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Master thesis in
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Interface Selection in 5G vehicular networks

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Ad Anna, che è da sempre al mio fianco

Abstract

In the last years, the amount of data shared among the world is increased exponentially thanks to the novel applications for security (e.g. home automation, smart cities, traffic control, autonomous vehicles) and infotainment (e.g. audio and video streaming, web browsing, massive online videogames). To support this trend, the major companies in the telecommunication industry are developing new standards that will be available to the final users in the next years and that will be presented as the Fifth Generation of Cellular Networks (5G). These standards provide improvements to the 4G standards (e.g. LTE, WiMax, DSRC) and brand new technologies (e.g. mmWaves, Visible Light Communication) to enable new services that demand extremely high throughput and low latency. In most cases these technologies will cooperate to ensure a reliable and accessible network in every situation.

One of the most promising applications of these new generation technologies is vehicular networks, a set of services that includes the communication with infrastructures, such as the download of a film from the Internet or the reception of information about the surrounding environment (e.g. a traffic light sends a message to an incoming vehicle to make it stop), or the communication between vehicles, in this case the datarate is tipically lower since the typical use will be, for example, to send information about the closest cars in order to decrease the number of accidents or to manage the traffic.

This thesis is focalized on the vehicular networks applications, it aims to analyze the performance of IEEE 802.11p protocol at different datarates in a typical V2V scenario, and to compare LTE and mmWaves using a V2I communication in different circumstances to show how each technology offers advantages for some applications while is not suitable for others.

Sommario

Negli ultimi anni, la quantità di dati condivisa nel mondo è aumentata esponenzialmente grazie alle applicazioni innovative che riguardano la sicurezza (e.g. domotica, smart cities, controllo del traffico stradale, veicoli autonomi) e i servizi di intrattenimento (e.g. audio e video streaming, ricerche web, videogiochi online di massa). Per supportare questo trend, le principali compagnie nell'industria delle telecomunicazioni stanno sviluppando nuovi standard che saranno disponibili agli utenti finali nei prossimi anni e che saranno presentati come la Quinta Generazione di Reti Cellulari (5G). Questi standard prevedono miglioramenti ai precedenti standard 4G (e.g. LTE, WiMax, DSRC) e tecnologie completamente nuove (e.g. onde millimetriche, comunicazione con luce visibile) per permettere la diffusione di nuovi servizi che richiedono un throughput estremamente alto e una latency bassa. Nella maggior parte dei casi, queste tecnologie dovranno cooperare per assicurare una rete affidabile e accessibile in ogni situazione.

Una delle applicazioni più promettenti di questa nuova generazione di tecnologie sono le reti veicolari, un insieme di servizi che includono la comunicazione con le infrastrutture, come il download di un film da Internet o la ricezione di informazioni riguardanti l'ambiente circostante (e.g. un semaforo manda un messaggio a un veicolo in avvicinamento per farlo fermare), o la comunicazione direttamente tra veicoli, in questo caso il datarate è tipicamente più basso dato che l'uso più tipico sarà, per esempio, mandare informazioni riguardanti le macchine più vicine per fare in modo di diminuore il numero di incidenti stradali o gestire il traffico.

Questa tesi è focalizzata sulle applicazioni per reti veicolari, l'obiettivo è di analizzare le prestazioni del protocollo IEEE 802.11p a diversi datarate in un tipico scenario V2V, e di confrontare LTE e mmWaves usando una comunicazione V2I in diverse circostanze, per mostrare come ogni tecnologia offra vantaggi per determinate applicazioni mentre non è adatta per altre.

Contents

List of Figures

Acronyms

3GPP Third Generation Partnership Project.

AM Acknowledged Mode.
APN Access Point Name.

BER Bit Error Rate.
BS Base Station.
BTP Basic Transport Protocol.

CDF Cumulative Density Function.
CSMA/CA Carrier Sensing Multiple Access with Collision Avoidance.
CTTC Centre Tecnològic de Telecomunicacions de Catalunya.

DSRC Dedicated Short Range Communication.
DUT Dalian University of Technology.

EARFCN E-UTRA Absolute Radio Frequency Channel Number.
E-UTRA Evolved Universal Terrestrial Radio Access.
eNodeB 4G LTE base stations.
EPC Evolved Packet Core.
EPS Evolved Packet System.
E-UTRAN Evolved Universal Terrestrial Radio Access Network.
E2E End-to-End.

gNodeB Next Generation NodeB.
GSM Global System for Mobile communication.

HARQ Hybrid Automatic Repeat Request.
HetNet Heterogeneous Network.

HSDPA	High-Speed Downlink Packet Access.
HSPA+	High-Speed Packet Access Evolution.
HSS	Home Subscriber Server.
IAB	Integrated Access and Backhaul.
ISD	Inter Site Distance.
ISI	Inter Symbol Interference.
LOS	Line-Of-Sight.
LTE	Long Term Evolution.
LTE-A	LTE Advanced.
LTE-V	LTE Vehicles.
MANET	Mobile Ad Hoc Networks.
MCS	Modulation and Coding Scheme.
METIS	Mobile and wireless communications Enablers for Twenty-twenty (2020) Information Society.
MIMO	Multiple Input Multiple Output.
MME	Mobility Management Entity.
mmWaves	Millimeter Waves.
NAS	Non-Access Stratum.
NGMN	Next Generation Mobile Networks.
NLOS	Non-Line-Of-Sight.
NS3	Network Simulator 3.
NYU	New York University.
OBUs	On Board Units.
OFDM	Orthogonal Frequency Division Multiplexing.
PDCP	Packet Data Convergence Protocol.
PDN	Packet Data Network.
PGW	PDN Gateway.

PRR Packet Reception Ratio.

QoS Quality of Service.

RAN Radio Access Network.

RAT Radio Access Technology.

RLC Radio Link Control.

RNG Random Number Generator.

RRC Radio Resource Control.

RSRP Reference Signal Received Power.

RSRQ Reference Signal Received Quality.

SAP Service Access Point.

SDMA Spatial Division Multiple Access.

SGW Serving Gateway.

SINR Signal-to-Interference-plus-Noise Ratio.

SUMO Simulation or Urban MObility.

TCP Transmission Control Protocol.

TDD Time Division Duplex.

TD-LTE Time Division LTE.

TM Transparent Mode.

UDP User Datagram Protocol.

UE User Equipment.

UM Unacknowledged Mode.

UMTS Universal Mobile Telecommunication System.

USIM Universal Subscriber Identity Module.

V2I Vehicle-to-Infrastructure.

V2V Vehicle-to-Vehicle.

V2X Vehicle-to-everything.

VANET Vehicular Ad Hoc Networks.

WAVE	Wireless Access in Vehicular Environments.
WiMAX	Worldwide Interoperability for Microwave Access.
WLAN	Wireless Local Area Network.
WSMP	WAVE Short Message Protocol.
WWW	World Wide Web.

Chapter 1

Introduction

Each time a new generation of cellular networks gets released, the way in which we communicate changes drammatically, a new set of services and applications becomes available and the whole world gets a bit more connected.

In 1979 the first commercially automated cellular network (1G) was launched in Japan, making possible to use multiple cell sites, and the ability to transfer calls from one site to another using handovers while the user travels between cells during a conversation. Around ten years later, the second generation (2G) started to use digital transmissions instead of analog transmissions introducing the Global System for Mobile communication (GSM) standard. This change enabled services such as SMS, longest lasting mobile batteries (digital transmissions consume less than analog ones), a more secure and safe mobile encryption and higher audio quality on the voice calls, increasing exponentially the use of mobile phones around the world. In the late 1990s, GPRS and EDGE were introduced, increasing the available throughput in mobile networks first up to 115 kb/s and than up to 384 kb/s, making World Wide Web (WWW) and e-mail service available to mobile phones. As the 2G phones became essential in the everyday life of the people, the need of data services such as the access to internet from mobile was clear, so new solutions started to be studied, and in the early 2000s third generation cellular networks (3G) was standardized. Changing the way in which the information travels in the network from circuit switching to packet switching, allowed faster mobile communications, enabling media streaming services in the phones for radio and television content. Once WWW becames available during mobility, the demand of higher data rate was foreseeable, therefore the research community started to think to new solutions, releasing first High-Speed Downlink Packet Access (HSDPA), that allows a data rate up to 14 Mb/s, and finally High-Speed Packet Access Evolution (HSPA+), reaching a speed of 42 Mb/s. Following the trend of the usage of data sharing over mobile networks, the industry started to develop solutions that allows user to share even more data and for more reasons, therefore smartphones was presented and new technologies to increase the available data rate was investigated. In 2010, Fourth Generation cellular network (4G) was released, enabling communications an order of magnitude faster to allow high quality audio/video streaming over Internet and brand new type of infotainment services. The main technologies introduced with 4G were Worldwide Interoperability for Microwave Access (WiMAX) and LTE. In the last years the research in this field is towards faster communications and more reliable connection between devices, to enable new services that require high throughput and low latency or reliable and secure connections. New technologies such as Multiple Input Multiple Output (MIMO) and LTE Advanced has been released in this regard, and new technologies will be available in the next years.

In the next few years, solutions to improve the 4G cellular networks has been studied, and in 2 years the Fifth Generation Cellular Networks (5G) will be released. This new generation will revolutionize the way we use our devices as long as every object we use in our everyday life. Indeed, as stated in [4] by Next Generation Mobile Networks (NGMN) Alliance, 5G network will make available:

- higly reliable communications
- massive usage of Internet of Things
- lifeline communications
- the availability of the network even in high mobility scenarios
- data rates up to 1 Gb/s in dense urban areas and at least 50 Mb/s everywhere
- End-to-End (E2E) latency of 10ms in general and of 1ms for the use cases which require extremely low latency

This means that current technologies need to be adapted to meet the requirements and that new solutions has to be proposed to overcome the limits that nowadays protocols have [5]. 5G will bring in our life new ways to communicate, both inside our houses and in an external environment. Indeed, if Internet of Things will connect every household appliance to make our abitations smarter (and our tasks easier), vehicular networks will increase the safety in the streets and the level of entertainment that one can have inside a vehicle.

The research in this regard, is searching solutions to make the vehicles aware of the surrounding environment, enabling communication with the infrastructures such as street lights, cellular network base stations, ecc.. (Vehicle-to-Infrastructure (V2I) communication) and directly with other vehicles (V2V communication).

With such a complex scenario, a lot of data will flow through the network, and given the 5G requirements, a very high datarate is required, especially for particular applications such as audio and video streaming. Since the portion of frequency spectrum used until now will saturate immediately in these conditions, the spectrum from 10 GHz to 300 GHz is under investigation. The technologies developed for this range of frequencies are grouped under the name Millimeter Waves (mmWaves) and they are one of the main innovation 5G will bring to the market.

Working with such an high frequency means satisfy 5G requirements in terms of datarate and latency at the cost of great limitations in the coverage range, since mmWaves have high sensitivity to blockages like buildings, bad environment conditions and even people between transmitter and receiver.

In order to exploit the potential of this novel technology and at the same time to offer a reliable service, mmWaves can be inserted in an Heterogeneous Network (HetNet) scenario togheter with other technologies with different propagation characteristics [6] [7]. In this way, mmWaves can be used when the channel is good enough to allow acceptable datarate and latency, in the other cases, other technologies, slower but more reliable, can be used.

This thesis aims at comparing mmWaves with other two technologies that can be integrated in the next years into the NR systems (the global standard for 5G wireless air interface) to allow vehicles to communicate (both each other and with some remote host through Internet) in the typical urban scenarios, in which many obstacles and an high level of mobility have to be taken into account. The technologies that will be investigated are WAVE (or IEEE 802.11p) and LTE, since they have very different characteristics and are often used for different tasks, the first is a low-rate communication protocol that ensures a reliable communication even in presence of some blockages, while the second is the main protocol used in 4G to communicate, it can reach higher datarates and relies on a high number of dedicated infrastructures. Results will be obtained through simulations in both random and more realistic scenarios using NS3.

The thesis is organized as follows:

- Chapter 2 reviews the state of the art on the interface selection systems proposed in the last years, with a particular interest to the solutions in which mmWaves are used;
- Chapter 3 introduces the reader to the vehicular networks, their definition and the main applications that will be developed;
- Chapter 4 describes the LTE architecture both at high level and at Radio Protocol Stack level;
- Chapter 5 introduces IEEE 802.11p/WAVE technology at large, showing the main features of each layer of the protocol stack;
- Chapter 6 is an overview on the possible architectures of the future NR 5G protocol;
- Chapter 7 describes the simulation framework used, introduces NS3 simulator and the main modules used and modified in the thesis: the New York University (NYU) mmWave module for NS3 is described in its main components and the functionalities that it provides are explained, while LTE, WAVE and buildings modules will be briefly described;
- Chapter 8 presents the simulation scenarios and how the simulation's parameters are tuned to obtained the wanted results;
- In Chapter 9 the obtained results are summarized in figures and they are discussed with a view to the most promising vehicular networks applications;
- Chapter 10 draws the conclusions and outlines the work that can be made in future using the results obtained.

Chapter 2

The interface selection problem

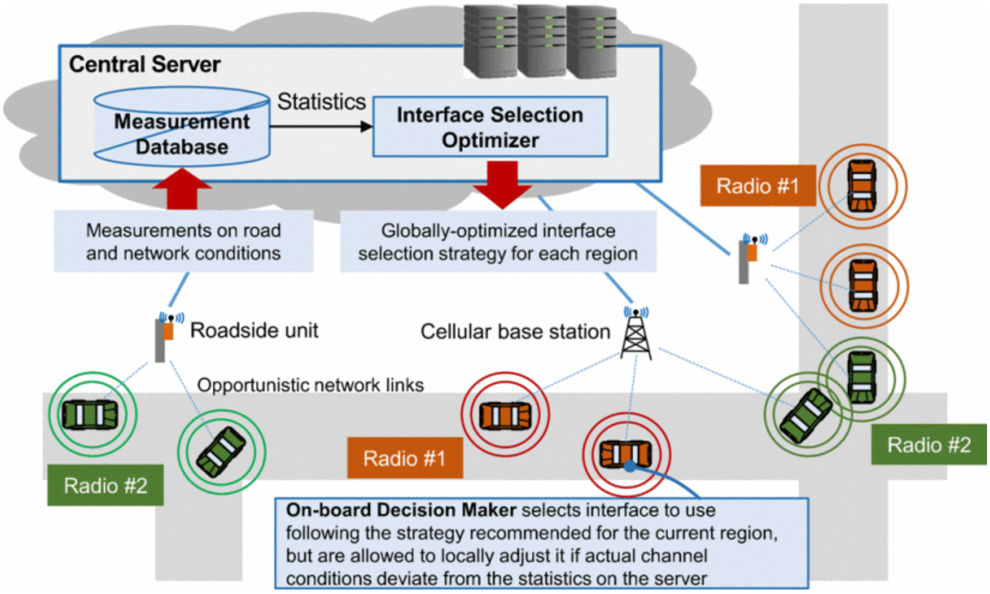
In the last few years, both in academic studies and in the industry, a connection between two devices that does not relies entirely on the physical technology used is topic of interest. More than 10 years ago, Ylianttila et al. in [8] described an heterogeneous environment in which User Equipment (UE) can move along different kind of networks (cellular and WiFi for example) exploiting the features of a *vertical multi-access network*, an approach widely used with the introduction of 4G. The authors provides an architecture for seamless location-aware integration of Wireless Local Area Network (WLAN) hotspots into cellular network and provides analysis for an optimal handoff decision algorithm in moving in and out of an hotspot. The algorithms to select the proper interface proposed are power or dwell-timer based and does not take into account the type of traffic to handle.

The innovation that 5G will bring is centered on the fact that, thanks to UE's interface selection capabilities, the technology to be used can be chosen based on the type of application, the requirements of the connection or the context in which the communication is made. The choice regarding the best technology to be used can be automated or can completely depend on the UE. The second case is the easier one since no algorithms are needed and UE can arbitrarily decide which is the most appropriate technology on his own, in the first case, several algorithms have been proposed over the years.

In the first papers that face this problematic [8][9][10][11], the proposed algorithms measure the statistics of the network in different ways and they attach the UE to the *best possible* network. Although these studies reach good results in ensuring good performances to the UE, they don't take in account the user's demand for resources. The approach that would be used in 5G is to take into account also the user preferences, to let each UE use the more suitable technology for the service he is using. The type of traffic in the network expected with the next generation of cellular networks will be extremely etherogeneous and it will depend from the diverse services 5G will enable. To make an example, in the next years, each vehicle would be able to communicate some short message with other vehicles in order to take real-time decisions based on the traffic situation and maybe at the same time would download some movies that the passenger asked to see. In this condition, the vehicle can communicate with the other vehicles using a low-rate (but reliable) technology (such as WAVE), so that it does not waste precious resources, and can download the movie with a faster communication like mmWaves or LTE.

Wang et al.[12] employ a self-selection decision tree to decide when is convenient to make handoff towards WAVE and WiMAX from third generation cellular network (3G). When a vehicle enters in a new access point coverage area, it feeds the decision tree with some predetermined metrics such as network statistics, type of service required or the speed of the vehicle to compute the probability to make handoff. Then the vehicle considers both the status of the current network and that of the new one and decides if handoff is convenient or not. Their analysis take into account both the throughput reached with the proposed technique and the switching times between two different networks in case of handover.

