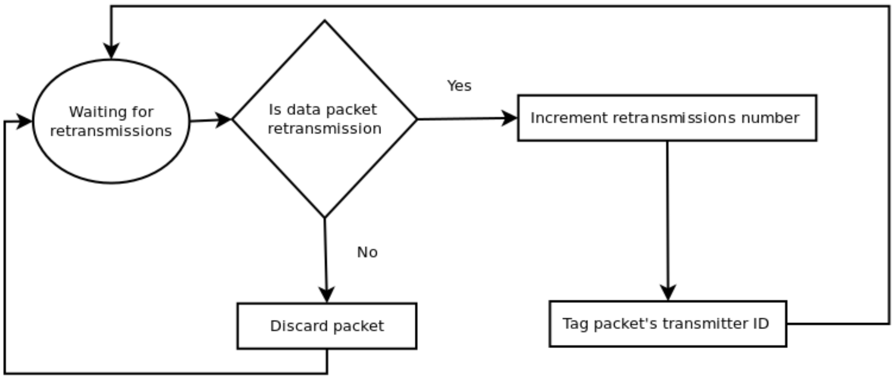


Figure 4.10: Record retransmissions number

Retransmissions at MAC layer are important events, since they are taken into account to find out transmissions' success ratio.

Figure 4.10 shows the flowchart that is implemented. The initial state is left when a retransmission occurs. If it is a data packet retransmission, the retransmission is considered, otherwise it is not.

4.4.8 Performance metrics

After defining the number of packets, interval time between packets, packet size, transmission power, number of nodes, nodes' velocity, distance between nodes, and after reading the information contained in packets relative to transmission parameters, it was possible to define appropriate metrics to evaluate a data rate adaptation algorithm performance:

- Average end-to-end packet delay;
- Throughput;

- Success Ratio;
- Percentage of retransmissions.

These metrics, which show how efficiently a data rate adaptation is performed, are determined over MAC layer, since the application layer is not able to analyse what is happening in terms of transmissions parameters. It was necessary to understand which metrics are suitable to compare data rate mechanisms. Thus, it was concluded through several simulations and results, that these mechanisms aim to provide the best throughput with the minimum packet delivery error rate and delay for the entire network. By its turn, the results shall compare all the network communications performance, instead of one particular communication between two nodes. Furthermore, the mean used rate by algorithms shall be associated to each one of them to understand their adaptation, since two different algorithms may provide different throughput and success ratio in the same scenario, under the same conditions. In this case, a certain algorithm can use a higher mean rate and obtain a larger throughput, but with a lower success ratio. This is the main point that differs between the two algorithms: provide the higher possible mean rate as well as the best throughput and success ratio. In this context, it is important to considerer this parameter in order to achieve more accurate comparisons between the algorithms and their metrics.

The referred metrics are explained below, except the percentage of retransmissions, that was already discussed. Packet delivery ratio, throughput and success ratio are obtained after parsing results from simulated scenarios.

4.4.8.1 Average end-to-end packet delay

It gathers all the possible delays due to buffering during route discovery latency, queueing, retransmission delays in MAC layer and propagation and transfer times. It is calculated by the difference between packet arrival time and its sending time at application layer. Figure 4.7 shows the instant that sending time is recorded.

4.4.8.2 Throughput

The total successfully received packets per time unit over MAC layer, by destination.

4.4.8.3 Success ratio

The ratio between the number of received packets and transmitted packets under MAC layer execution. Therefore, in MAC the total number of transmitted packets is the sum between the number of retransmission packets and the number of sent packets by UDP application.

However, it is calculated using the packet delivery error ratio as shows equation 4.4:

$$SuccessRatio = 1 - \frac{RetransmissionsNumber}{RetransmissionsNumber + SentPacketNumber} \tag{4.4}$$

4.4.9 Simulated scenarios

A scenario can be seen as the highest level of simulation, where devices are built according to network characteristics through specific attributes. This abstraction was developed to execute and evaluate the referred rate adaptation mechanisms. This scenario is developed dynamically to facilitate its usage by users, once the influence of many parameters need to be tested. Consequently, some attributes are defined as inputs in the main scenario. Several scenarios are evaluated by changing its arguments.

The scenarios are composed by the following methods:

- **RateAdaptationTest:** Constructor that initializes simulation variables by default;
- **Configure:** Configure simulation variables according to user specifications;
- **Run:** Execute simulation;
- **Report:** Display results.

Attributes	Value
Transmission power	14 dBm
Number of packets	26000
Time interval between packets	0.0075 Sec
Packet size	1024B
Number of nodes	4,6,8,12,16,20 and 24
Nodes velocity	5, 11 and 25m/s
Seed	100, 200, 300, 400 and 500
Simulation duration	210 and 310Sec
UDP session duration	200Sec
Distance performed by nodes in the highway scenario	1000, 2200 and 5000m
Maximum retransmissions per packet	7
Distance between nodes in the highway scenario	100, 200, 300m
Area considered in the urban scenario	1.4 Km^2

Table 4.3: Simulated scenario attributes

The attributes are presented in table 4.3. The ones that have more than one value are defined as inputs to simulate different cases without changing the code; the remaining parameters are set as dynamic variables:

- --nWifi: Number of mobile nodes;
- --TraceFile: Vehicles' mobility;
- --DurationSimulation: Simulation duration;
- --DurationUDP: UDP session duration;
- --Seed: Seed number in use;
- --RateAdaptation: Rate adaptation in use.

Varying the number of nodes through "nWifi" allows the evaluation of the impact of nodes density in vehicular networks in terms of rate adaptation. In fact different scenarios are tested for each case of number of nodes: 4, 6, 8, 12, 16, 20 and 24. This procedure was repeated with different trace files to test the influence of velocity and distance between nodes. Therefore, it is also tested the following nodes velocity: 5m/s, 11m/s and 22m/s and the following distance between nodes: 100m, 200m and 300m. UDP session and simulation duration were properly adjusted to achieve results that could be directly compared.

The goal of this approach is to find out the most suitable rate adaptation mechanism under different conditions of velocity, distance and node density. This topic will be deeply explored along its results in chapter 5.

Finally, to execute the simulation the user has just to type a command like this:

```
./waf --run ”scratch/RateAdaptationTest --FirstParam=value1 --SecondParam=value2 ... --NParam=valueN ”
```

Table 4.4 explains the command variables meaning.

Variable	Meaning
FirstParam, SecondParam...NParam	Scenario input
Value1, Value2...ValueN	Parameters value
logResult.dat	File in which it is recorded the output

Table 4.4: Command variables meaning to execute one simulation

4.5 Challenges

Indeed, evaluate data rate adaptation mechanisms in vehicular networks is a sophisticated conceptual challenge to identify which elements affect it and how to consider them.

MAC layer deals with all transmission parameters; however, it is not able to access to elements such as nodes velocity, nodes density or distance between nodes. All of these parameters are intrinsic to vehicular network due to its high and constant mobility. Define the best performance metrics to evaluate rate adaptation mechanisms was also challenging to identify the most suitable mechanisms for vehicular environments.

Abstracting from application layer and focusing on MAC layer was also complex, since rate adaptation occurs between transmitter and receiver node over MAC layer.

Finally, realize how MAC and PHY layer interact was also essential. Accordingly it was possible to understand which parameters are able to be exchanged between PHY and MAC layer in order to adapt the data rate.

In addition to these, challenges related to mechanisms and concepts implementation can also be described:

- Some mobile nodes start communicating simultaneously with similar origin point and velocity, leading to packet interference causing collision or data errors. These is owing to data, control and management packets, which are sent at the same time periodically. As a solution, it was introduced a delay between each transmission starting time of each node.

- Situations like network and reception/transmitter buffer overload shall be avoided; otherwise rate adaptation performance is not clearly reflected in the metrics results. Therefore, it is required to find out the best trade-off between transmission parameters, that are associated to traffic generation by UDP sessions and metrics results to avoid deteriorated conclusions. In fact it was an elaborated exercise to achieve this trade-off, wherewith it was required to understand network behaviour, after simulating it several times with different transmission parameters. After determining the transmission parameters, it was required a final validation under several mobility traces.

- The number of nodes, the amount of data traffic flow and the simulation time led to complex and demanding simulations, which required long real running time to be completed. In fact, the available hardware did not have processing capabilities enough to assure a shorter real running time. The solution was to adequate the values of scenarios' parameters in order to have reasonable real running time.

4.6 Summary

This chapter starts with a brief description of the existing modules in NS-3 such as PHY and MAC layer, which were the base of simulations.

In section 3.4 it was explained all the modules that were used from NS-3 in order to simulate a VANET. Then, it was analysed the rate adaptation mechanisms that were tested: AARF-CD, CARA, Minstrel and Ideal. Their flowchart was also presented and described.

In sub-section 3.4.7, it was explained through flowcharts the methodology that was used to access to several parameters such as current rate, number of retransmissions, RSSI and transmitter ID. These parameters were used to determine performance metrics. Therefore, in sub-section 3.4.8 it was discussed the metrics that were used to compare the mentioned algorithms. Sub-section 3.4.9 presented the attributes that were used during simulations and how they were manipulated. Finally, section 3.5 discussed conceptual and implementation challenges that were faced and were overcame.

The following chapter will analyse and compare the final results from different scenarios and rate adaptation mechanisms.

Chapter 5

Simulation results

5.1 Introduction

The previous chapters described the main concepts of VANETs and the implementation that was performed to prepare the evaluation scenarios. By its side, this chapter presents the results relative to the chosen adaptation mechanisms under different scenarios.

Section 4.2 describes the traces that were used to evaluate each algorithm, referring the parameters that were varied and compared. Moreover, it explains the features of each type of scenario: highway and urban scenario.

Before analysing the results, it is presented a preliminary evaluation in order to determine which is the most suitable data traffic rate to apply in simulations. It is important to define appropriate transmission parameters to avoid extreme running conditions.

Then, in section 4.3 it is evaluated each algorithm through the mentioned metrics: delay, throughput, success ratio and percentage of retransmissions. The results are presented and compared to conclude which algorithm has the best behaviour.

This section is divided according to the trace that is being used, highway or urban, and according to the parameter that is being changed: density, velocity and distance.

It is also important to refer that all the results are obtained through 5 simulations with different seeds. It is calculated the mean performance of all UDP transmission for each seed. Then, considering the 5 seeds, it is calculated the mean network performance and the respective confidence interval of 95 percent.

5.2 Scenarios

According to literature [94, 95] two types of scenarios shall be considered in order to obtain accurate results: urban and highway.

Vehicles behave differently in urban environments, since their route is unpredictable and more dependent on neighbour vehicles. In these scenarios, communications are also more affected by infrastructure and higher network overload.

By its turn, highway scenarios suffer fewer infrastructure and neighbour communications interference. Normally nodes density is lower when compared with urban environments, while its routes are predictable, since they have always the same direction. However, lower nodes' density can originate gaps in network topology, limiting the network range.

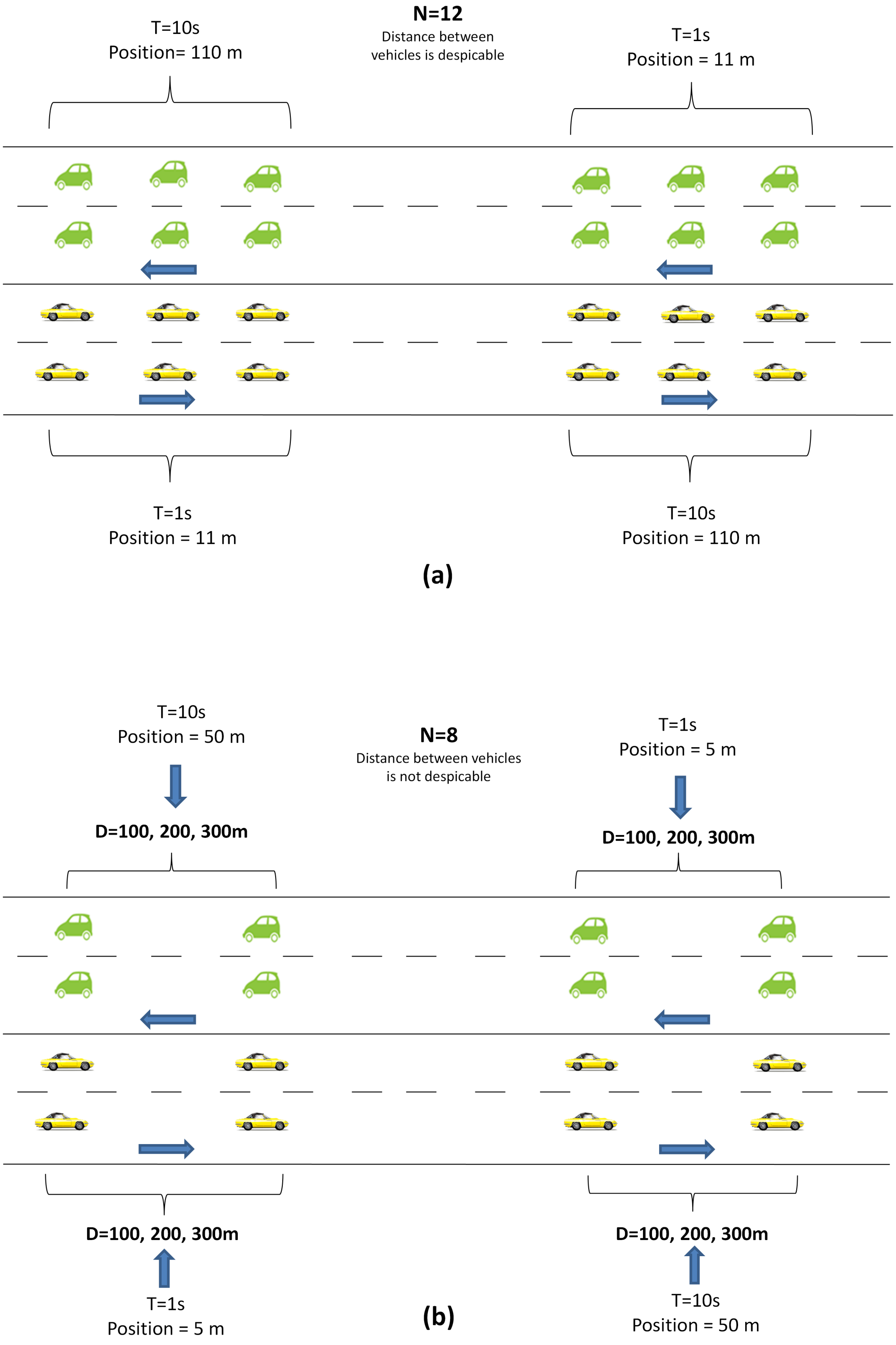


Figure 5.1: Mobility traces schemes

Additionally, velocity shall be considered in highway environments due to its high impact in communications performance.