In [1] a novel approach to the problem is proposed, in which interface selection is controlled by a remote central server. The server provides vehicles with recommended interface selection strategies optimized based on statistical knowledge. The vehicles would normally follow server's directives, they can take some controlled decision whenever the actual channel conditions deviates from the statistics on the server. The architecture used and the decision process are schematically reported in Fig. 2.1 and Fig. 2.2. The authors tried this system by simulation, integrating Dedicated Short Range Communication (DSRC) with WiFi, but they state that also other technologies would be supported, as long as the channel load can be accurately measured by On Board Units (OBUs). This is a limitation for those technologies that has critical signal propagation characteristics such as mmWaves, since a real-time measurement of the channel is not always possible. This double-checking mechanism increase the flexibility of the vehicles on the decision and exploit the advantages of both centralized and distributed systems.



On-board Decision Maker selects interface to use following the strategy recommended for the current region, but are allowed to locally adjust it if actual channel conditions deviate from the statistics on the server

FIGURE 2.1: Basic architecture used in [1] for hybrid V2V communication

Although an optimal decision in the technology to use is fundamental to enable some services and to ensure a reliable network, a high number of handovers

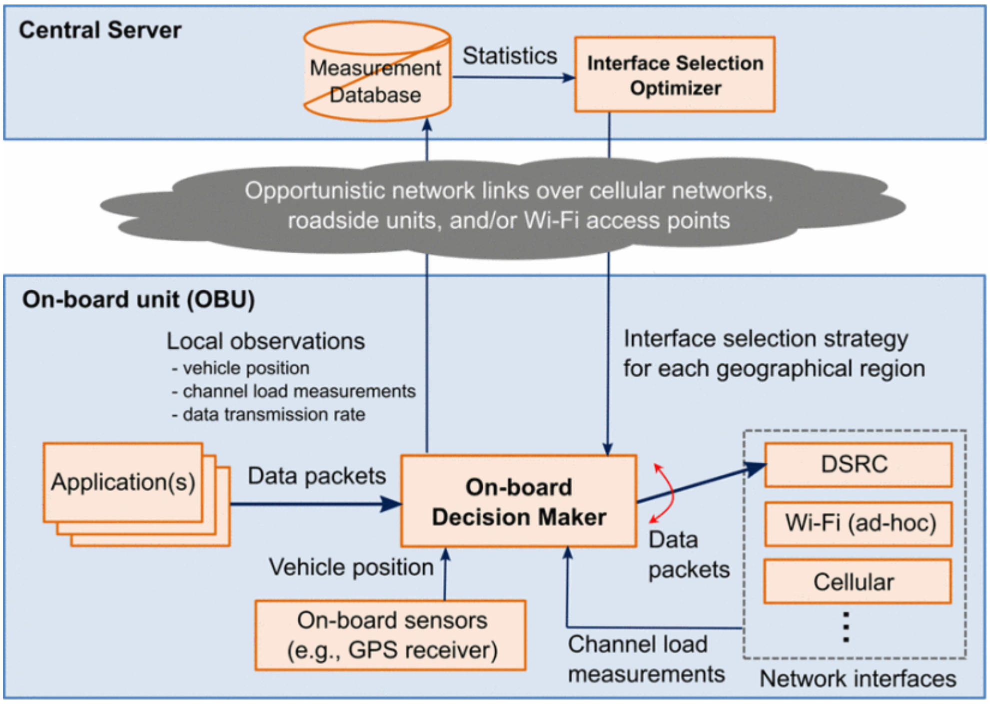


FIGURE 2.2: System-level view of hierarchical decision maker as explained in [1]

during a communication may degrade mobility reliability due to the heavy signaling load and can compensate the advantages obtained with a multi-connectivity system in terms of network capacity. Zhang et al. in [13] tries to reduce the number of handovers in dense networks without impact on the throughput of the network. In their proposal, the nearest access points in mobile user's vicinity serve user for data transmission, while only the best one among them is used to send control messages. This approach reduces the network overhead and the handover probability, without degrading the throughput performance.

Focusing on vehicular networks, the applications in this kind of network can be classified in road safety, traffic efficiency and infotainment [14]. Road safety services can rely on a V2V type of communication, since these applications require typically low latency and high reliability and they do not require high throughput. Traffic efficiency applications aim to optimize flows of vehicles by reducing travel time and traffic congestion. These applications can be realized both with a V2V and a V2I connectivity, they have no strict requirements on delay and reliability but the service degrades with increasing in packet loss and latency. Infotainment services are based on V2I communications and demands large bandwidth and a good Quality of Service (QoS).

Given the diverse type of services that will be introduced with 5G, in this thesis, LTE and DSRC will be presented as supporting technologies for mmWaves in a multi-connectivity environment. Their suitability in vehicular communication has been proved in [15] and [14], they have potential in this field at the cost of some limitations. WAVE has proved to be a good technology for vehicular communication for its easy deployment, low cost and the capacity to naturally support V2V communications, although presents limitations like unbounded delay, limited radio range and lacks of a pervasive roadside communication infrastructure. LTE, instead, ensures large coverage, high throughput and low latency, however since all the packets need to pass through an infrastructure, these advantages can not be ensured in presence of large number of users.

Some solutions have been proposed to adapt LTE to Vehicle-to-everything (V2X) communication in a vehicular networks environment. The most promising system in this regarding has been presented by Third Generation Partnership Project (3GPP) as LTE Vehicles (LTE-V),a new architecture based on LTE that will enable the use of this technology in both V2I and V2V communications. LTE-V includes 2 modes [16]:

LTE-V-direct a decentralized architecture based on Time Division LTE (TD-LTE), a variant of LTE, that provides short-range direct communication, low latency and high reliability improvements in V2V communication;

LTE-V-cell a centralized architecture, also base on TD-LTE, that optimizes radio resource management for better supporting V2I.

The cooperation between LTE and WAVE has been proposed by Zheng et al. in [17]. Adding mmWaves will improve the performances in the network at the cost of a more complex decision algorithm to choose the right technology at the right time.

Several research groups are currently designing systems for V2X using mmWaves. Antonescu et al. in [18] describe methods for deriving channel propagation models via ray-tracing simulations for mmWave transmission in V2X communications, taking into account the diffuse scattering, the high blockage-sensitivity of mmWaves and multipath fading in urban scenarios.

In [19], the authors provides techniques to improve the reliability of initial access procedures for 5G mmWaves cellular in massive V2X communications scenarios. They state that sending multiple random access preamble, the success probability to transmit at the first attempt is at least twice higher than that with the legacy approaches.

Moreover, NYU together with University of Padova is developing a full-stack simulator of a multi-connectivity system where mmWave and LTE are integrated, based on NS3 simulator [20]. This simulator and the correspondent mmWave module are also used in this thesis.

Chapter 3

Vehicular Networks

With the increasement of the number of vehicles in the world, both public or private, the necessity of a network that allow these vehicles to communicate and systems that collect data from them has becoming a topic of special interest in the research community. The motivation is that the number of fatalities that occur due to accidents on the road is increased dramatically. The expense and the related dangers have been recognised as a serious problem for the modern society. The necessity of a complex system to increase the safety on the roads, as well as the great possibility of speculation in this field, has meant that the industry has started to research and design solutions in the vehicular networks context.

The name with whom vehicular networks are globally recognized is Vehicular Ad Hoc Networks (VANET) and are classified as a particular case of Mobile Ad Hoc Networks (MANET), although they differ from MANET for architecture, requirements and applications. In MANET, nodes communicate each other without a fixed infrastructure, they support dynamically topology and work with limited bandwidth and energy. Moreover, MANET are autonomous networks, hence mobile nodes can be located on airplanes, ship, trucks or cars. In VANET, nodes communicate in a similar way but with higher speed, different mobility characteristics that cause frequent changes in the topology and bandwidth and energy is not limited in general. VANET mobility characteristics offer some advantages: the mobility model of a vehicle is constrained to the roads in which the vehicle travels, thus the movements of the vehicles can be predicted (taking into account an acceptable error). Moreover the expected number of nodes in a VANET is much higher than the one for MANET and this number will change a lot during a day.

VANET can be classified by kind of services and applications or by type of communication. Taking into account the kind of service offered, vehicular networks applications can be classified in:

- Safety applications
- User Applications

If considered instead the type of communication, users in VANET can communicate in two type of different networks:

- Vehicle-to-Vehicle (V2V) communication
- Vehicle-to-Infrastructure (V2I) communication

3.1 Safety applications

Safety applications are those applications that increase vehicle safety on the roads, in general they aim to reduce the number of road accidents. According with some studies [21], 60% of the car accidents could be avoided if a driver were provided with an alert half a second before the possible collision.

These kind of applications can be grouped under three main categories:

- Accident prevention
- Post-accident safety and investigation
- Traffic control

Accident prevention applications tries to warn the driver of a possible incoming collision just a few moments before of the accident; post-accident safety and investigation is used to warn the user of an accident has happened nearby or that an emergency vehicle is trying to reach as soon as possible an accident site; traffic control is used to try to keep the vehicles distributed as homogeneous as possible to avoid traffic jams that increase the probability of collisions and fatalities.

In the follows the main safety applications offered by vehicular networks are presented in brief.

3.1.1 Intersection collision-avoidance

Driving near and through intersections is one of the most complex challenges that drivers face, since two or more traffic flows intersect, and the probability of collision is high. The number of accidents would decrease if a safety application warned the driver of an impending collision.

These systems are V2I-based, the infrastructures gather, process and analyze the information from the vehicles moving close to the intersection, if there is a non-negligible probability of car accidents or hazardous situations, a warning message is sent to the involved vehicles. These services work typically at a low frequencies, and with a range of 200-300 m.

3.1.2 Sign warnings

A good practice to avoid collisions is to respect the road signs positioned along the road. Systems that warn the drivers of the signs they have to be aware of would increase the overall attention of the drivers and thus decrease the number of possible collisions.

These applications rely usually on a V2I type of communication at extremely low frequency (1 Hz can be enough to ensure the in-time delivery of warning messages to each vehicle in the coverage area) and within a range of 100-500 m.

3.1.3 Cooperative collision warning

Using a V2V type of communication, vehicles can share information regarding the condition of the road, visibility (in case of foggy weather for example) or more advanced information about the traffic.

To make some example, a vehicle can have a blind spot while changing the lane of the road; in this case, a V2V message can be sent to the closest vehicles to warn them of the possible accidents due to the blind spot. An interesting application in this regarding is called cooperative collision warning: drivers are warned if an accident in the closer roads is predicted with a considerable probability combining together information about the position of the close vehicles, their velocity, acceleration and the surrounding environment [22] [23] [24]. Each in-vehicle unit elaborates these information combining it with the information of the vehicle itself and compute the probability of accident.

3.1.4 Cooperative adaptive cruise control

The speed of a vehicle depends on the speed limit of the road and on the speed of the vehicles ahead and behind the vehicle itself. This speed can be actively adjusted elaborating information incoming from the nearby vehicles using V2V communication and from the infrastructure (e.g. the speed limit) using V2I communication.

One of the most promising applications in this field is Platooning. The platooning concept can be defined as a set of vehicles that travel togheter, actively coordinated in formation, this can be done setting the relative speed between the vehicles involved close to zero and making constant the inter-vehicle distance [25]. This application would be useful especially for transport companies making their trucks travelling together to consume less and to control better their expeditions.

3.1.5 Approaching emergency vehicle warning

When an accident takes place, the emergency vehicle response time has to be reduced to the minimum. For this reason a V2V communication can be set when an emergency vehicle is approaching to send messages containing the emergency vehicle's velocity, direction, lane information and path in order to clear the road.

An example of this situation is showed in Fig. 3.1

3.1.6 Emergency vehicle signal preemption

In according with the last application presented, a V2I communication can be also used by infrastructures to send messages to all the traffic lights involved to set all the lights to green when the emergency vehicle is nearby, in order to minimise the time that the vehicle spends to reach the accident site.

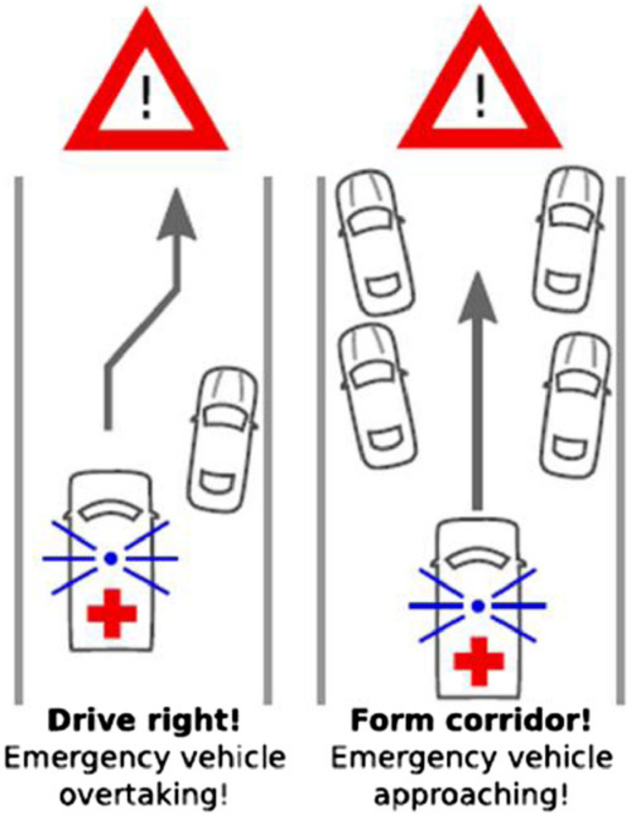


FIGURE 3.1: Approaching emergency vehicle warning example

3.2 User Applications

While safety applications require usually low rate communication, user applications, that are considered non-safety, can require both low or extremely high rate depending on the type of service. These applications can provide road users with information, advertisements and entertainment during their journey to make the driver experience more pleasant.

User applications can be grouped under two main categories: Peer-to-Peer applications, Contextual Information Retrevial and Entertainment services.

3.2.1 Peer-to-Peer applications

These set of applications would allow passengers to contact other people in nearby vehicles to alleviate boredom. Passengers would, for example, share music and movies or chat with other passengers.

To enable these services an Internet connection is not mandatory even if some kind of service would rely on remote servers accessible only through Internet. The datarate required by these applications ranges from some Mbps in case of live chat or music streaming, to hundreds of Mbps when video streaming is required.

These services can be enabled both using a V2V or a V2I communication, depending on the kind of service required.

3.2.2 Contextual Information Retrevial

Users in a vehicle may want to know some information about the surrounding environment, for example weather and traffic information, details on the nearby shops or restaurants, news etc.

This service requires a constant access to Internet, hence a V2I communication is needed, but it requires usually medium datarates. Given the dependance from an Internet connectivity, the vehicles have to be capable to communicate with remote servers through the standards cellular network protocols (e.g. LTE) at a datarate on the order of tens of Mbps.

3.2.3 Entertainment services

Users may want to spend their time inside a vehicle using some resource-demanding service. To this set of applications belong video and audio streaming from Internet, massive online games, videochat through Internet, etc.

To ensure a reliable connection able to support this kind of services, high datarate and low latency are required. Datarate required can be up to 1Gbps and latency should be reduced to some millisecond. Technologies available nowadays are not able to satisfy these requirements in all the situation, thus new technologies with an higher frequency or a novel and more efficient architecture are needed to fullfill the lack.

Moreover, these new technologies will face a considerable problem considering the high mobility and the dynamic topology of vehicular networks.

3.3 Autonomous Vehicles

Considering all the possible applications of VANET both for safety and infotainment, the best way to minimise the number of accidents would be to make the vehicles completely autonomous and replicate the human decision-making process. The distribution of these systems in the market is still a far-off thing in the future, given the ethical problems that society has to face and since the telecommunication technologies are not ready, but the attuation of the presented applications would be a big step towards the final objective.

Taking into account the technologies needed for autonomous cars, 5G will be a revolution in the way things and people communicate each other. Indeed autonomous cars will be able to use all the applications presented in this chapter at the same time, with the consequence that diverse requirements will be demanded and different technologies will be used to reach those requirements.

The solution that 5G will offer is to use several technologies of fourth or third generation (WiMAX, LTE, DSRC, etc.) combined with novel technologies like mmWaves or visible light communication to offer a good channel and a reliable communication in each situation the user can be.

A capillar network of cellular infrastructure will be deployed and multi-connectivity and interface selection systems will be designed and developed leveraging the different advantages of each technology.

The first models of autonomous cars are planned to be available in the market with the introduction of 5G, even if human actions are still needed in some situation. In the next years the research community will improve both the communication in vehicular networks and the functionalities that autonomous cars can offer to allow the introduction of this great innovation in the world.

Chapter 4

LTE architecture

LTE development was started in 2004 by 3GPP and is the evolution of Universal Mobile Telecommunication System (UMTS), the standard for mobile communication in the third generation of mobile networks. The aim of this technology is to provide high data rate, low latency and packet optimized radio-access technology supporting flexible bandwidth deployments to allow the spread of data demanding applications such as streaming or online gaming.

The high-level architecture of LTE is composed by three main components:

- UE
- Evolved Universal Terrestrial Radio Access Network (E-UTRAN)
- Evolved Packet Core (EPC)

EPC communicates directly with the internet and the interfaces between the different parts are called Uu, S1 and SGi, as shown in Fig. 4.1

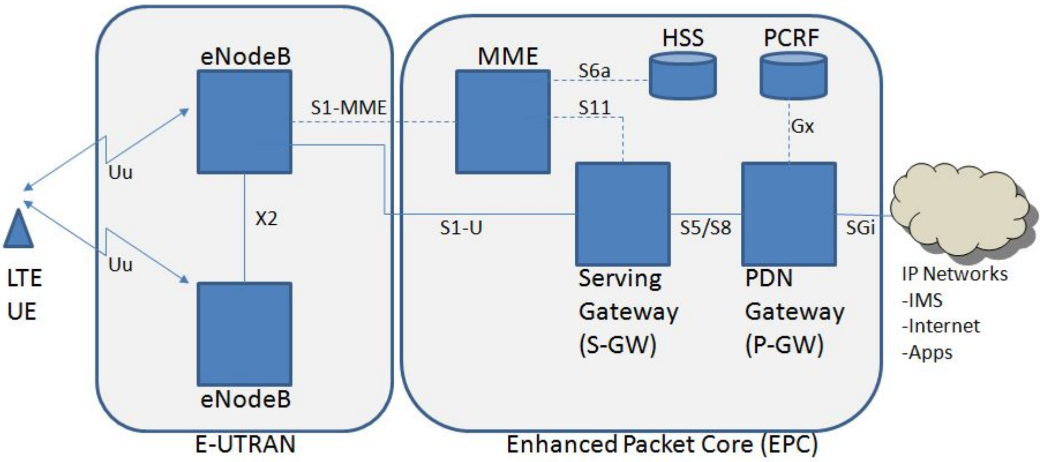


FIGURE 4.1: High-level architecture of a LTE Network

4.1 High level architecture

4.1.1 User Equipment (UE)

UE is the final part of the network, it communicates with the E-UTRAN segment thanks to a specific SIM card called Universal Subscriber Identity Module (USIM).

4.1.2 E-UTRAN

The E-UTRAN handles the communication between UE and the core network, it has only one component, the 4G LTE base stations (eNodeB). Each eNodeB controls one or more cells area, and communicates directly with the users. The users can communicate only with a single eNodeB at a time (its serving eNodeB), with which can send or receive radio transmission or it receives signalling messages to configure the connection (handovers, channel information ecc..)

eNodeB communicates each other by means of the X2 interface, used mostly to exchange messages during handover procedures, and is connected to EPC through the S1 interface.

4.1.3 Evolved Packet Core (EPC)

EPC interfaces the E-UTRAN with the Internet and it is composed by several parts:

Home Subscriber Server (HSS) is a component inherited from UMTS and GSM, is a database that contains information about all the users subscribed in the network;

Mobility Management Entity (MME) controls the high-level operations of UEs by means of signalling messages;

Serving Gateway (SGW) is the main gateway for the E-UTRAN, it forwards the data between eNodeB and Packet Data Network (PDN);

PDN Gateway (PGW) is the last part of the LTE network and is in charge of the communication with the PDN. Each user has access to Internet through a PDN, and is connected to its PDN through an Access Point Name (APN). PGW connect each user to the right APN, all the information about the subscriptions in the network are contained in the HSS.

Each component is connected with the others with a specific interface, the scheme of EPC is reported in Fig. 4.1, where dashed lines represents the control links while the others are data links.

4.2 LTE Radio Protocol Stack

The radio protocol architecture of LTE can be divided in User Plane and Control Plane. User plane protocol stack is responsible of incapsulating packets and send them through the network using the traditional transport protocol such as Transmission Control Protocol (TCP) and User Datagram Protocol (UDP), the protocol stack configuration for this part is reported in Fig. 4.2. The most relevant layers in the stack are PHY, MAC, Radio Link Control (RLC) and Packet Data Convergence Protocol (PDCP). The Control Plane protocol stack is in charge of maintaining the signalling system between UE and MME, it has an additional layer between UE and eNodeB called Radio Resource Control (RRC). The relative configuration is shown in Fig. 4.3. In the following, the main layers will be described.

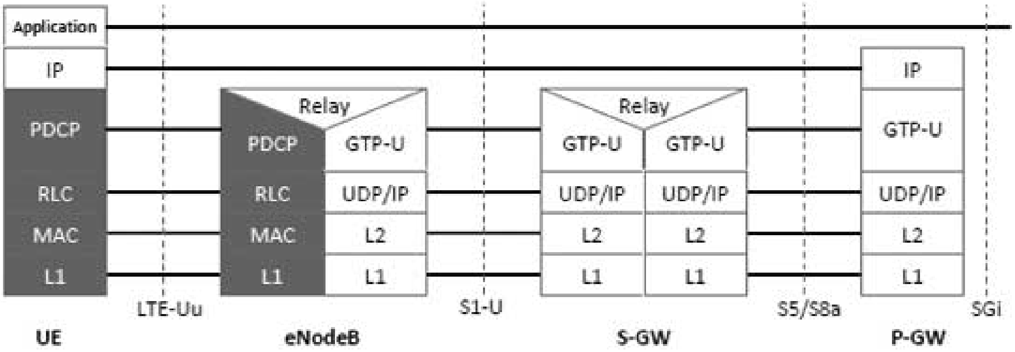


FIGURE 4.2: Configuration of LTE User Plane protocol stack from [2]

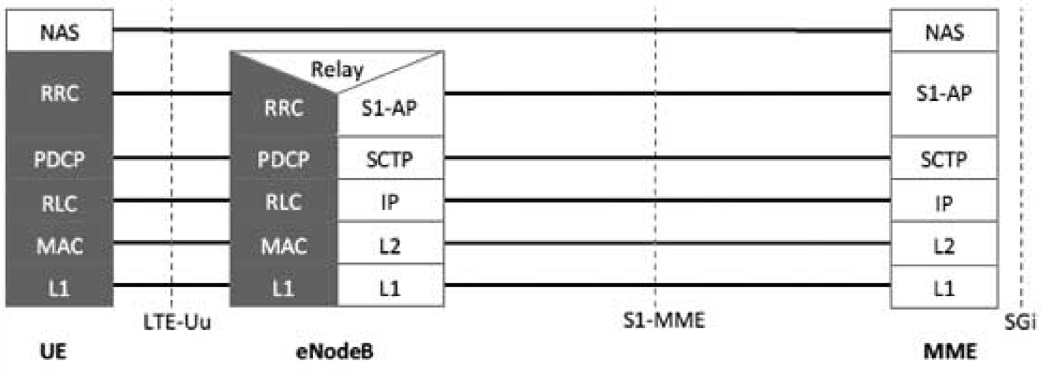


FIGURE 4.3: Configuration of LTE Control Plane protocol stack from [2]

4.2.1 LTE Physical and Medium Access Control layers

The LTE physical layer carries all the packets created in the upper layers from a terminal to another using the air interface. Is responsible of power control, cell search (in the initial phase and to manage handovers) as well as low-level tasks like modulation, framing and synchronization.

The MAC layer is in the middle between PHY and RLC, its connection with the lower level is through transport channels, while the one with the upper layer is through logical channels, MAC layer's main task is to map the data incoming from the upper layers into packets suitable for transport channels and viceversa, performing multiplexing and demultiplexing between the two type of channels.

MAC contains an entity that performs Hybrid Automatic Repeat Request (HARQ) operations, and a Random Access entity that manages the scheduling of the transmissions and the random access channel procedure.

4.2.2 Radio Link Control (RLC) layer

The RLC layer stands between PDCP layer and MAC layer, it manages the PDCP PDUs to make them suitable for MAC layer, and it reorders the RLC PDUs incoming from MAC in case they are received out of order due to the HARQ retransmissions. This is a major difference with UMTS, since in the previous technologies HARQ was managed at MAC level, in LTE MAC has been released of this task allowing it to be more performant. In these terms, RLC's main task is to interface PDCP layer with MAC.

RLC is present both in UE and eNodeB and there is an *RLC entities* for each Evolved Packet System (EPS) bearer (a data flow), each one can have 3 different data transmission modes:

Transparent Mode (TM) : the RLC entity is transparent to the PDUs that pass through it, no operations are made on the data and no overhead is added to the packet.

Unacknowledged Mode (UM) : the entity's tasks are performed but no acknowledgements are required, providing therefore an unidirectional data transfer service.

Acknowledged Mode (AM) : the entity is able to transmit and receive, it uses retransmissions to ensure an error-free communication. This mode is used mainly for error-sensitive and delay-tolerant non real-time applications.

4.2.3 Packet Data Convergence Protocol (PDCP) layer

PDCP layer is present both in User Data plane and in Control Data plane and it has a different architecture and different tasks depending on the context in which it is used. In case PDCP layer is used in User Data plane, it has the following tasks:

- header compression and decompression;
- chipering and dechipering;
- reordering and in-sequence delivery of PDUs for the layer above (the relay in eNodeB and IP in UE) during handovers;
- management of the data mapped on RLC when lossless handovers is a requirement;
- discarding of packets where timeout has expired.

In case instead of Control Data plane, the tasks PDCP has to fullfill are:

- chipering and dechipering;
- integrity protection and verification
- reordering and in-sequence delivery of PDUs for RRC layer during handovers;

Given the amount of tasks PDCP has to manage in User Data plane, the architecture in this side is much more complex.

4.2.4 Radio Resource Control (RRC) layer

RRC layer is the layer above PDCP and below Non-Access Stratum (NAS) in the Control Data plane [26]. It is in charged of the most important high-level control procedures, it ensure the establishment of the connection and its release, it broadcast system information over the EPC network, it manages the radio bearer connection and configuration and is responsible of the mobility from one Radio Access Technology (RAT) to another (when it is needed). It also collects measures from the UE's physical layer and it forwards them to the serving eNodeB, to keep this last one updated on the UE status.

Chapter 5

IEEE 802.11p/WAVE

In the last years the number of vehicles on the road has increased exponentially, decreasing, as a consequence, the safety both for drivers and pedestrians. The research community is trying to minimizing the main discomforts that a driver can experience in nowadays roads, in particular they are trying to decrease the number of accidents, limit the traffic congestion on the road and predict the speed of the neighbour vehicles in order to maintain a safe limiting distance. Vehicular networks will help to increase the overall safety introducing new services both inside the vehicles or infrastructure-side. For these type of communications, a safe and efficient way to deliver messages is required, is not required instead neither large bandwidth or high frequencies, since shared messages for safety purposes are short and they do not have stringent requirements in terms of throughput.

The most suitable technology for this task has been introduced in 2008 by IEEE [27], is called WAVE and is part of the 802.11 suite with the name IEEE 802.11p. This technology enable the intensive use of vehicular communication both V2V and V2I in presence of high mobility and without the need to rely on a structured network such as UMTS or LTE, at the cost of a limited range (say 100 to 500 meters) and throughput [28]. The scheme of WAVE protocol stack is reported in Fig. 5.1.

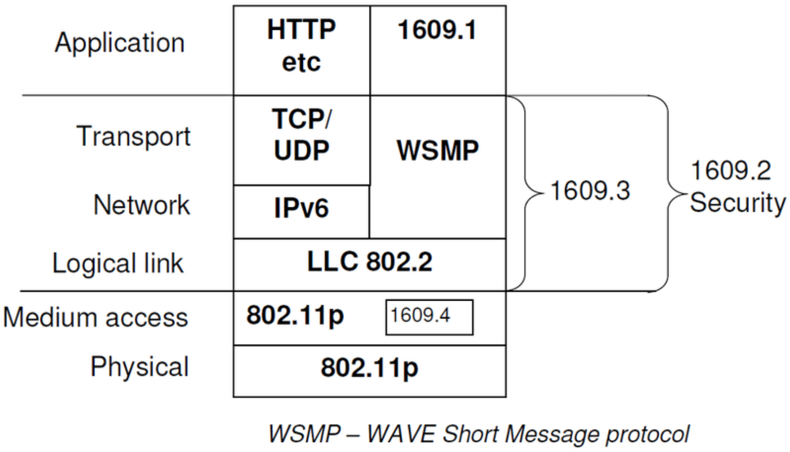


FIGURE 5.1: Overview of WAVE protocol stack from [3]

5.1 WAVE Phisical layer

WAVE physical layer exploits Orthogonal Frequency Division Multiplexing (OFDM) to support different datarates determined by coding rate and modulation type. The band used by WAVE is 5.85-5.925 GHz, these 75 MHz are divided in seven 10 MHz channels with a guardband of 5 MHz at the lower end of the spectrum [29], the way in which the frequency band is divided is showed in Fig. 5.2. Channels 172 and 184 are safety dedicated channels, they provide security solutions and congestion avoidance. Channel 178 is a control channel (CCH) and is responsible for controlling the transmission broadcast and link establishment. The other four channels are service channels (SCH) and are allocated for bidirectional communication between the UEs. These last four channels can be combined together to form two 20 MHz channels [30]. Usually multi physical layer devices work in CCH and at least one SCH, while single physical layer devices have to switch between CCH and SCH. Given this limitation on the single physical layer devices, synchronization is needed to ensure all the WAVE devices monitor the CCH at the same time interval. WAVE standard implements a basic synchronization algorithm in which all WAVE devices align their radio resource to a globally accurate clock every time period.

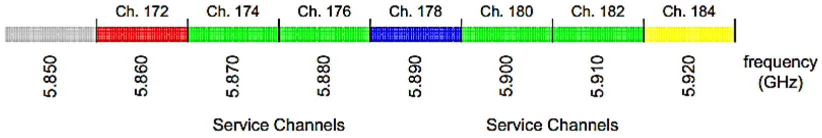


FIGURE 5.2: IEEE 802.11p/WAVE channel frequency band

Thanks to OFDM and to the particular Modulation and Coding Scheme (MCS) used, eight operating modes are supported, resulting in a physical data rate which ranges from 3 to 27 Mbps.

5.2 WAVE MAC layer

WAVE MAC layer behavior is defined by the IEEE 1609.4 standard [31], it extends IEEE 802.11e paradigm to support two channel operations, the architecture of this layer is reported in Fig. 5.3.

WAVE MAC layer offered services can be divided in two planes, the Data Plan and the Management Plan. Data Plan provides data services to the higher layers, while Management Plan performs low-level tasks including synchronization and channel access. In the management plan, WAVE implements the Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) as channel access method, where a node listen to the wireless channel before sending. On one hand, CSMA/CA allows for reduced signaling overhead if compared with the other channel access algorithms, enable uncoordinated channel access and prevents the definition of resource allocation mechanisms. On the other hand, the system is prone to the *hidden node problem*, i.e. there are unavoidable collisions if an out-of-range station is transmitting towards the same potential receiver, for this reasons, CSMA/CA does not scales well with congestion and density of the scenario.

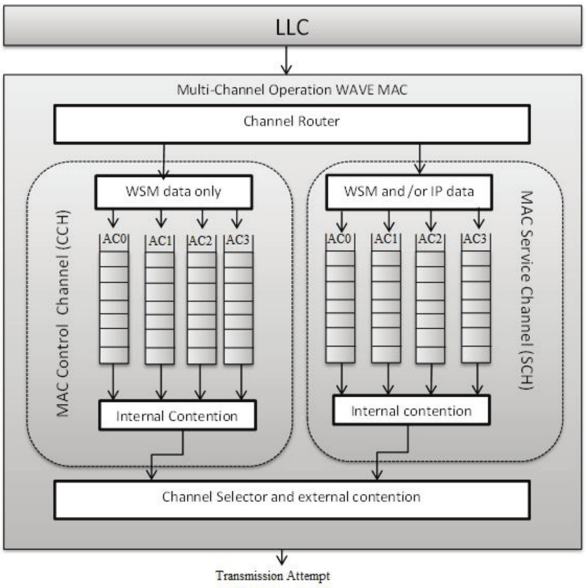


FIGURE 5.3: IEEE 802.11p/WAVE Multi Channel MAC layer

5.3 WAVE Network and Transport layers

WAVE network and transport layers are described in IEEE 1609.3 and IEEE 1609.2 standard protocols [32][33], the first describes the network and transport stacks while the second describes security functions and services.

WAVE supports two different network stacks: IPv6 and WAVE Short Message Protocol (WSMP), the first is the classical protocol used all over the Internet to exchange messages, the second is a particular communication mode which enable the exchange of messages in a rapidly varying radio frequency environment, is a suitable protocol for high priority time-sensitive applications. Moreover, WAVE implements also an extension of IPv6 that supports high network mobility, called *GeoNetworking*, this protocol provides ad hoc packet delivery utilizing geographical positions for addressing and forwarding.

On the top of this routing protocol Basic Transport Protocol (BTP) is defined, a transport protocol provides a connection-less service with low overhead similar to UDP [34]. Nevertheless, TCP and UDP as well as other transport protocols are supported for specific applications.