Therefore, it was created a highway and an urban scenario resorting to SUMO. Urban scenario is a Manhattan grid with 1.4 Km^2 and 400m between roads. Initially, it was introduced 6 vehicles and then 12 and 24 vehicles which circulate randomly with equal turn probabilities (25 percent for each side) using the simulator's car-following model. Vehicles slow down when approaching intersections, creating queues as in real situations. Finally, there are no traffic lights available and the maximum speed is 13.9m/s (50Km/h).

The highway scenario is illustrated in figure 5.1 through two examples. Figure 5.1 (a) shows 12 vehicles (6 in each side) moving at 11m/s while in (b) there are 8 vehicles distanced by 100, 200 or 300m, moving at 5m/s. The first case was used to evaluate rate adaptation with different nodes' density and velocity, whereas distance between nodes was analysed as explained in figure (b).

These scenarios were used to evaluate algorithms under different conditions of:

- **Density**: It was simulated 4, 12, 16, 20, 24 vehicles in each side, all of them with the same velocity (5m/s). Vehicles from each side circulate in opposite directions as in a real highways. The distance between them is insignificant.

- **Velocity**: It was used the previous scenario, but now, it was varied the vehicles' velocity. Beyond 5m/s, that was used to analyse vehicles' density impact, it was also simulated 11m/s and 25m/s for all vehicles from both sides. According to the velocities, these scenarios can be seen as: very slow (5m/s), slow (11m/s) and fast (25m/s) scenarios. Once again, distance between them is despicable.

- **Distance**: Within of each set of vehicles, transmitters were placed at 100m, 200, and 300m from the respective receiver. Vehicles' velocity were 5 m/s for all of them.

Regarding urban scenario, it is tested the impact of nodes' density: low, medium and high density. In this type of scenario velocities and distances were not considered, since vehicles have an unpredictable behaviour in real urban environments. Vehicles experience different velocities and distances between them according to the trajectory defined by the urban mobility model.

5.3 Global evaluation

Before performing simulations, it was analysed the amount of packets that shall be sent by applications to avoid excessive data traffic in the network. According to figure 5.2, it is simulated three cases of data traffic: 3.3, 33 and 330 packets/sec. In this simulation, it is considered a packet size of 1024B and several nodes' density. Vehicles are moving at 5m/s.

As expected, the mean delay per packet is almost zero for 3.3 and 33 packets/sec schemes, and it increases as the data traffic rate increases. For the higher case of rate of packets per second sent to the network, the delay is larger than the previous cases and increases as the nodes' density increase.

Indeed, the delay in (c) is high for VANETs requirements, reaching unbearable values. In the referred scheme, each UDP application sends 2.7Mbits/s of data to the network.

Thus it was decided to use a data traffic rate of 133 packets/sec, which is a middle case between (b) and (c) scheme from figure 5.2. In this manner, it is offered a significant amount of traffic to the network, without overloading the network.

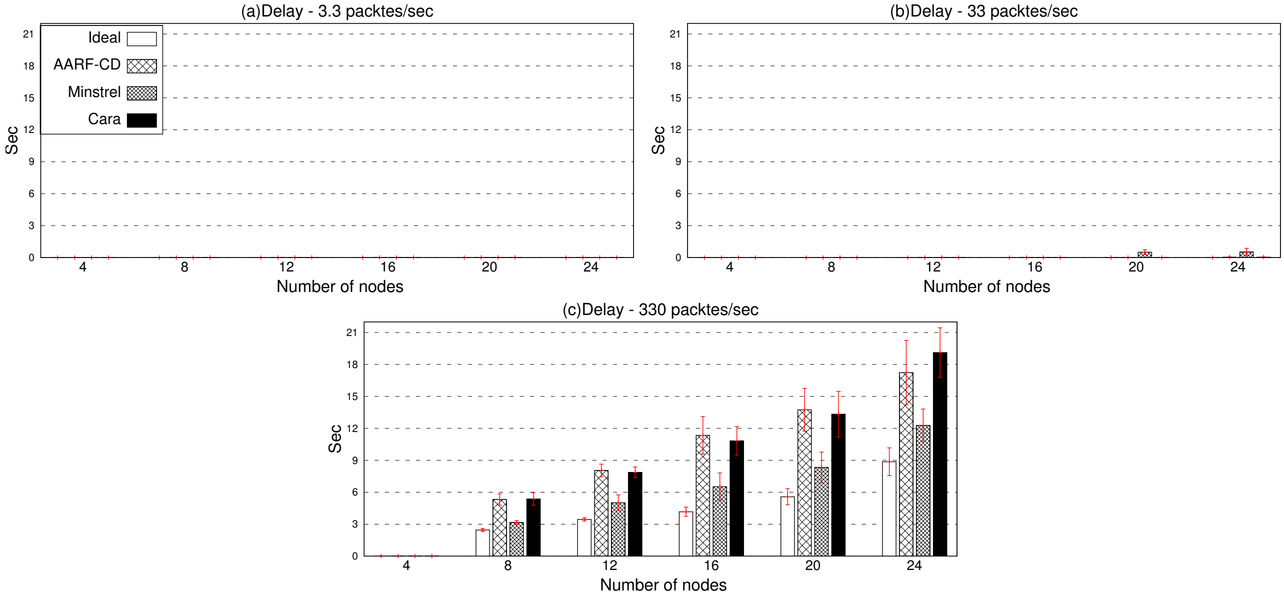


Figure 5.2: Delay for different data traffic rate schemes

The following section presents the main results and conclusions. It is important to remember that algorithms are compared using the following metrics: mean delay per packet, network throughput and success ratio and percentage of retransmissions.

In order to simplify notation, it is considered a symbolic representation for data rate, as shows table 5.1.

Rate (Mbits/s)	Symbolic notation-Rate level
3	0
4.5	1
6	2
9	3
12	4
18	5
24	6
27	7

Table 5.1: Symbolic notation of data rates

The values that are placed on the top of the bars in the following figures correspond to the weighted average of data rate level defined by each algorithm during the transmissions. It is calculated according to equation 5.1

$$Rate_{weighted} = \frac{7 * (TimeAtThisLevel) + ... + 0 * (TimeAtThisLevel)}{\sum_{i=0}^{7} TimeAtThisLevel_i} \tag{5.1}$$

5.3.1 Highway scenario

The considered scenarios represent a real highway: two lanes in each direction with real width and separated by 7m. This sub-section is divided according to the parameter that is being evaluated: density, velocity and distance. Vehicles travel 1500m in all scenarios.

5.3.1.1 Density

As already explained, interference among communications increases as the nodes' density gets higher. Figure 5.3 shows the evolution of mean delay per packet, throughput, success ratio and percentage of retransmissions for different cases of nodes' density: 4, 8, 12, 16, 20 and 24.

As expected, delay and percentage of retransmissions increase when the number of nodes increase, for all algorithms. In the opposite side, success ratio and throughput decrease with the same conditions. In terms of delay Minstrel stands out negatively, reaching 5.5sec of mean delay per packet, while Ideal and CARA obtained the lowest delays. Their maximum delay was 3.3 sec for 24 nodes, which corresponds to 12 UDP active sessions (2 nodes per session).

Regarding network throughput, Ideal reached the highest, and Minstrel has the worst performance. By its turn, CARA obtained a throughput lightly better than that of AARF-CD for all cases of number of nodes, since it used a larger weighted rate than that of AARF-CD. However, AARF-CD achieved better success ratio when compared with CARA, and consequently, lower percentage of retransmissions. This relation allows to conclude that for these scenarios, AARF-CD provides the best rate adaptation, since it used lower weighted rate than CARA and reached the best trade-off between the specified metrics.