5.4 WAVE applications

WAVE has been introduced to allow the spread of vehicular technologies and communications, in particular V2V communication, in which no infrastructure are required and the nodes (vehicles) are self organized. The most promising applications for this technology are:

Road Hazard Signaling (RHS) : delivering information on emergency vehicle approaching or hazardous locations;

Intersection Collision Risk Warning (ICRW) : which refers to potential vehicle collisions at intersections;

Longitudinal Collision Risk Warning (LCRW) : to prevent rear-end or head-on collisions.

All this applications require an extremely reliable network in which short message are exchanged between vehicles with low latency and a low Bit Error Rate (BER).

Chapter 6

NR architecture

The architecture of the global standard for the upcoming 5G air interface is still not well defined, in the last years Mobile and wireless communications Enablers for Twenty-twenty (2020) Information Society (METIS) indentified the requirements for the new generation of cellular networks and the industry is developing the optimal solution to face this new challenge.

The new air interface is called NR and its key features are currently under investigation. Due to the extreme variety of requirements in 5G services, it is clear that the 5G Radio Access Network (RAN) must be designed to operate in a range of spectrum as wide as possible with diverse characteristics, such as channel bandwidth and propagation conditions [35]. The approach chosen by the main industries and research groups is to use LTE Advanced (LTE-A) for communication that exploit the portion of spectrum below 6 GHz and to use a novel technology for frequencies above 6 GHz. The technology more suitable for this task is certainly mmWaves.

mmWaves bands ranges roughly from 30 GHz to 300 GHz, even though this range can be extended also to lower frequencies (above 6GHz) used in 5G NR. This portion of radio frequency spectrum is already used by some commercial application that does not suffer from shadowing, or Non-Line-Of-Sight (NLOS) communication (e.g. satellite and point-to-point backhaul communication), they were considered impractical for mobile access network due to the harsh propagation characteristics and the vulnerability of environment condition (shadowing, rain, fog, etc.). It has been recently shown that these limitations can be overcome with high-gain communication and directional antennas, making its use in the mobile networks possible.

The idea is to use LTE-A for the less demanding applications in terms of throughput and latency and where a very low Packet-Error-Rate is expected (e.g. Machine-To-Machine communications, control signaling, etc.), while mmWaves will be used for applications that demand massive capacity and are tollerable to some errors.

The challenge in this approach is to find a way to integrate the different air interface standards into one overall 5G air interface such that standardization and complexity are minimized without sacrificing the performance of the several technologies used. In the follows, as described in [36], some key aspects for a good integration between the different technologies are considered:

Protocol harmonization Two different air interfaces with two completely different radio protocol stacks are too complex and expensive to deploy. In 5G

NR the protocol stacks related to different air interfaces should derive from the same definition through parametrization. UE's network procedures (e.g. initial access and mobility) should be similar or even shared between the different technologies and using different frequency bands; the lower layers of the protocols stacks could be adaptive through parametrization or activation, addition or removal of certain features via physical or logical implementation.

Service Multiplexing A single instance of a radio protocol stack should be able to handle multiple bearers or flows related to different type of services and devices, therefore it should be able to manage two different air interfaces at the same time.

Layers aggregation The possibility to harmonize different protocols in one single radio protocol stack will enable several solutions to exploit the multi-connectivity capability of the network. Even if PHY procedures can differs between the diverse technologies, a single MAC layer can be useful to implement cross-RAT scheduling, PDCP aggregation can enable similar features to make the architecture more suitable for distributed deployments and to remove the need to aggregate the lower layers (that may be unfeasible due to physical limitations of the technologies).

These aspects can be adopted to integrate only novel 5G air interfaces or to integrate them with 4G standard air interface (i.e. LTE). Clearly, in the second case the harmonization and the protocol stacks aggregation will be more complex due to the constraints of a yet standardized protocol. In Fig. 6.1 the said considerations are summarized.

In the final version of NR architecture, is expected that the majority of Core Network and Service-Layer functions are deployed as virtual network functions, running in virtual machines inside servers in a datacenter, exploiting the flexibility of Software-Defined Networking. The advantages of this implementation can be the deployments of the network segments (i.e. Control Plane and User Plane) in different locations, depending on the requirements in terms of latency, storage capacity, etc.

Moreover, in [37] 3GPP proposes a logical split between Core Network, RAN and Service-Layer functions, the exact architecture of this new kind of network is in definition, but EPS seems to be the best candidate as baseline for the split. In order to fulfill the requirements a new Core Network/RAN interface has been defined, called S1*, with tasks similar to the original S1 interface but integrating multi-RAT procedures and extremely adaptive to each kind of service. Also X2 will evolve to X2* to support multi-connectivity and mobility and to support multiple RAT. A scheme of a possible future NR architecture is reported in Fig. 6.2.

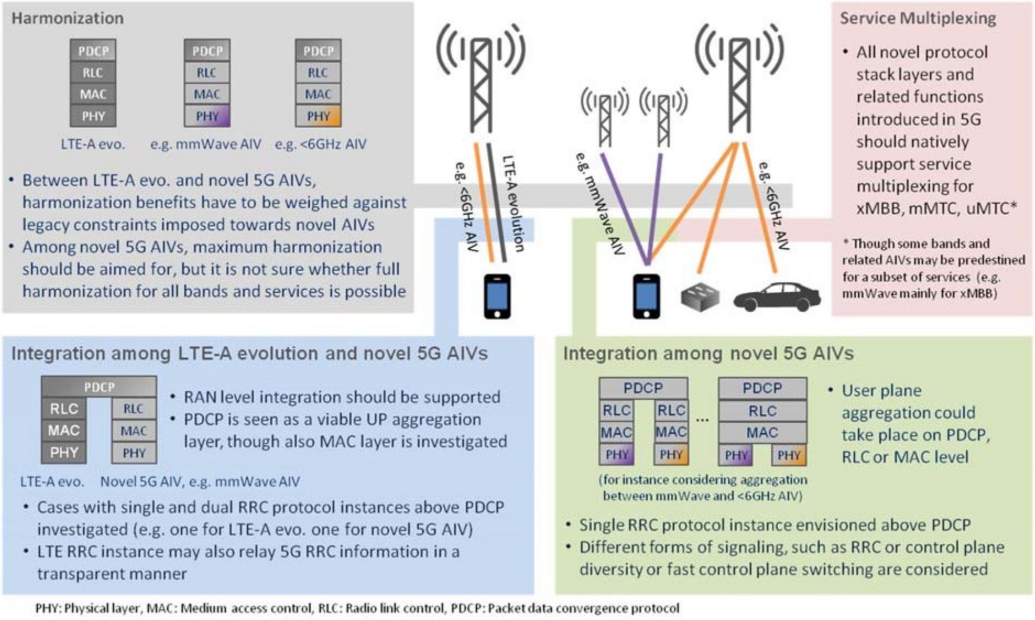


FIGURE 6.1: Key considerations on future 5G New Radio architecture

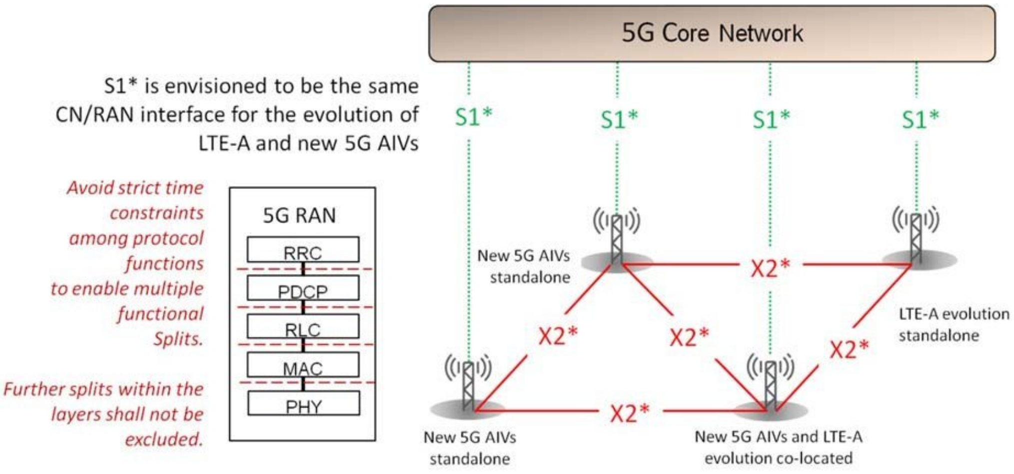


FIGURE 6.2: Example of future 5G New Radio architecture

Chapter 7

Simulation framework

In this chapter we will introduce the main tools used in this thesis. The work is developed using NS3 simulator, a simulator spreadly used in the academic and professional research regarding the telecommunication networks, moreover several NS3 modules have been used to simulate the different technologies.

In Chapter 7.1 we will introduce briefly the reader to NS3, its architecture and the main features it offers, in Chapter 7.2 the main features of NS3 LTE module used in this thesis will be presented, in Chapter 7.3 the module that allow to use IEEE 802.11p/WAVE is described and finally in Chapter 7.4 the mmWave module developed by NYU will be presented deeply.

7.1 Introduction to NS-3

NS3 is a discrete-event network simulator targeted primarily for research and educational use. NS3 is completely open source and can count on a large community of researchers and developers that maintain and expand it [38]. It is written in C++ and Python, and has been created to provide researchers, students and developers a complete tool able to simulate each aspect of a modern network. The main features of this simulator are the following:

- construction of virtual networks (nodes, channels, applications) and support for items such as event schedulers, topology generators, timers, random variables, and other objects to support discrete-event network simulation of Internet-based and non-Internet-based network systems.
- support for network emulation: the ability for simulator processes to emit and consume real network packets
- distributed simulation support: the ability for simulations to be distributed across multiple processors or machines
- support for animation of network simulations
- support for tracing, logging, and computing statistics on the simulation output

NS3 has a modular implementation, the core of the simulator is composed by a set of main libraries that contains the definition of the essential tools in a network simulator, such as Random Number Generator (RNG), debugging objects, simulation time objects, the classical schedulers, tracing objects and generic packets. Then a second set of libraries defines abstract base classes that will be extended by users and researchers to describe a specific behavior, in this set are defined objects like nodes, channels and network devices. Finally, users may write their own libraries and modules, usually extending the default ones, to describe the behavior of a specific protocol or a novel technology. The complexity of this simulator stimulated the developers to write a complete and self-contained documentation that is good practice to keep updated and choerent.

The modules that will be used in this thesis are the mmWave module developed by NYU and presented in [39], the LENA module developed by Centre Tecnològic de Telecomunicacions de Catalunya (CTTC) [40] and the WAVE module developed by Qingdao Agriculture University and Dalian University of Technology (DUT) [41].

7.2 LTE module

A first trial in developing a complete and open source LTE network simulator was made in [40], this supports the main feature of LTE such as single and multi-cell environments, QoS management, multi users environment, user mobility, handover procedures, scheduling, and frequency reuse techniques. The problem of network simulators designed for a single technology, is that they can not be used in researches in which several technologies have to be compared or they are used cooperatively.

The LTE module designed in 2011 by CTTC is part of NS3 and focuses mainly on modeling the Evolved Universal Terrestrial Radio Access (E-UTRA) part of the system (the air interface of LTE [42]), with a particular level of detail on the channel, PHY and MAC layers. The module is composed by two main components:

LTE Model includes the LTE Radio Protocol stack (RRC, PDCP, RLC, MAC, PHY). This takes care of the UE and eNodeB nodes.

EPC Model includes the core network interfaces, protocols and entities. This part models the SGW, PGW and MME nodes, and part of eNodeB nodes.

In Fig. 7.1 is reported an overview of LTE module's architecture.

LTE module does not take into account the presence of blockages or buildings when propagation loss is calculated, but can use the classes implemented by `buildings` module that set the most appropriate propagation loss model depending on the type of scenario deployed, it defines a new mobility model and, in case of buildings in the simulated area, it models the phenomenon of indoor/outdoor propagation.

In the follows the `buildings` module is described.

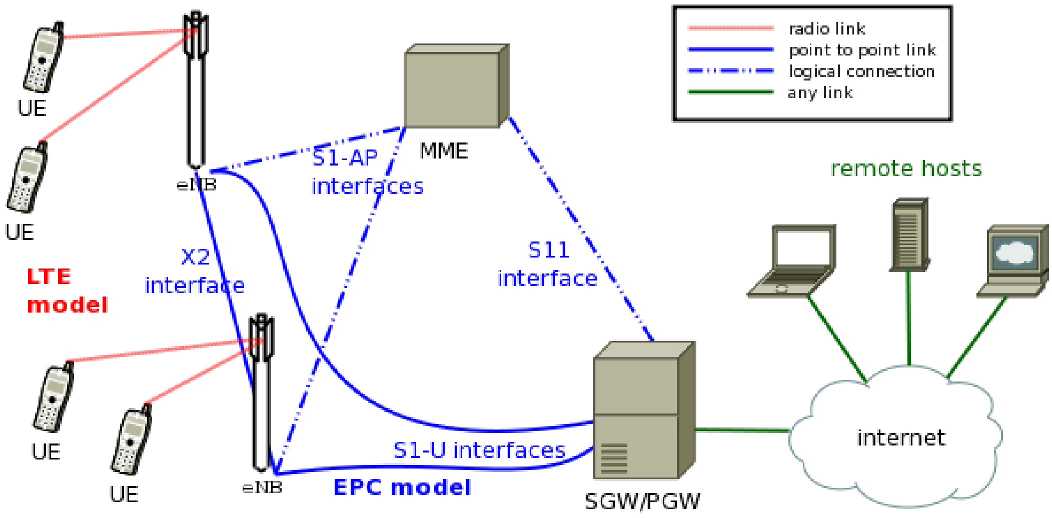


FIGURE 7.1: Overview of the LTE-EPC simulation model

7.2.1 Buildings module

The Buildings module contains classes and tools to allow the introduction of blocks and buildings inside NS3 simulations. The main features provided by the module are:

- the class `Building` that models the presence of a building in a simulation scenario;
- a container class with the definition of the most useful pathloss models in this context and the correspondent variables called `BuildingsPropagationLossModel`;
- a new propagation model called `HybridBuildingsPropagationModel` that is the only propagation model in the latest stable release of NS3 that takes into account also indoor-to-outdoor scenarios, outdoor-to-indoor or that update the state of the user during the simulation, and that work with multiple propagation loss models;
- a simplified model working only with Okomura Hata (`OhBuildingsPropagationLossModel`) that considers both indoor and outdoor propagation in presence of buildings.

In this thesis, `HybridBuildingsPropagationLossModel` has been used to calculate the attenuation of the signal when using LTE technology, since there is the need to update the state of Line-Of-Sight (LOS)\NLOS of the UE as it moves. This model is obtained through the combination of the following pathloss models in order to mimic different indoor and outdoor scenarios:

- `OkumuraHataPropagationLossModel`
- `ItuR1411LosPropagationLossModel`

- `ItuR1411NlosOverRooftopPropagationLossModel`
- `ItuR1238PropagationLossModel`
- other pathloss models defined by `BuildingsPropagationLossModel` that describe the behavior of a signal inside a building or indoor-to-outdoor attenuation.

`OkumuraHataPropagationLossModel` is considered for nodes at a distance greater than 1 km and above the rooftop level; `ItuR1238PropagationLossModel` implements a building-dependent indoor propagation loss, it takes into account specific types of buildings (i.e. residential, office and commercial), and is used to calculate the loss between nodes inside the same building. In all the cases in which these two propagation loss model can not be applied, `ItuR1411LosPropagationLossModel` or `ItuR1411NlosOverRooftopPropagationLossModel` are used.

By default, when an ITUR1411 propagation model has to be used, this class tries to guess if the nodes are in LOS comparing their distance with a tunable threshold (`itu1411NlosThreshold`) set initially to 200 m. If the distance is greater than the threshold, the nodes are supposed in NLOS and `ItuR1411NlosOverRooftopPropagationLossModel` is used.

Although this approach can be used for some application that does not require an high accuracy in terms of propagation loss, I extended `HybridBuildingsPropagationLossModel` with some methods that improve the accuracy of the propagation model. In the new approach, is checked if the line that pass through the two nodes intersect at least a building, in that case the channel condition is set to NLOS, otherwise is in LOS, independently from the distance between the nodes. This improvement makes the simulations slower, since each time the position of the nodes have to be compared with the location of all the buildings, but allows to perform detailed analysis on the percentage of time in which nodes are in NLOS during the simulation.

7.3 WAVE module

The need for analyzing the performance of vehicular networks in an end-to-end environment has motivated the development of a specific module for NS3, called WAVE. WAVE module for NS3 is focused mainly in simulating MAC and Multi Channel Coordination layers, and since the current WiFi NS3 module models many features required by IEEE 802.11p systems, WAVE extends it introducing the features that are not part of the basic WiFi technology.

One of the novel features introduced by WAVE module is the presence of `OcbWifiMac`, a new MAC class which supports operations outside the context of the base stations (OCB), a basilar requirement in the future vehicular networks. The key design aspect of WAVE-compliant MAC layer is that, in conformity with OCB systems, it provides devices with the capability of switching between control and service channels, using a single radio or using multiple radios. Therefore devices can communicate with others in single or multiple channels, which can support both safety related and non-safety related service for vehicular environments.

At the physical layer, the biggest difference is the use of the 5.9 GHz band with a channel bandwidth of 10 MHz, while WiFi physical layer uses both 10 MHz and 20 MHz bandwidth. The implementation of this mechanism is both in `ns3::Wifi80211pHelper` and `ns3::WaveHelper` classes, and they allow the correspondent `NetDevices` to combine their `OcbWifiMac` class with the only WiFi features supported by the used architecture. These physical layer changes can make the wireless signal relatively more stable in the short range, without degrading throughput too much (ranging from 3 Mbps to 27 Mbps).

As can be noticed, WAVE module offers both an helper for IEEE 802.11p and for WAVE. Indeed both general IEEE 802.11p and WAVE devices are supported, the helper to be used depends on the specific application. The internal architecture of NS3 WAVE module is reported in Fig. 7.2.

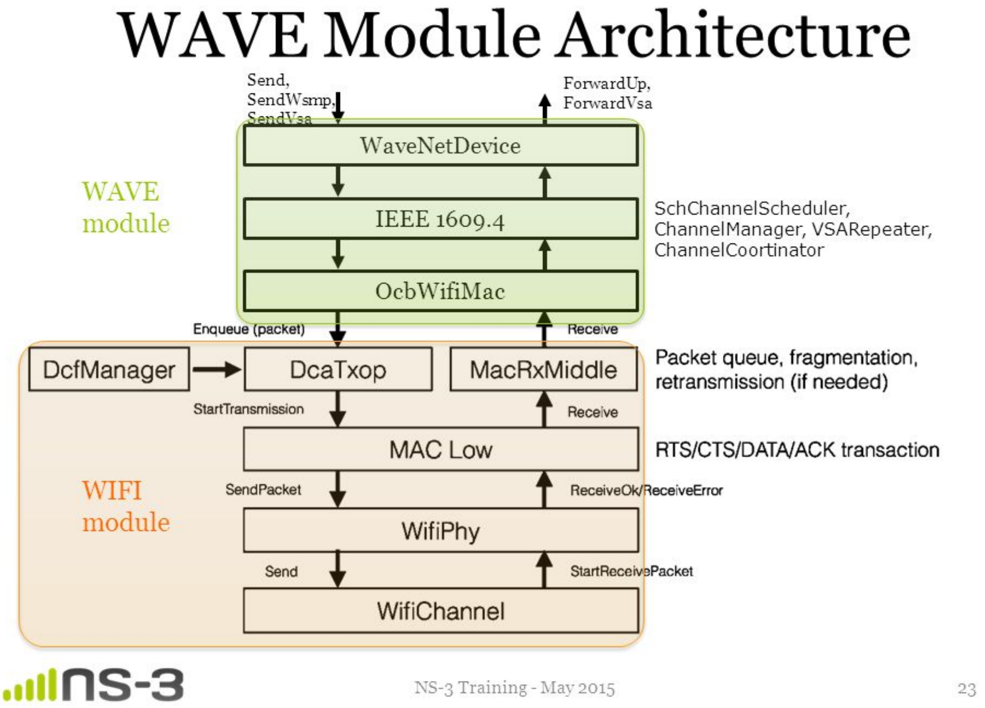


FIGURE 7.2: Internal architecture of NS3 WAVE module

Although this model implements a set of methods to be used in a vehicular environment, it does not take into account any mobility model, but thanks to the modular NS3 architecture, the *mobility* module can be used together with this module to run simulation with vehicular mobility. In the current version of WAVE module, is also included an example in which real mobility traces are taken from the city of Zurich. Moreover, personalized mobility traces can be created using vehicular simulators like SUMO.

By default, the module does not use neither fading and shadowing propagation model, these can be added in `YansWifiChannelHelper` class.

7.4 mmWave module

The mmWave module for NS3 has been developed by NYU together with University of Padova to simulate the behaviour of this technology in the possible scenarios and to assess the performance that can be reached (and of course the limitations) with an high frequency protocol. The module has been developed as an extension of the LTE module, and its focus is on the characterization of the lower layers of the radio protocol stacks (PHY, MAC, PDCP). mmWave module is interfaced with the Core Network of LTE module, in order to allow full stack simulation of end-to-end connectivity and to design and simulate other advanced features such as dual connectivity. The development of this module is of great importance to help the research to assess the performance of their theoretical model and to evaluate the impact of channel and Physical layer of this technology in the whole protocol stack, helping the development of systems with features like adaptive beamforming and beam-tracking, directional synchronization and dual connectivity, fundamental to design a robust and reliable system.

As shown in Fig. 7.3, the module is built upon LTE module, it leverages the detailed implementation of LTE/EPC protocols and implements custom PHY and MAC layers.

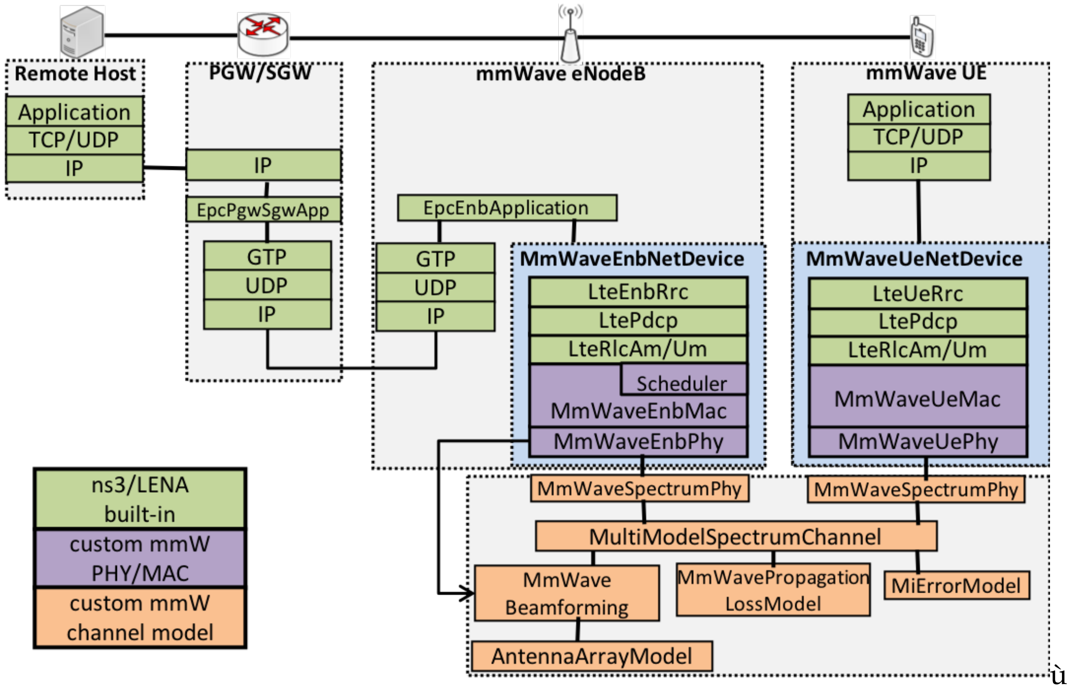


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FIGURE 7.3: Class diagram of mmWave NS3 module

The module implements:

- a custom mmWaves channel model developed to characterize the behaviour of this high frequency technology together with classes that define aspects like antenna arrays, beamforming, propagation loss model or error model;

- the lower layers of the radio protocol stack (Physical and MAC layer) together with specific features introduced by mmWaves.

The higher layer of the stack (RLC, PDCP and RRC) are inherited by LTE module, to reduce the complexity and with a view to dual connectivity implementations. The module implements the classes `MmWaveEnbNetDevice` and `MmWaveUeNetDevice` which define the mmWave gNodeB and UE radio protocol stacks, respectively.

7.4.1 Channel model

The mmWave module allows to choose between 3 different channel models, one can choose the more appropriate model based on the computational complexity, the flexibility and the level of detail expected. In the follows a brief introduction of each channel model is reported.

3GPP Statistical Channel Model

The most flexible and detailed channel model is described in [43] and is based on the official 3GPP channel model for frequencies from 6 to 100 GHz [44]. It takes into accounts both spatial consistency in presence of mobile users and a random blockage model. It defines different scenarios, which describe different possible cellular networks deployments: urban, rural and indoor, each scenario has a different parametrization inside the model.

The pathloss of this channel model is implemented by `MmWave3gppPropagationLossModel` and provides a probabilistic LOS/NLOS condition characterization based on the distance of the UE from the serving gNodeB. The bigger the distance, the higher the probability, for the UE, to be in NLOS. It also provides the pathloss computation considering outdoor and indoor penetration loss. `MmWave3gppBuildingsPropagationLossModel` class instead, exploits the channel model provided by `MmWave3gppPropagationLossModel` but computes the LOS/NLOS condition according to the relative position of UE and gNodeB and to the presence of buildings or obstacles in the scenario defined thanks to the `buildings` module described in Chapter 7.2.1. Since this second model has to compute the presence of blockages between transmitter and receiver, is computationally more demanding but it is more realistic. This model also add a shadowing component to the pathloss.

The fading model is implemented in `MmWave3gppChannel` class and is the more computational demanding task in the channel model implementation given its level of detail. The channel is described by a channel matrix $H(t, f)$ where t is the time and f is the frequency, this matrix is generated by a method of the class taking into accounts the antenna arrays of the transmitter and the receiver and the multipath components of the signal. This class offers also the possibility to simulate the spatial consistency of the channel when the UE moves. Moreover `MmWave3gppChannel` provide an option to generate random blockages such as cars, human bodies, trees, etc. to compute the impact of the shadowing in the channel performance.

Given its flexibility and adaptability to different scenarios, and since it can compute an accurate channel propagation loss model in presence of an high number of buildings, this model is used in this thesis to model the mmWave channel when mmWaves are simulated.

Ray-tracing or Measurement Trace Model

The second model provided by mmWave module is based on traces from measurements of a third-party ray-tracing software. Is implemented in `MmWaveChannelRaytracing` and takes into account pathloss and fading. The trace samples need to contain very detailed information on the scenario to be simulated (e.g. number of paths, propagation loss, delay, angle of arrival and angle of departure for each path), for this reason simulation scenario has to be chosen before the actual simulation and traces have to be generated with a ray-tracing generator.

NYU Statistical Model

The third and last model has been implemented in [39] and is based on traces generated with a MATLAB script. The limitation is that this model is available only for the 28 and 73 GHz frequencies. It provides two pathloss models, one that takes into account the behavior of the signal when UE and gNodeB are in LOS (`MmWavePropagationLossModel`) and the other when they are in NLOS (`BuildingsObstaclePropagationLossModel`). To choose which model have to be used, a virtual line is drawn between transmitter and receiver, if it intersect any object deployed with the aim of the *buildings* module, the condition is NLOS, otherwise LOS is assumed.

In the model, some parameters are pre-calculated in MATLAB to decrease the computational complexity of the NS3 simulation (e.g. the channel matrix), and they are updated during the simulation, while others, such as the fading, are calculated at every transmission, since they depend from parameters like the speed of the vehicle. The other parameters that depend on the environment are assumed constant to make the simulation lighter in terms of computational complexity.

The transition between LOS and NLOS is also considered, in this case the blockage measurements have been performed in a simplified manner in a lab.

7.4.2 Beamforming gain and Interference

For long-term statistical channel model, the beamforming vectors are computed with MATLAB, while for other channel models there are some methods implemented in `MmWaveBeamforming` class and currently only *analog* mode is available (i.e. devices can communicate in only one direction at a time).

Given the directional nature of mmWaves antenna beams, interference is often negligible. Nethertheless, the module takes into account the interference in dense topologies, where devices are very close each other , and calculates the intra-cell interference where Spatial Division Multiple Access (SDMA)/Multi-User MIMO is used, since users are multiplexed in the spatial dimension but share time-frequency resources.

Finally, the error model used by mmWave module leverages the one implemented in LTE module.

7.4.3 Physical and MAC Layer

The physical layer of NS3 mmWave module provides a fully customizable Time Division Duplex (TDD) and a custom frame structure, together with a system of feedback to ensure a reliable communication. In order to satisfy the strict requirements for the latency given by 3GPP and METIS vision, and to offer an improved utilization of the large bandwidth available, 5G mmWave systems must use TDD operations. MmWave module implements a custom system in which each frame is subdivided into a fixed number of subframes defined by the user , each subframe is split into a number of slots of fixed duration that contains a specified number of OFDM symbols. A slot can be either used for control messages or for data, in the uplink or downlink. In Fig. 7.4 is shown the scheme of a typical frame structure, in which the first two slots of each subframe are assigned for control in the downlink and uplink direction respectively, the others are used for data. Each time the allocated direction change from uplink to downlink (or viceversa), a gap of $1\mu s$ is introduced. In the frequency domain, each OFDM symbol is also subdivided in different sub-bands each of width 13.89 MHz [39].

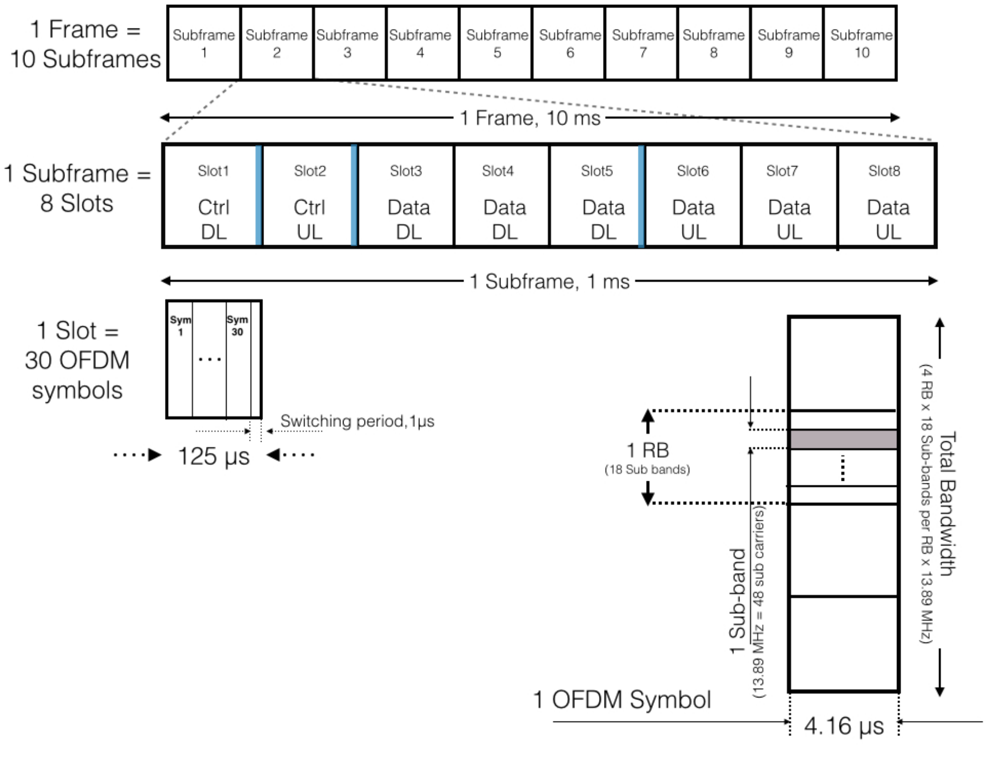

FIGURE 7.4: Example of mmWave frame structure

The parameters of the frame structure are accessible and completely customizable from the attributes of the `MmwavePhyMacCommon` class.

`MmWaveEnbPhy` and `MmWaveUePhy` classes model the physical layer for the mmWave gNodeB and UE respectively, and are similar to the correspondent `LtePhy` class in LTE module. The main tasks of these classes are:

- to handle the transmission and reception of physical control and data channels;
- to simulate the start and the end of frames, subframes and slots;
- to deliver received and decoded packets (control or data) to the MAC layer.

The timing of the end and start of frames, subframes and slots in the physical layer is controlled by the scheduler, dynamically configured by MAC layer through the MAC-PHY SAP. SAP are defined in several classes and are the interface between PHY and MAC layer and MAC layer and the scheduler. The relationship between MAC, PHY and scheduler through their associated SAP are shown in Fig. 7.5.