Due to the reasons previously described, the algorithm considered as Ideal got the worst success ratio, though it had achieved the best throughput. Hence, it has the highest percentage of retransmissions.

It is also important to refer that Ideal has the lowest delay due to its high throughput. On the other hand AARF-CD achieved higher delay owing to its lower throughput when compared with CARA.

It is supposed that rate adaptation algorithms shall provide the suitable rate to each frame transmission. Thus, in environments with lower interference, the mean rate is larger, as well as the throughput. Higher mean rate also leads to lower delays due to the higher throughput. All algorithms were submitted to the same external conditions; however, the mean rate provided by them was different, since they differ in the mechanism that adapts the data rate.

In fact, mean rate, throughput and success ratio are closely related. According to figure 5.3, the mean rate decreases as the number of nodes increases. Nonetheless, the algorithms decide to use the same mean rate for the case of 4 and 8 nodes, considering that the interference was not enough to decrease the data rate. The usage of the same mean rate, but with worst conditions, provoked a decrease in the success ratio for 8 nodes, comparing with the 4 nodes scenario.

5.3.1.2 Velocity

As already referred, two more velocities were tested: 11m/s and 25m/s. Figure 5.4 and 5.5 illustrate the overall performance for each case. These two cases will be compared, along with figure 5.3.

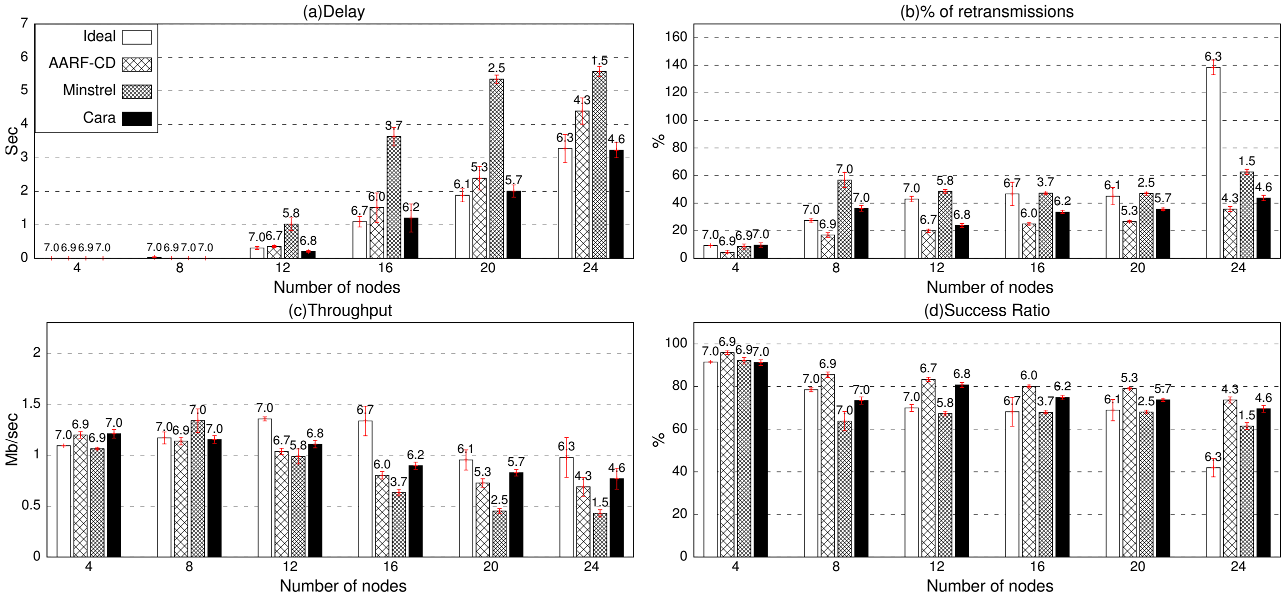


Figure 5.3: Comparison between rate adaptation mechanisms for highway scenario, v=5m/s

Considering the three cases of velocity, CARA performed much better than Minstrel and Ideal in terms of throughput, percentage of retransmissions and success ratio.

Comparing CARA and AARF-CD individually, AARF-CD was slightly outperformed by CARA, in terms of throughput and delay. However, AARF-CD obtained the best overall performance: it has the best success ratio for the three cases of nodes' velocity. For all of them, when the number of nodes are larger than 8, AARF-CD completed all the transmissions with a success ratio of around 80 percent with a satisfactory throughput.

Indeed, algorithms seem to be lightly affected by velocity, adapting well to the environment changes. A deeper insight allows to conclude that as the velocity increases, the zone of interference between nodes is passed faster.

For example, when the number of nodes is 20 and the velocity equals to 5m/s, each group of nodes from each direction, traverses slower the zone of interference caused by nodes, unlike the case of higher velocities. In these last cases, the time of interference among nodes is smaller, which leads to lower delays and higher throughputs considering scenarios with high nodes' density (16, 20 and 24 nodes). This zone has a range of 450m approximately, since it is being used IEEE 802.11p standard.

Thus, in these cases larger velocities reduce the communication interference due to density of nodes.

When the velocity is lower nodes' density provokes high interference in communications leading to packet losses due to collisions. In this context, hidden terminals arise as a large challenge for rate adaptation mechanisms.

Through figure 5.4 and 5.5 the mean rate was dynamically adapted as the number of nodes increases. The algorithms behaved more strictly, since both velocity and density of nodes affect negatively the channel condition. Moreover, the mean rate is lower than the previous case: velocity of 5m/s, in order to provide an acceptable network performance. There is a large difference between scenarios with 4 nodes, considering the velocity of 11 m/s and 25

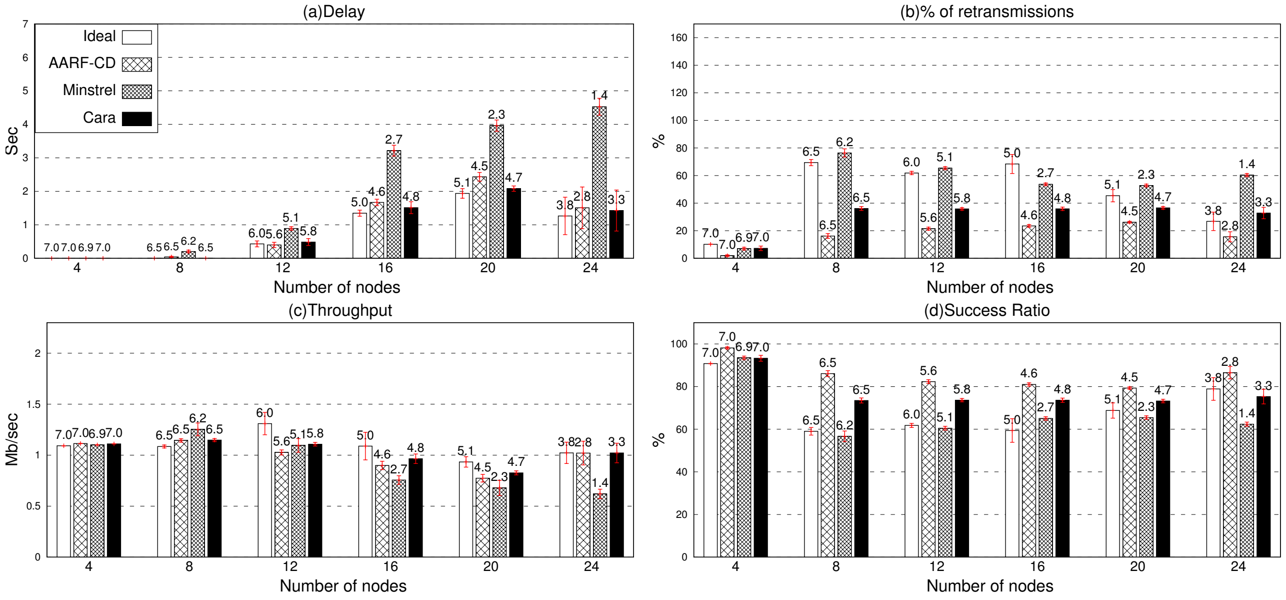


Figure 5.4: Comparison between rate adaptation mechanisms for highway scenario, v=11m/s