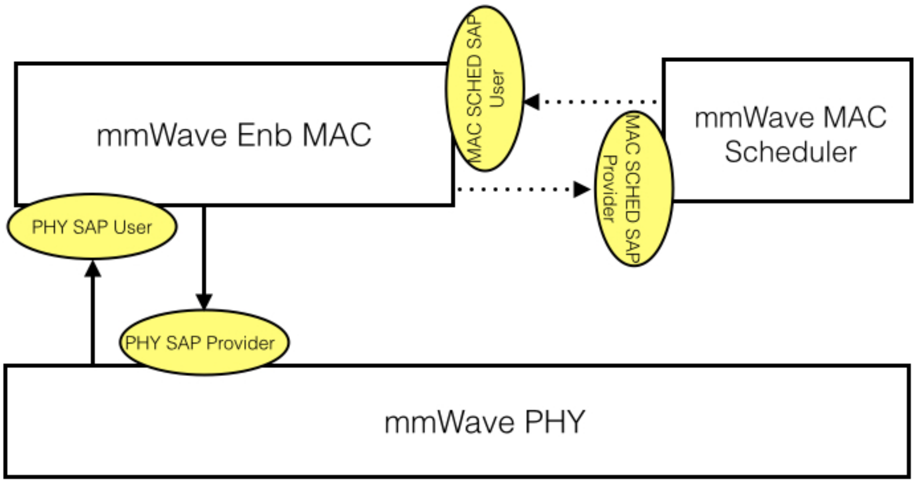

FIGURE 7.5: Relationship between PHY, MAC and scheduler through SAP

MAC layer in mmWave module is implemented by the class `mmWaveMac`, which is the base class for `mmWaveEnbMac` and `mmWaveUeMac`, that model the MAC layer for mmWave gNodeB and UE respectively. The main task of this layer is to deliver data packets coming from upper layer (Network and Transport layers) to the PHY and viceversa, synchronizing the delivery based on the used TDD mode thanks to the scheduler. It also communicates the resource allocation decision processed by `MmwavePhyMacCommon` to the PHY layer and it is in charge of the Hybrid ARQ at MAC level implemented in `MmWaveHarqPhy`. With the information received from the HARQ feedback messages, the scheduler at the gNodeB can assign new resources and pass the information to the PHY layer.

The higher layers in mmWave module are inherited almost completely from the LTE module, with the exception of RLC AM retransmission entity that has been modified to be compatible with mmWave PHY and MAC layers and the introduction of Active Queue Management (AQM) in RLC layer that is a new feature available for the management of the buffers in routers, middleboxes and base stations in order to improve the performance of TCP protocol and avoid the manual tuning of the buffer size.

7.4.4 Dual Connectivity Extension

In the latest releases, the possibility to use dual connectivity (mmWave and LTE) has been introduced in NS3 mmWave module. In this case, each UE is provided of a dual-stack architecture and can be connected both to an LTE eNodeB or to a mmWave gNodeB. This configuration assumes that mmWave and LTE uses the same core network, that the different base stations are connected each other with X2 interfaces and that they are connected to MME and PGW nodes through S1 interface. The two technologies share the same protocol stack from application layer to PDCP one, than for lower layers they are divided since they offer different services. Dual Connectivity is implemented in mmWave module by `McUeNetDevice` class, that is based on `NetDevice` class. This class holds pointers to the custom lower layer stack classes, and has a `Send` method that relays the packets to the higher layers that are part of TCP/IP stack.

A dual RRC layer is considered, the LTE RRC layer manages both the LTE and Dual Connectivity connection, while the mmWave RRC layer manages only the mmWave link.

This Dual Connectivity extension will be useful to assess the performance of the integration of these two technologies in different scenarios, with a view to the NR standard that will be used in the next generation of cellular systems. Thanks to this module, an optimal design for the 5G systems Radio Protocol Stacks can be investigated, and new solutions can be proposed.

Chapter 8

Simulation settings and scenarios

In this thesis, We assessed the performance of the three modules described in the previous chapters, in a vehicular environment with high mobility, testing the potential of each technology in this novel field. After a period of study of the state of the art and of the possible (and significative) implementations, we developed NS3 scripts to simulate the scenarios in which these technologies will be used in 5G networks. For each simulation, the Monte Carlo method has been used [1] to make results statistically robust. Three different scenarios have been implemented: the first one, described in Chapter 8.1, is a V2V scenario in which WAVE will be used to communicate between two vehicles, the last two are discussed separately since a V2I communication is simulated, these are presented in Chapter 8.2. The first V2I scenario is an urban scenario in which both LTE and mmWaves are used to assess their end-to-end performances, and is presented in Chapter 8.2.1, the second is an highway scenario described in Chapter 8.2.2 in which mmWaves to assess its performance with a view to the future applications such as proactive caching [45] or other demanding 5G services.

8.1 V2V scenario

In a V2V scenario, a great flexibility is needed in terms of topology and routing, given its major use in unstructured and self organized networks IEEE 802.11p/WAVE is a suitable candidate for this type of networks.

8.1.1 IEEE 802.11p/WAVE

In this scenario, two vehicles are positioned at a distance d each other and communicates using UDP. The vehicles' speed is 0, this takes into account both the eventuality in which the vehicles are stopped or have the same velocity and the same direction, for example in an platooning scenario. The simulation parameters are based on realistic system design consideration and are summarized in Tab. 8.1.

At physical layer the channel propagation model used is `LogDistancePropagationModel`, to characterize basic attenuation in outdoor highway environments. As just said in Section 7.3, WAVE does not take into account fading and shadowing

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[1] The computational complexity of the simulator and the complexity of the scenarios deployed makes difficult to run an high number of simulations, will be part of future works to make the results more statistically meaningful.

Parameter	Value	Description
T_{sim}	10 s	Simulation time
τ_p	800, 8, 0.8, 0.08, 0.008 ms	Inter-packet interval
R	0.01, 1, 10, 100, 1000 Mbps	Application rate
D	1000 $bytes$	Packet size
h_{ch}	`OfdmRate6MbpsBW10MHz`	Channel model
m_0, m_1	1.5, 0.75	Nakagami-m
f_c	5.875 GHz	Carrier frequency
W	10 MHz	Bandwidth
P_{tx}	16 dBm	TX power
NF	7 dB	Noise figure
Γ_{th}	-96 dBm	Energy threshold

TABLE 8.1: Main WAVE system-level simulation and channel parameters

natively, so to make the simulations more realistic, I have used `NakagamiPropagationLossModel` to characterize the fading in the channel and transform a deterministic propagation loss model in a probabilistic one. `RandomPropagationLossModel` is finally applied to take into account also the shadowing caused by obstacles between the two vehicles.

The default values of the parameters for MAC and PHY layers have been used, which support acceptable communications in a range of 160 meters from the UE. The transmission power P_{tx} is set to 16 dBm, that is slight low if compared with the current specifications for this technology that allow a maximum transmitted power of 33 dBm for private use and 44.8 dBm for Public Safety. The minimum received energy threshold Γ_{th} is set to -96 dBm in the simulations, this means that if a packet is received by the simulator with an energy lower than this threshold, is not successfully received since in the real world would probably be indistinguishable from the noise.

Each UDP application generates packets of $D = 1000\ bytes$ at a constant interarrival rate ranging from $\tau_p^{min} = 0.008\ ms$ up to $\tau_p^{max} = 800\ ms$. With a simple calculation reported in Eq. (8.1), the application datarate corresponding to each inter-packet interval can be computed, datarate ranges therefore from a minimum of $R_{min} = 0.01\ Mbps$ to a maximum of $R_{max} = 1000\ Mbps$, respectively.

$$R = \frac{D \cdot 8}{\tau_p} \tag{8.1}$$

In contrast with the other technologies, in WAVE we included also a very low-rate communication (0.01 $Mbps$), this since low-rate transmissions identify advanced safety services which have very stringent requirements in terms of communication delay (immediate reaction to emergency is desirable) but are fairly flexible on the throughput given the small amount of information exchanged. High throughput is also consierated for demanding sensors applications in which exchange of data like images, audio or videos are required, the most promising one is the semi or fully-automated driving experience. The vehicles are at a constant distance ranging from $d_{min} = 2\ m$ to $d_{max} = 160\ m$.

8.2 V2I scenarios

V2I communication will be larged used in future 5G cellular networks, LTE and mmWaves will be the technologies most used in this regarding. In this work two main scenarios will be considered and investigated with a view to the future applications. LTE technology relies on an almost complete coverage in terms of offered service, since its architecture has been larged used in fourth generation mobile networks. This great amount of infrastructures can be exploited in V2I services in a vehicular environment. mmWaves instead did not have a network of infrastructures deployed at the moment, but given the great advantages that this technology will bring to the cellular networks, a massive deployment has been planned.

The first scenario considered is an urban scenario in which both LTE and mmWaves will be used by the UE to communicate with the nearby base stations, its characteristics and the parameters set in the simulations are reported in Chapter 8.2.1. The second scenario replicate an highway environment in which a user communicate with the closer gNodeB using only mmWaves, performance will be assessed showing the advantages of this technology in a scenario free of considerable blockages, the description for this part is in Chapter 8.2.2.

8.2.1 Urban scenario

In this thesis a scenario with randomly positioned buildings and base stations have been simulated, to assess the performance of this technology in a situation similar to an urban environment.

The scenario deployed is a square area of side l, in which a fixed number of buildings have been randomly positioned. In this area, base stations have been positioned also randomly at a fixed height. The number of base stations in the scenario ranges from 4 to 31 eNodeBs per km^2. A single UE is positioned in the middle of the scenario and receives packets from the base stations using UDP protocol. UE moves in a single direction with a speed of 20 m/s for the entire duration of the simulation. Initially UE is attacched to the closest base station, then during the simulation it may hand over to base stations with better channel condition once the Signal-to-Interference-plus-Noise Ratio (SINR) decreases below a custom threshold.

An example of the scenario used is reported in Fig. 8.1, moreover the main parameters used in the simulations are reported in Tab. 8.2

In the follows the setting for the two technologies simulated are described separately.

LTE

Although a density of 20 or 30 bs/km^2 is not realistic for LTE, has been taken into account also high base stations density to compare the behavior of this technology with the one of mmWave in the same environment condition. Due to this choice, a

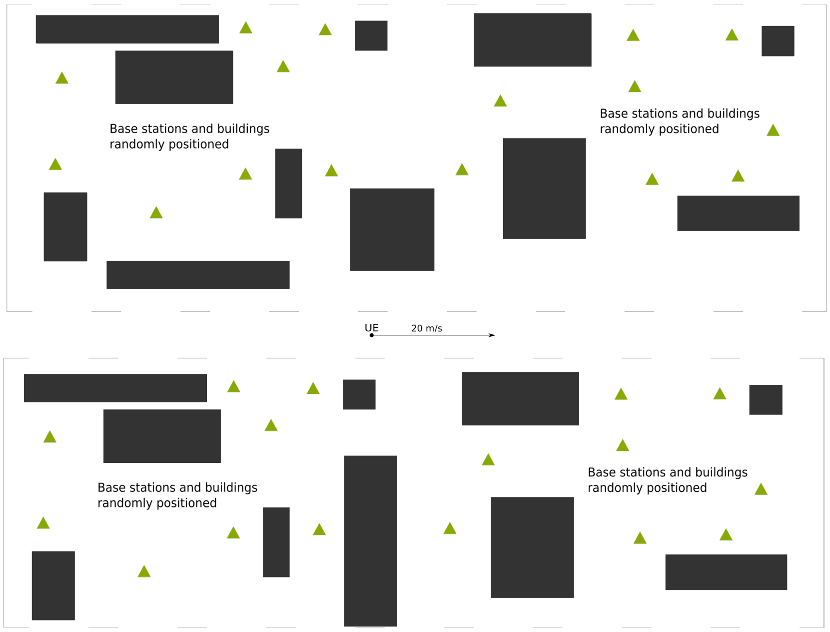

FIGURE 8.1: Example of a random simulation scenario, base stations and buildings are generated randomly in the designated area.

Parameter	Value	Description
T_{sim}	10 s	Simulation time
l	800 m	Scenario square side
ν_b	47 $buildings/km^2$	Buildings density
v	20 m/s	UE speed
λ_{bs}	4.7, 7.8, 15, 31 bs/km^2	Average eNodeB density per km^2
τ_p	11.2, 1.12, 0.112, 0.0112 ms	Inter-packet interval
R	1, 10, 102, 1020 Mbps	Application rate
D	1400 $bytes$	Packet size
P_{tx}	30 dBm	base station TX power

TABLE 8.2: Main system-level simulation and channel parameters for Urban scenario

problem arised: LTE antennas are omni-directional, thus they suffer from an high interference if base stations are too close. To limit this problem, each base station has been configured with a different E-UTRA Absolute Radio Frequency Channel Number (EARFCN), corresponding to a specific carrier frequency in according to [46] at Section 5.7.3. The assigned EARFCN ranges from 100 to 2850, the distance between two consecutive EARFCNs is at least 100, thereby ensuring a frequency difference of 10MHz between the base stations, and only the values that support the chosen transmission bandwidth (20MHz) have been considered thereby reducing Inter Symbol Interference (ISI). This solution does not remove completely the interference between base stations, but, given that eNodeBs are randomly positioned, it is reasonably reduced. In a real application frequency reuse would be used to avoid interference problems in the network, but a similar approach in this work would have increased drammatically the computational complexity of the simulation, thus the described solution has been adopted.

At the physical layer, the channel propagation models used are `HybridBuildingsPropagationLossModel` with the improvements described in section 7.2.1 and `FriisPropagationLossModel`. The first propagation loss model used is designed for fixed scenarios, since there are a set of parameters to set carefully to make the model accurate (i.e. average street width, orientation, etc.), and is not the case of this scenario, thus the obtained results are pessimistic. Given that the model used in case of NLOS is `ItuR1411NlosOverRooftopPropagationLossModel`, the height of the buildings is modeled as an uniform random variable that spans from 7 to 22 m, notice that the maximum height is lower than the height of the antennas, in according with the requirements of the model.

The same scenario has been simulated using `FriisPropagationLossModel`, that gives a deterministic estimation of the attenuation of the signal that does not take into account buildings and the condition of LOS or NLOS of the UE. This second propagation model has been simulated to have an optimistic prediction of the measured metrics. The equation used by Friis propagation loss model is in Eq. (8.2), where P_{RX} is the received power, P_{TX} is the transmitted power, G_t the transmission gain, G_r the reception gain, λ is the wavelength of the communication, d is the distance between UE and eNodeB and L is the system loss that by default is set to 1 dB.

$$P_{RX} = \frac{P_{TX} G_t G_r \lambda^2}{(4\pi d)^2 L} \tag{8.2}$$

Given the presence of multiple eNodeBs, the UE can make handover from one to another based on the strength of the signal received. The metrics considered to decide when to make handover are usually Reference Signal Received Power (RSRP) and Reference Signal Received Quality (RSRQ). RSRP is the power of LTE reference signals spread over the full bandwidth and narrowband, while RSRQ indicates the quality of the received reference signal. In the simulation, the algorithm used to manage the handovers is called `A2A4RsrqHandoverAlgorithm`, this algorithm is based primarly on RSRQ measurements, specifically on event A2 and event A4. Event A2 is verified when serving cell's RSRQ becomes worse than a threshold, the threshold can be set changing the attribute `ServingCellThreshold` that is 30 by default and corresponds to a measured RSRQ between -5 dB and -4.5 dB as specified in section 9.1.7 of [47]. Once event A2 is detected, the UE starts to look for the neighbour cell with the best RSRQ, when UE finds a cell with an RSRQ higher than the serving cell's RSRQ of at least `NeighbourCellOffset`, Event A4 is verified and the handover to this cell is triggered. This last parameter is set to 1 in the simulation.

In this scenario LTE eNodeBs are at an height of 25 meters.

mmWave

Also in the case of mmWaves, the base stations density ranges from 4 to 31 gNodeB/km^2, with the difference that these values of density for mmWave's gNodeB are realistic since the coverage of a base station is considerably smaller than the one of an LTE eNodeB. The size of the simulated scenario is the same but no frequency reuse policies are needed, mmWave's antennas are directional and thus inter-cell interference is limited. For this reason all the gNodeBs are configured with the same EARFCN. gNodeB's height is 10 meters, the carrier frequency used by mmWave module is of 28 GHz and uses a bandwidth of 1 GHz.

8.2.2 Highway scenario

The second scenario implemented to assess the performance of mmWaves is an highway scenario with one single user.

The user moves along the road in a single direction at a velocity of 36 m/s, that corresponds to 130 km/h and gNodeBs are positioned along the road at an height of 25 meters. No buildings have been deployed in the scenario, since is reasonable to assume that no buildings influence the communication in an highway scenario and since the aim is to implement a scenario in which the user is in an optimal situation to compare the results with the worst random scenario. The distance between two consecutive gNodeB, called ISD, is fixed and ranges from 200 m to 1000 m.

A scheme of the highway scenario developed is reported in Fig. 8.2, while the parameters used are reported in Tab. 8.3.

Parameter	Value	Description
T_{sim}	10 s	Simulation time
l	1500 m	Scenario length
v	36 m/s	UE speed
ISD	200, 500, 800, 1000 m	Distance between two consecutive gNodeB
τ_p	11.2, 1.12, 0.112, 0.0112 ms	Inter-packet interval
R	1, 10, 102, 1020 Mbps	Application rate
D	1400 *bytes*	Packet size
P_{tx}	30 dBm	gNodeB TX power
NF_{enb}	5 dB	gNodeB noise figure

TABLE 8.3: Main mmWaves system-level simulation and channel parameters for highway scenario

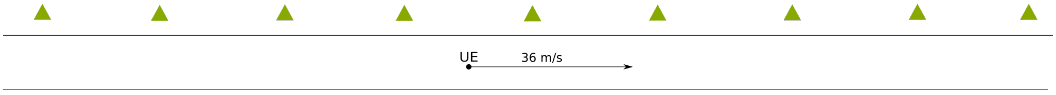

FIGURE 8.2: Example of an highway simulation scenario

Chapter 9

Results

In the simulations, the following end-to-end metrics are measured, averaged over multiple independent runs and analyzed:

Packet Reception Ratio (PRR) : the number of correctly received packets divided by the total number of transmitted packets;

Experienced throughput : the throughput perceived by the user during the simulation.