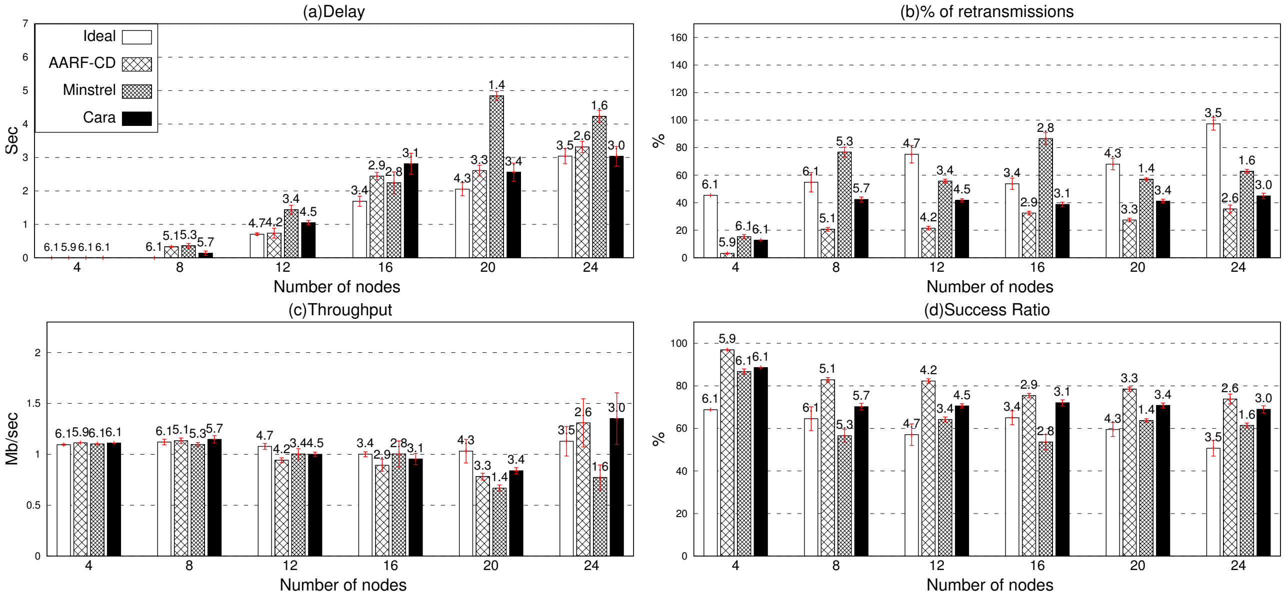


Figure 5.5: Comparison between rate adaptation mechanisms for highway scenario, v=25m/s

m/s: in the first case it is provided the maximum available rate by all algorithms, whereas in the later case, the algorithms only provided a mean rate around of 6. This variation is due to the velocity impact, since it was roughly doubled.

5.3.1.3 Distance

In these scenarios, three different distances were tested between the transmitters and the receivers. In all simulations, nodes were moving at 5 m/s. Therefore, the distance between them stayed unchanged.

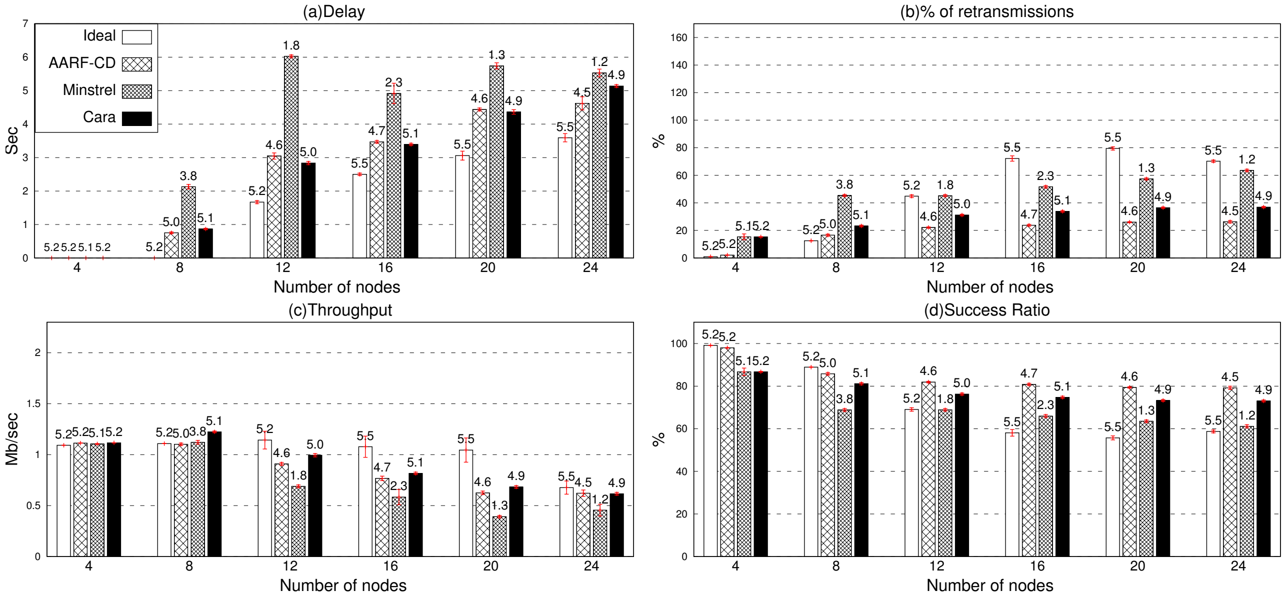


Figure 5.6: Comparison between rate adaptation mechanisms for highway scenario, d=100m

Results from figure 5.6, 5.7 and 5.8 correspond to the following distances: 100m, 200, and 300m.

Distance has a large impact in network performance, specially in delay. This metric has worse results since throughout decreased and transmissions consumed more time due to the physical distance between nodes. Note that transmissions with lower throughputs take more time to conclude. They deliver fewer data per second, which leads to bigger delays.

Accordingly, in these three cases, the weighted rate is lower then the previous schemes. Moreover it is dynamically adapted as the distance between nodes increases. When the number of nodes is 16, AARF-CD uses a rate of 4.7, 3.4 and 2.8 for distances of 100, 200 and 300m, respectively.

Indeed, as it is shown in table 5.2, this adaptation is more substantial than when it is considered the impact of nodes' density in the 200m scheme. In this case, AARF-CD used 3.8, 3.6, 3.6, 3.4, 3.4 and 3.2 for 4, 8, 12, 16, 20 and 24 number of nodes. According to table 5.2, in this case rate adaptation due to the distance is more effective, ranging from 4.7 to 2.8Mbits/s, once density of nodes is affected by the considered distance between vehicles, reducing its density.

Lastly, although success ratio is not very high, it maintains approximately between 70 and 80 percent in the three cases for all algorithms, except Ideal. There is not a large discrepancy between these schemes since the weighted rate is decreased by adaptation mechanisms.

Rate adaptation is very challenging in VANETs environment, since it presents very dynamic channel conditions. In this type of scenario, AARF-CD achieved the best performance

Nodes number-(200m)	Rate (Mbits/s)
4	3.8
8	3.6
12	3.6
16	3.4
20	3.4
24	3.2

Distance (m)-16 nodes	Level (Rate)
100	4.7
200	3.4
300	2.8

Table 5.2: AARF-CD adaptation considering 200m scheme and 16 nodes of each distance scheme

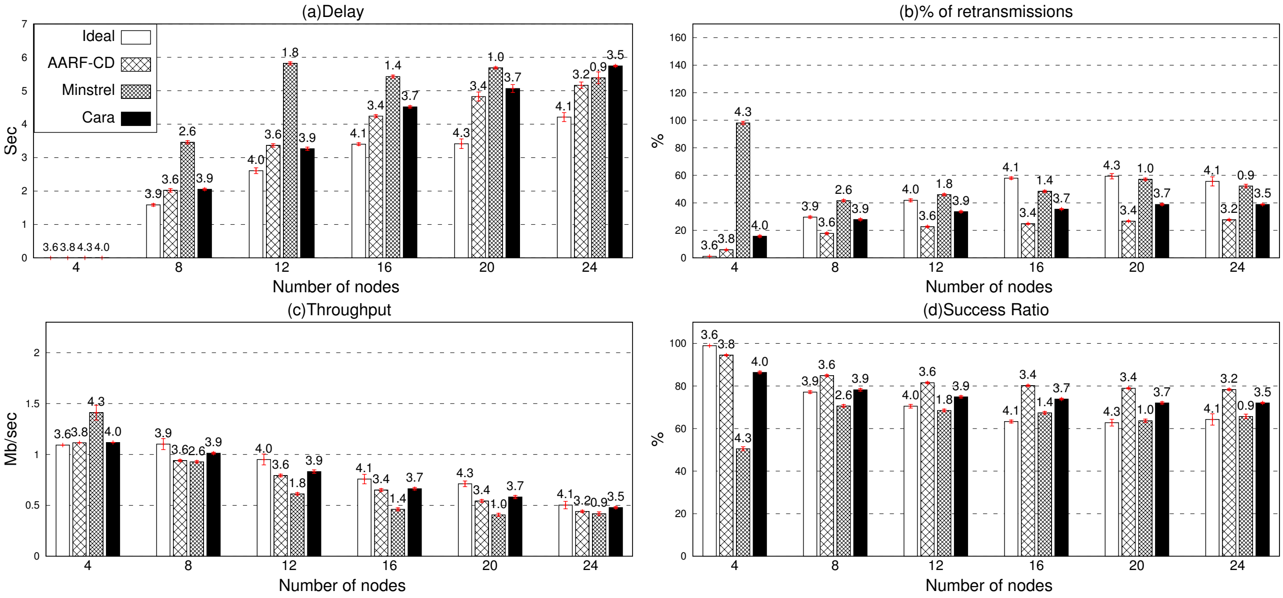


Figure 5.7: Comparison between rate adaptation mechanisms for highway scenario, d=200m

along with CARA. The first main conclusion from these results is that loss differentiation algorithms perform better in dynamic and dense environments than those without loss differentiation. They can provide an efficient recovery strategy, since they are able to distinguish the loss cause and find out whether to decrease rate. To sum up, AARF-CD obtained the best performance followed by CARA, since its performance provides more accurate loss differentiation than CARA. For all number of nodes, AARF-CD always uses a lower mean rate than CARA, since its loss differentiation is more rigorous leading to better channel evaluations.

Considering the distance between vehicles, the mean rates from figure 5.6, 5.7 and 5.8 are lower than the remaining. However, it does not require a large adaptation as the density of nodes with velocity of 5 m/s. In this case, nodes experienced a larger adaptation from the case of four until twenty-four nodes. Thus, it is easy to realize that density of nodes has larger impact in rate adaptation process than distance. By its turn, the parameter distance experienced a larger adaptation than velocity from the case of four nodes until twenty-four.

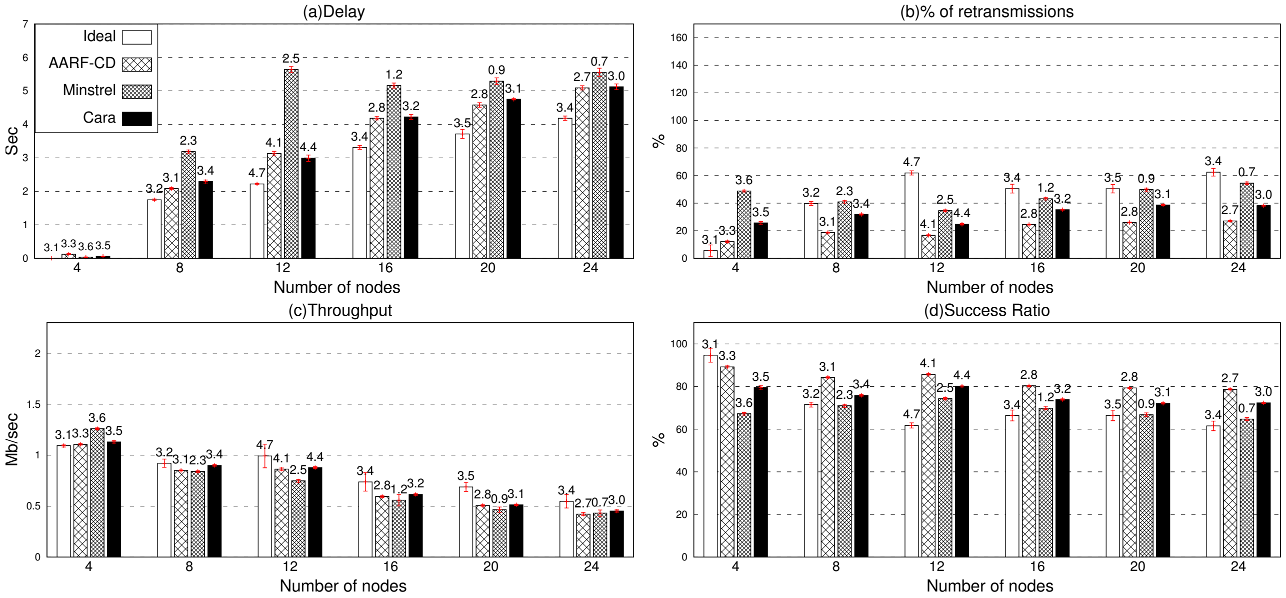


Figure 5.8: Comparison between rate adaptation mechanisms for highway scenario, d=300m

5.3.2 Urban scenario

As referred before it is also created a Manhattan grid to simulate a urban scenario. This scenario considered the cases of 6, 12 and 24 vehicles. Applications send 133 packets/s during 300 seconds, and the simulation stops after 310 seconds. Vehicles circulate randomly with a maximum speed of 13.9m/s (50Km/h) and equal turn probabilities (25 percent for each side). Therefore vehicles' velocity and distance will be not considered in these simulations. In this section, only the variation of density is evaluated, since both distance and velocity are generated by the mobility model.