PDCP latency : the average latency of the only successfully received packets.

Handover latency : the handover latency averaged over all the handovers triggered in each simulation.

Number of handovers : the number of handovers triggered in each simulation.

PRR has been measured at IP level for all the technologies, while experienced throughput and latency has been measured at IP level for WAVE and at PDCP level for LTE and mmWaves. PRR and latency have been computed in the same way in both the scenarios: PRR is measured counting the packets transmitted and dividing the resulting number by the number of packets correctly received, latency have been calculated measuring the time a packet spends from the moment it is enqueued in the transmission buffer at IP or PDCP layer until the fully reception at the correspondent layer in the receiver, averaging it over the simulation time (10 seconds) and finally averaging the results over all the simulations.

Given that the channel conditions when using WAVE remain the same for all the duration of the simulation, the experienced throughput S has been simply calculated as the number of bytes correctly decoded over the duration of the simulation in seconds. At the contrary, in the second scenario, given its highly randomness, the channel condition varies during the simulation, passing from a good condition when base station and UE are in LOS to a bad condition when a building is between them (NLOS condition). For this reason, non-overlapping temporal windows w of fixed duration t_w have been applied to the traces measured, and S has been calculated with the equation in Eq. (9.1).

$$S = E\left[\frac{B_{RX}^{w}}{t_w}\right] \tag{9.1}$$

In that equation, the number of bytes received in each window B^{w}_{RX} has been divided for the duration of the window in seconds t_w and than the result has been averaged over all the windows in which the simulation has been divided.

Different values for t_w have been tried (0.1, 0.2 and 0.5 seconds) and the difference in the results were negligible, so $t_w = 0.5\ seconds$ has been chosen as final value, this choice ensures an high enough precision in the throughput calculation and an acceptable computational complexity. Notice that lower values of t_w will results in an higher complexity in the metric calculation and thus a longer computational time.

In the V2I part, a single user has been simulated, hence the measured throughput is the maximum offered throughput of the cell, or the cell capacity. Considering more users the throughput of the single user would be affected by the presence of the other users served by the cell, thus will be lower.

9.1 IEEE 802.11p/WAVE

In Fig. 9.1 is plotted the PRR vs the inter-vehicle distance d for the scenario described in Section 8.1. High values of PRR are required for all the applications, in particular for safety application.

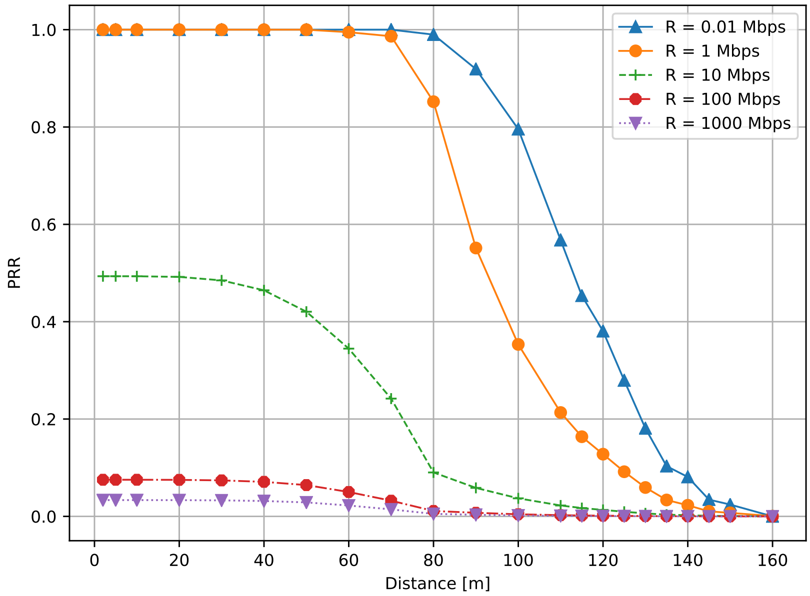

FIGURE 9.1: PRR vs. inter-vehicle distance d for different values of the application rate R.

Looking at the plot t can be noticed that, as expected, higher PRR are registered when considering short-range communications, since as the vehicles get closer, the quality of the channel improves. Low rate communications at 0.01 Mbps and 1 Mbps have a PRR equal or very close to 1 when vehicles are at a distance less than

70 meters, as the distance between the vehicles increases, the channel starts to deteriorate leading to a lower PRR. For the higher rate communications, the effect of a highly saturated channel makes the number of received packets decreasing dramatically, thereby resulting in unacceptable values of PRR even for short distances. According with 3GPP specifications [48], extremely high of PRR (e.g. $> 99\%$ for advanced autonomous driving applications) must be guaranteed since the possible consequences that a failure of these kind of application can be catastrophic.

From this analysis can be deducted how WAVE communication without using retransmissions, is not suitable for long-range applications, but can satisfy the requirements for short-range communications up to 70 m distance. Notice that this distance is enough for a good part of the safety real-time application in a V2V scenario.

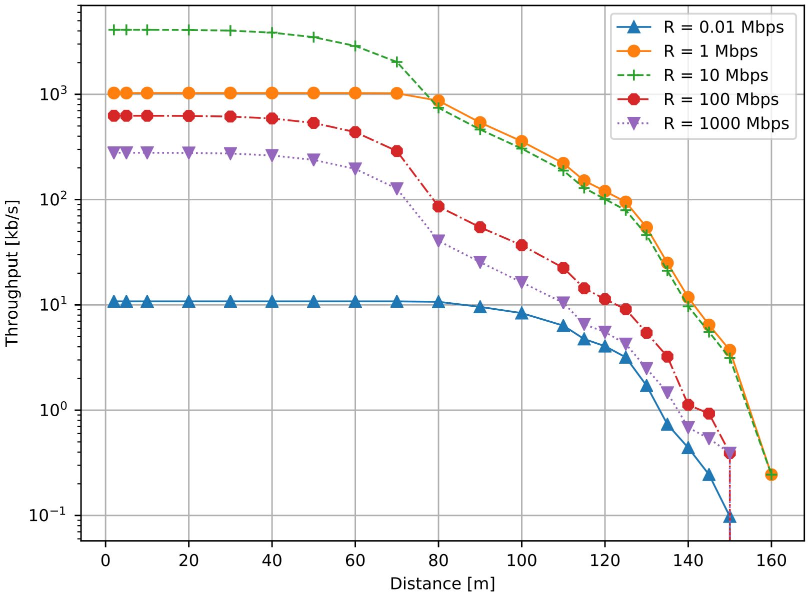

FIGURE 9.2: Average throughput vs. inter-vehicle distance d for different values of the application rate R.

In Fig. 9.2 is reported the average throughput that the UEs experience at different distances. This figure gives and idea of which application datarates are well supported by WAVE and which instead are too high for this technology. The throughput monotonically decreases for increasing values of d since the power received at the receiver is every time lower, making the channel weaker, in accordance with the results obtained for the PRR. As can be seen looking at the plot, high datarates are not supported by WAVE connections, which suffer of a limited capacity due to the low-bandwidth physical channel, in particular, in case of channel saturation (this is the case of 10 Mbps, 100 Mbps and 1000 Mbps), the higher the application datarate, the higher the packet loss, the lower the achievable throughput.

This figure confirms how WAVE, although it does not provide a good coverage range, it is suitable for short-range and low-rate vehicular services such as public safety, with the advantage that a network infrastructure is not required.

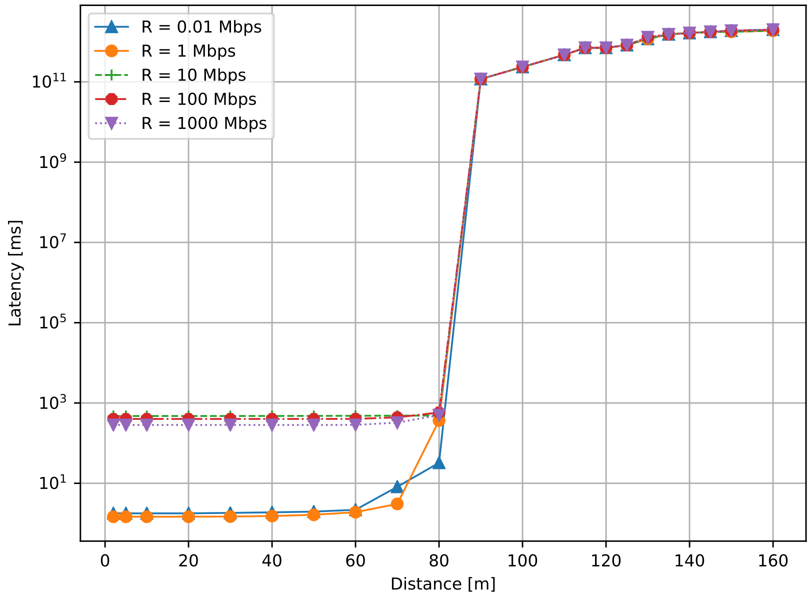

FIGURE 9.3: Average latency vs. inter-vehicle distance d for different values of the application rate R.

The last metric investigated for this technology is the end-to-end latency in function of the inter-vehicle distance and the application datarate. The latency reported in Fig. 9.3 is measured for each packet, from the time it is generated at the network layer of the sender to when it is successfully received at the network layer of the receiver, therefore this latency does not take into account the lost or unsuccesfully-received packets.

This metric is of special interest since usually is calculated at MAC or physical layer, measuring it at network layer, the latency added by the MAC layer is taken into account, that means that also events like buffer overflow or queue delay are considered.

For the rate R=0.01 Mbps and R=1 Mbps, the latency is extremely low for distance $d < 70m$ (i.e. below 5 ms), a distance suitable for some V2V applications in a real scenario, while for higher application rates the end-to-end latency is three orders of magnitude higher, enhancing how WAVE systems cannot ensure time critical message dissemination in case of filled MAC queues.

The figure illustrates that, when $d > 70m$, the latency increases uncontrollably for all the application rate configurations. The reason is that, after a certain distance, the received power is below the minimum received energy threshold Γ_{th}, preventing the transmission of new data packets and thereby increasing the buffer occupancy at the transmitter side (it will therefore requires a stronger effort, i.e., a longer time, for forwarding the queued packets to the intended receiver).

9.2 LTE and mmWaves

In this second part of the results the outcoming of the V2I simulations are presented. LTE and mmWaves will be firstly considered separated and finally a comparison between the two technologies will be made.

Taking into account only LTE, a comparison between the two propagation loss models used can be made. In Fig. 9.4 the PRR measured using `HybridBuildingsPropagationLossModel` and `FriisPropagationLossModel` has been plotted at three different datarates.

Notice that the measures taken using the hybrid propagation loss model are pessimistics, since they do not consider the randomness of the scenario and the channel is in a bad condition every time UE and eNodeB are in NLOS. In reality, LTE uses lower frequencies than mmWaves, hence has penetration characteristics that allow, in some cases, to communicate at an acceptable datarate even if an obstacle is in the middle of transmitter and receiver. This propagation loss model considers this eventuality but the effect are visible in a fixed scenario in which all the parameters are known.

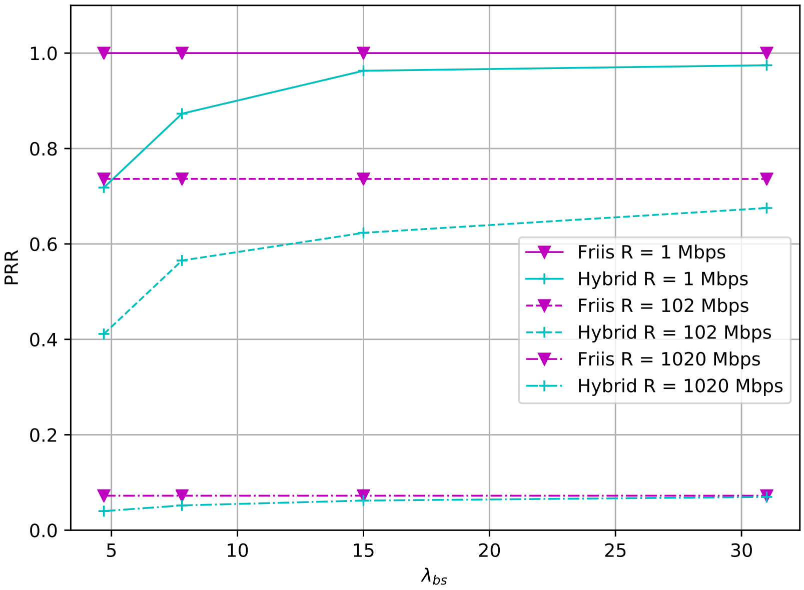

FIGURE 9.4: Average PRR vs. base stations density λ_{bs} for different values of the application rate R using `HybridBuildingsPropagationLossModel` and `FriisPropagationLossModel`.

Friis propagation model instead does not consider the presence of obstacles or buildings, thus the outcoming measures are optimistics. The figure shows how the hybrid model is strongly affected by the presence of obstacle in the simulated area and reach the results obtained with Friis only with a great (and irrealistic) base station density. Nevertheless, the PRR is still under 80% for high datarates even using Friis propagation model.

The results for the throughput in Fig. 9.5 are in accordance with those obtained for the PRR. The throughput measured using Friis shows the maximum throughput offered by the eNodeB at a given datarate and is clear how in this condition the throughput saturates at less than 75 Mbps. The measures taken with the hybrid model depends on the eNodeB density and reach the values obtained by Friis for high densities.

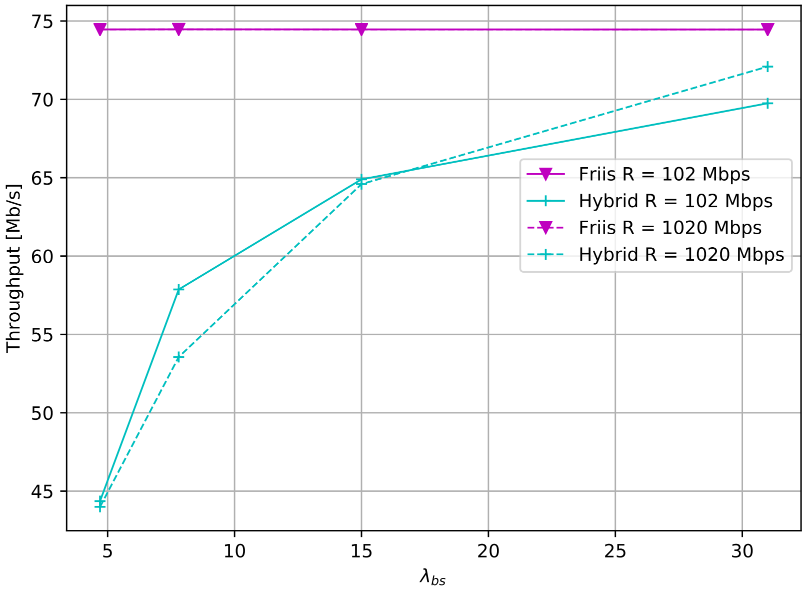

FIGURE 9.5: Experience throughput vs. base stations density λ_{bs} for different values of the application rate R using `HybridBuildingsPropagationLossModel` and `FriisPropagationLossModel`.

Considering mmWaves, Fig. 9.6 and Fig. 9.7 show its behavior varying the datarate and the gNodeB density in the random scenario. As expected, mmWaves work better in presence of an higher gNodeB density, since the higher the number of infrastructures in the simulated area, the higher the probability to have transmitter and receiver in LOS, due to the strong presence of buildings in the scenario. In accordance with the literature, mmWaves can support all the simulated throughput, even if an high number of base stations is required. Indeed looking at the higher datarate, when the gNodeB density is 4.7 $gNodeB/km^2$, the measured throughput is less than 600 Mbps, while the required throughput of 1000 Mbps can be almost reached when 31 $gNodeB/km^2$ are deployed. These results are confirmed by the measures of the PRR: this metric in general decreases when the datarate increases, but it remains over 80% for the higher base stations density while is unacceptable for the lower density.