5.3.2.1 Density

Figure 5.9 illustrates the results using an urban scenario. In fact, throughput and success ratio do not exceed 1.2 Mbits/s neither 80 percent, respectively. Regarding delay, it increases as the number of nodes increase, and it is only acceptable for the scenario with 6 vehicles.

AARF-CD requires the lowest number of retransmissions to complete all the transmissions, obtaining the highest success ratio, while CARA achieves the second best. By its turn, Minstrel provided the highest throughput for 6 and 12 vehicles schemes. For 24 vehicles, Ideal reached the best throughput, although its success ratio was the worst in all schemes.

AARF-CD achieved the best trade-off between throughput and success ratio, and the lower delay when compared with Minstrel and CARA. Thus, independently of the number of vehicles, it provides the closest rate to the optimal one.

Once again, AARF-CD achieved the best performance followed by CARA. Loss differentiation algorithms also obtained better performance in urban scenarios. This fact complements the first conclusion: they provide better adaptation in dynamic and dense environments, than algorithms without loss differentiation. AARF-CD and CARA provided a similar mean rate,

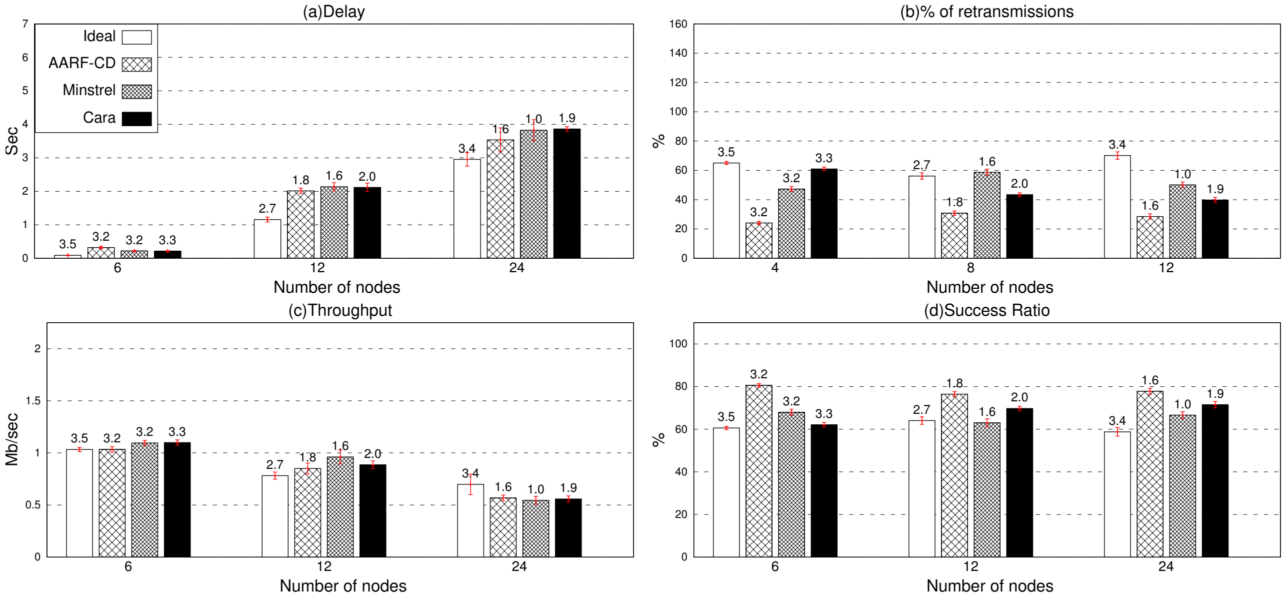


Figure 5.9: Comparison between rate adaptation mechanisms for urban scenario

however that slightly difference causes a significant enhancement in the AARF-CD performance. For example, considering the case of 12 nodes, AARF-CD and CARA differs around of 10 percent in their success ratio and only 0.2 in their mean rate. This allows to realize, that transmissions success is very sensitive to channel conditions and the data rate that is being used.

5.3.3 Proposed solution

After comparing these algorithms, it was concluded that a rate adaptation mechanism designed for VANETs must be context aware, and consider this information according to the impact of each parameter in its performance. Thus, it must be assigned the correspondent weight to each parameter: distance, velocity and density of nodes.

The results showed that density of nodes affects more the rate adaptation than velocity or distance. In this context, it shall be assigned a larger weight to the impact of density of nodes and a lower weight for the remaining parameters. The weights for each parameter shall be obtained according to figure 5.10. After evaluating the impact of each parameter in the previous sub-sections, weights shall be assigned and refined towards the ideal ones, through an optimization process which will converge to the optimal solution.

The context information: velocity and distance of the receiver and transmitter nodes as well as the density of nodes that are communicating, is provided to the MAC layer by the application layer. Then, MAC notifies the rate adaptation mechanism which will be able to perform the rate adaptation through the weights and the context information. Figure 5.11 outlines this interaction between layers.

The core operation of this algorithm will be based on AARF-CD, since it obtained the best performance. In this approach, AARF-CD will consider the external parameters and their weights. Density of nodes, which has a specific weight value, will be used to determine

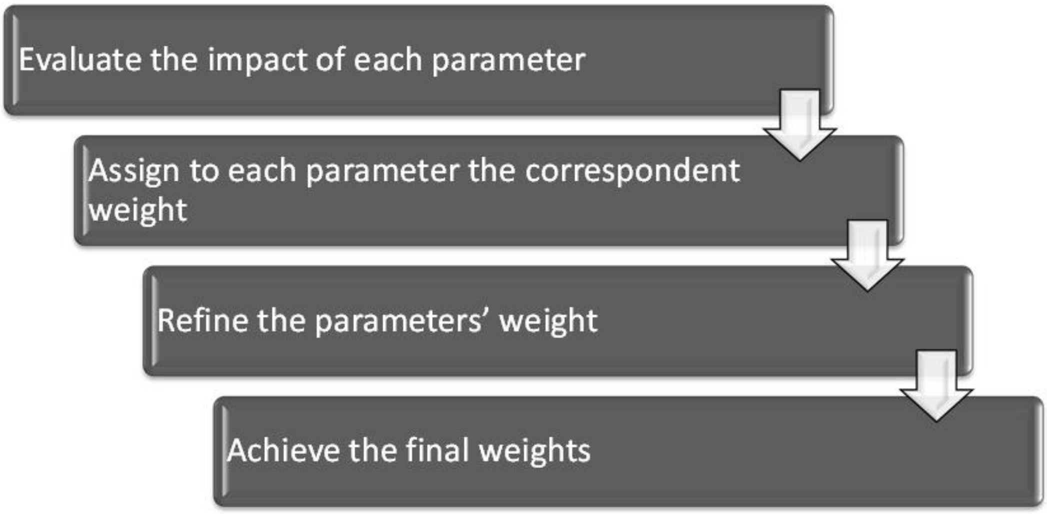


Figure 5.10: Process to obtain the optimal weights

whether to use RTS/CTS mechanism to avoid network overload.

Velocity and distance also have a specific weight. They will be considered to decide when the data rate should increase or decrease. Density of nodes will also be used in this decision. It will be used a threshold as a reference to compare the value that is obtained through these weighted parameters, the number of consecutive failures and success frame transmissions, in order to adapt the data rate.

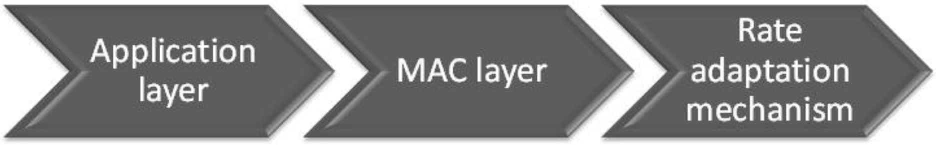


Figure 5.11: Linkage between application and MAC layer

5.3.4 Summary

In this chapter, it was performed the data traffic rate calculation using NS-3 and mobility traces from SUMO to find out the amount of packets that shall be sent by UDP applications. For that purpose, several nodes' density and data rate were tested to achieve accurate results. After obtaining these parameters, it was proceeded the evaluation of each rate adaptation mechanism for several mobility traces.

In section 4.2 it was proposed a set of traces for highway and urban scenarios to perform the evaluation. These scenarios were imported from SUMO to simulate the movement of vehicles with a car-following model. Each algorithm was compared through mean delay per packet, network throughput, success ratio and percentage of retransmissions. Then comparisons were made, concluding which algorithm provides the best adaptation.

The results show that AARF-CD outperforms the remaining adaptation mechanisms, by accurately selecting the most suitable rate in each transmission. In a general way, it achieves an uniform performance with success ratios around of 80 percent for all scenarios, even with 12 or more vehicles.

AARF-CD reached a throughput around of 1 Mbit/s for scenarios with variation of nodes' density and velocity. However, for scenarios with the variation of distance between nodes, it achieved a throughput around of 0.5Mbits/s. It was also concluded that algorithms with loss differentiation, such as AARF-CD and CARA, provide better rate adaptation in dynamic scenarios. Nevertheless, AARF-CD achieved the best results since it has more accurate loss differentiation.

Finally, it was proposed an algorithm based on AARF-CD that considers context information: velocity, distance and density of nodes. These parameters will be associated to weights according to their impact in the rate adaptation process.

Chapter 6

Conclusion and future work

6.1 Conclusion

The unique characteristics of VANETs, such as dynamic topology, frequent loss of connectivity and high mobility, turn the rate adaptation scheme into a complex issue, where the decision time and accuracy is vital for overall systems performance.

High network performance depends on rate adaptation mechanisms, which must operate according to a set of variables. These mechanisms, must be dynamic enough in order to face different types of scenarios.

Although a large amount of mechanisms have been proposed in the literature, none of them were exhaustively evaluated an compared under real VANETs scenarios. Neither parameters such as nodes' velocity, density and distance were deeply considered. Furthermore, evaluations within the same settings and/or conditions resorting IEEE 802.11p are also scarce.

Two main scenarios were considered in this dissertation: highway and urban scenario. Then mechanisms' performance was evaluated under many different parameters. These scenarios represent real environments with realistic traffic flows. They were compared through the achieved results of network throughput and success ratio, mean delay per packet and the percentage of retransmissions. These metrics were already widely discussed, being consensual its usage to evaluate rate adaptation mechanisms.

Considering the algorithms which were available in NS-3 and the literature that was presented, it was decided to evaluate four algorithms: AARF-CD, CARA, Ideal and Minstrel.

Regarding highway scenarios, it was concluded that loss differentiation algorithms perform better in dynamic and dense environments when compared with those without loss differentiation. Indeed, they provided an efficient recovery strategy, since they are capable to distinguish the frame loss cause. An overall insight allows to conclude that AARF-CD obtained the best performance followed by CARA. It provided the best trade-off between throughput and success ratio. CARA outperformed AARF-CD in terms of throughput, however its success ratio did not achieve high results as AARF-CD. Finally, in this scenario AARF-CD had lower delay when compared with CARA, independent of the number of nodes. In fact, AARF-CD achieved better results than CARA due to its more accurate loss differentiation and adaptation strategy, since it has more strict conditions to increase or decrease the rate, and to use CTS/RTS mechanism to react over contention problems. Note that AARF-CD increases the rate dynamically according to the success of transmissions attempts, and decreases the rate taking into account if it is using a new rate or not. By its side, CARA only uses a fixed threshold to increase and decrease the rate.

In urban scenarios it was only considered the number of nodes, since vehicles had a free behaviour in terms of velocities, directions and distance between them. They circulated randomly with equal turn probability (25 percent for each side) using the simulator's car-following model. Therefore, in this scenario, it was concluded that AARF-CD outperformed again the remaining algorithms. Another conclusion that matches with the previous one, is that loss differentiation algorithms obtained the best performance: AARF-CD and CARA.

Through the presented results, it was also possible to compare the influence of velocity, density and distance on rate adaptation process. Rate adaptation mechanisms were more sensitive to density of nodes when compared with other parameters. Distance and velocity are the second and the third parameter with larger impact in rate adaptation. It was showed that AARF-CD, the best algorithm, performed a higher adaptation considering the density of nodes with velocity of 5 m/s. On other hand, the throughput achieved by algorithms was lower in scenarios where the distance was varied. In these cases, the weighted rate was lower to guarantee the best possible success ratio.

As overall conclusion, it is notorious that loss differentiation algorithms achieved the best performance in both scenarios. Accordingly, AARF-CD attained the best global performance in urban and highway scenario.

However, in these very dynamic scenarios, a more effective and timely adaptation could lead to better results regarding network throughput, success ratio and mean delay per packet.

6.2 Future work

The evaluation that was performed in this dissertation only considered two scenarios: urban and highway scenario. However, more scenarios with different topologies could be tested. Additionally, other algorithms that provide satisfactory rate adaptation in dynamic environments, could be used to achieve more accurate conclusions.

More parameters such as altitude and directions could be analysed within the same settings and/or conditions. In fact, evaluating these parameters along with velocity, distance and density of nodes through more realistic scenarios could provide new strategies to develop better rate adaptation schemes.

As future work, in order to increase the reliability of results, it is suggested to evaluate the same mechanisms under the same tested conditions, but now in real scenarios. Then, it would be possible to collect the best features and strategies of each algorithm to adapt the data rate. After comparing results from simulated and real scenarios, an algorithm can be designed and implemented in a real testbed. The testbed already developed in Porto is a valid solution to perform the testing.

To develop this algorithm two procedures should be adopted. The first one is to assign weights to each parameter according to its impact in the rate adaptation process. According to the results, parameters that affect more the rate adaptation would be associated to larger weights. Thus, rate adaptation would be based on a weighted process according to external conditions effect. Results show that rate adaptation mechanisms are more sensitive to density of nodes than velocity and distance. Furthermore, they are more effective in scenarios based on distance between nodes than scenarios in which it is varied the velocity. Therefore, according to these conclusions, a possible algorithm based on weighted rate adaptation, should be designed with larger weight for nodes density impact and a lower weight for velocity impact.

The distance among nodes would have a mean weight. Note that parameters' weights have to be well refined to guarantee the best possible rate adaptation; otherwise, network performance will be extremely affected.

Finally, rate adaptation mechanisms for VANETs should be aware to external conditions on real time. They should adapt taking into account the environment conditions, since the same scenario can have different features due to vehicles' behaviour. In this manner they could access to parameters like transmitter's and receivers' velocity, distance from receiver or density of vehicles in order to adapt the data rate using the respective weights.

This scheme presupposes an intelligent rate adaptation mechanism, which shall be informed regarding environment conditions by application layer. In this way, this rate adaptation scheme could be more effective over fading channels as well as environments where collisions predominate. Moreover, it could be faster to respond against abrupt channel variations, providing long-standing performance.

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