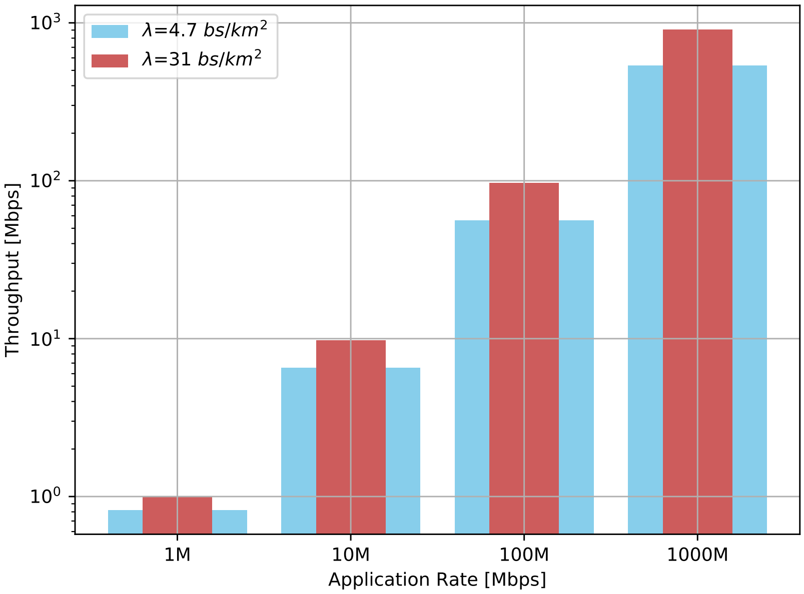

FIGURE 9.6: Experience throughput vs. datarate R for different values of gNodeB density λ_{bs} using mmWaves.

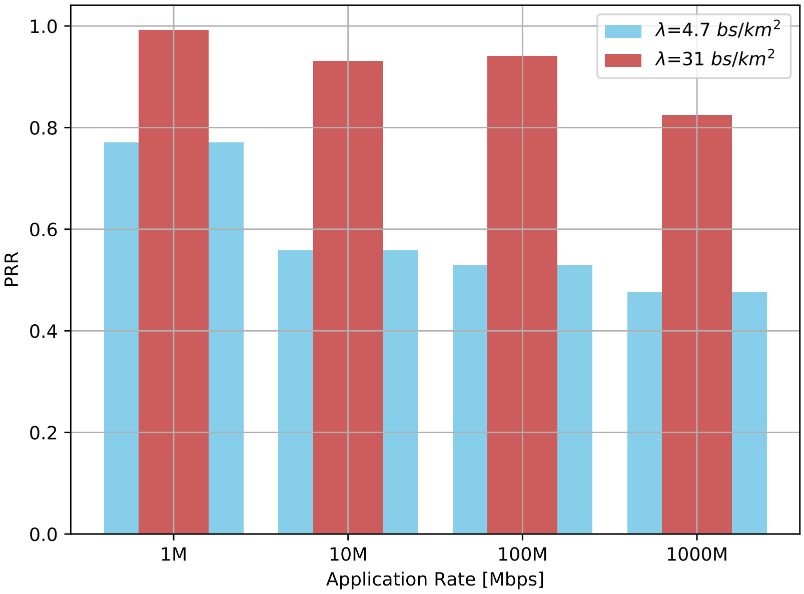

FIGURE 9.7: PRR vs. datarate R for different values of gNodeB density λ_{bs} using mmWaves.

The number of handovers that the UE triggers in a simulation is an interesting indicator of the behavior of the network at different base station densities. The Cumulative Density Function (CDF) of the number of handovers for the gNodeB densities simulated using mmWaves is shown in Fig. 9.8. The figure underlines how

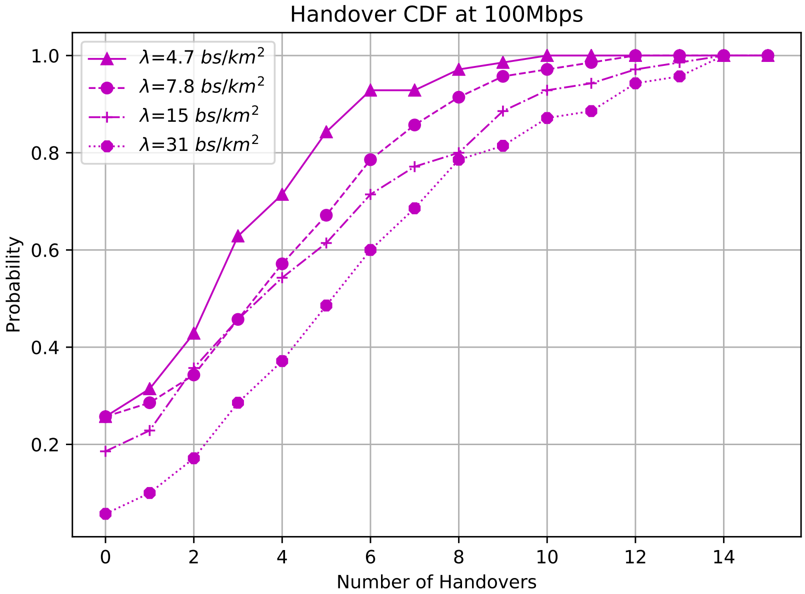

FIGURE 9.8: Cumulative density function of the number of handovers at 100 Mbps for different values of gNodeB density λ_{bs} using mmWaves and random scenario.

the average number of handovers triggered in a simulation increases as increase the number of gNodeB deployed in the scenario. Indeed, looking at a specific number of handovers, 6 handovers for example, the probability to have 6 handovers or less goes from a minimum of 60% when 31 gNodeB/km^2 are deployed to more than 90% when 4.7 $gNodeB/km^2$ are deployed.

Assuming that the UE is attached to a cell and the condition of the channel is LOS, when the condition switches from LOS to NLOS, the UE has to search a nearby cell that offers an RSRQ higher enough than the one offered by the current serving cell. In case of few base stations per km^2 the UE has a low probability to find a cell with a good channel condition, thus it remains attached to the current cell even if in a bad condition. In case, instead of high base station density, the probability to find a cell with a good channel condition is higher, so UE can trigger the handover to the new cell.

This reasoning justifies the trend showed in Fig. 9.8, in general the more base stations nearby the UE the more handovers the UE triggers on average. The only exception to this behavior can be observed when the base stations nearby the UE, have all a similar channel condition. In this case the UE can not recognize which is the best gNodeB causing a ping-pong effect between the cells, increasing uncontrollably the number of handovers.

In the following, the results obtained from the random scenario are compared with those obtained in an highway environment.

Looking at Fig. 9.9 can be seen how mmWaves can easily reach the required throughput in an highway environment in which the infrastructures are in LOS all

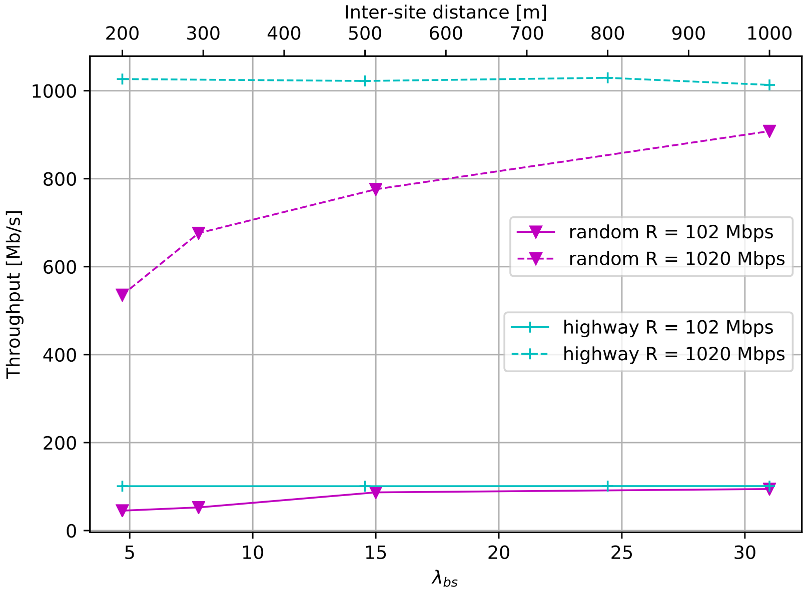

FIGURE 9.9: Experienced throughput measured in random and highway scenario varying ISD and density of gNodeB respectively for different values of the application rate R using mmWaves.

the time. It is clear the difference with the random scenario in which mmWaves suffer from the presence of blockages.

Notice that in the figure the upper axis is referred to highway scenario and indicates the ISD between two consecutive base stations. ISD ranges from 200 meters to 1000 meters, where the higher the ISD the higer the probability to be in NLOS for a UE due to the distance from the gNodeB.

For a better comparison, the upper axis should be inverted to have on the left side of the figure the values of ISD correspondent to a bad channel condition, in according with the lower axis referred to the random scenario. Nevertheless the upper axis is in ascending order for the sake of clarity.

PRR in Fig. 9.10 shows how mmWaves ensure an almost perfect reception rate in highway environment while they suffer of bad channel condition in random scenario.

Moreover looking at Fig. 9.11 can be noticed the strongly dependance of the performance of mmWaves from the presence of buildings in the middle between transmitter and receiver. Indeed, while in highway scenario the latency is under 1 ms for all the values of λ_{bs}, in a random environment these values are reached only when more than 31 gNodeB/km^2 are deployed.

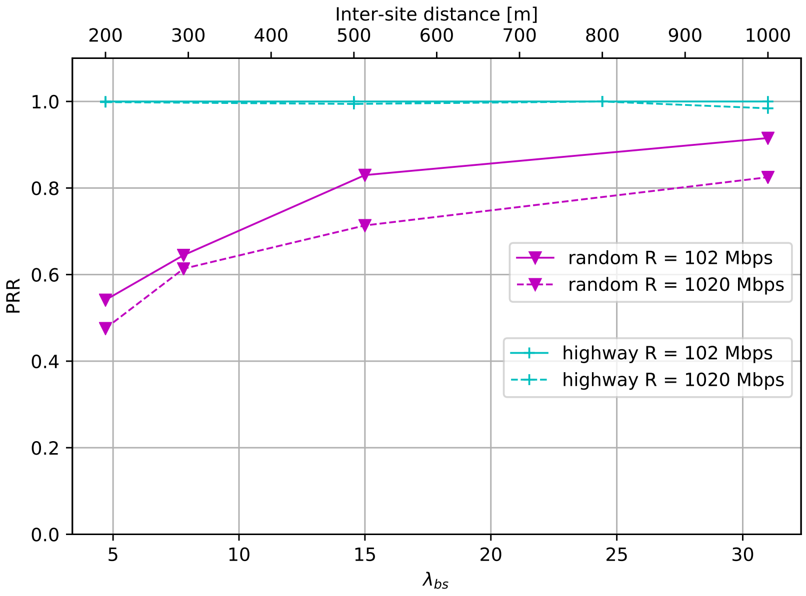

FIGURE 9.10: PRR measured in random and highway scenario varying ISD and density of gNodeB respectively for different values of the application rate R using mmWaves.

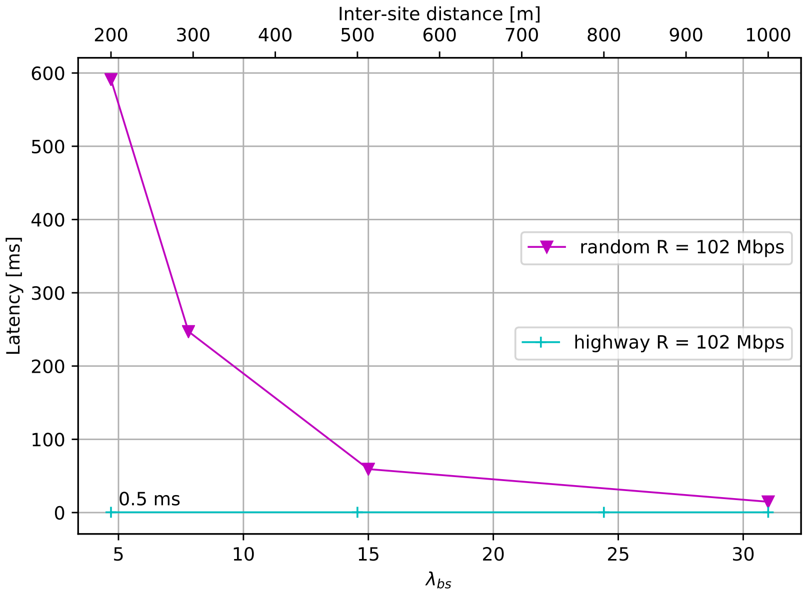

FIGURE 9.11: latency measured in random and highway scenario varying ISD and density of gNodeB respectively for different values of the application rate R using mmWaves.

To compare the two technologies simulated, in Fig. 9.12 is reported the throughput of mmWave and LTE in two of the four different datarates simulated in the

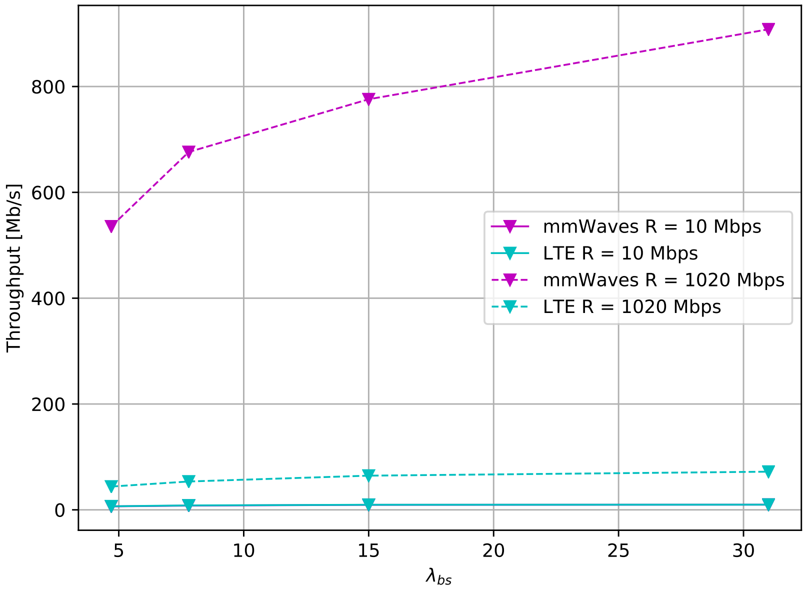

FIGURE 9.12: Experienced throughput vs. base station density λ_{bs} for different values of the application rate R using `HybridBuildingsPropagationLossModel` in LTE.

random scenario vs gNodeB or eNodeB density. For low values of base stations density, the channel is most of the time in NLOS condition, so the communication between the devices is harder.

Looking at the lowest datarate, that is 10 Mbps, the throughput reaches the desired value using both the technologies, this because even if for lower base station density, the channel is in NLOS most of the time, on average the devices are in LOS for an interval of time large enough to send and receive all the data. During the NLOS interval the packets to send are queued in the transmission buffer and they wait a good channel condition to be sent, once the condition becomes LOS the packets are sent according with the maximum channel capacity. The effect of these phenomen will be clear looking at the other plots.

At 1000 Mbps, the LTE maximum achievable throughput is around 80 Mbps, showing how LTE technology can not support this huge datarate, and mmWaves are strongly affected by the number of gNodeB in the scenario. Indeed the experienced throughput increases with the gNodeB density starting from a value around 500 Mbps and reaching more than 900 Mbps when 31 gNodeB/km^2 are deployed. For both the technologies, the throughput is slightly increasing with the base stations density, this due to the presence of an high number of buildings in the scenario that reduces considerably the probability of LOS condition when using few base stations.

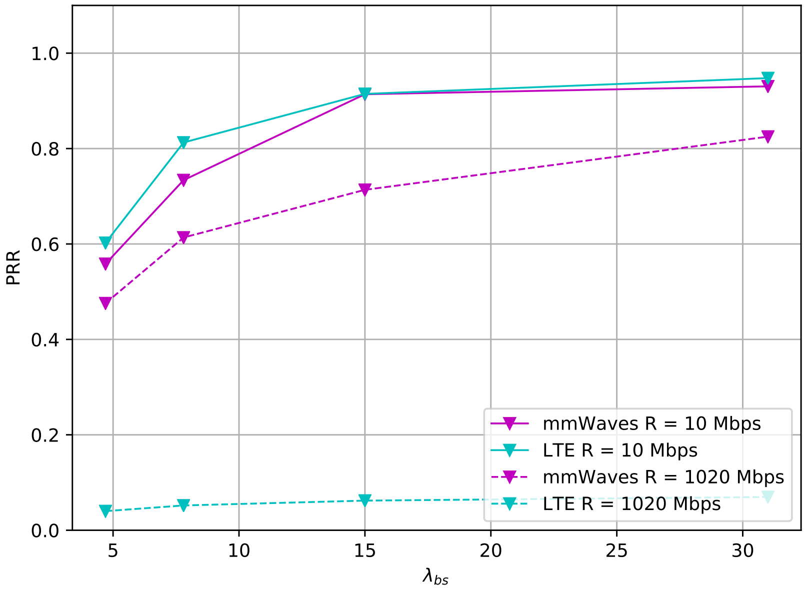

FIGURE 9.13: PRR vs. base stations density λ_{bs} for different values of the application rate R.

In Fig. 9.13 the PRR registered again for 10 Mpbs and 1000 Mbps application rates. According to the throughput's results, LTE shows an extremely low PRR for 1000 Mbps, in particular the UE receives less than the 10% of the packets transmitted. This justifies the bad behavior of LTE at this datarate showed in Fig. 9.12.

For what regards the lower application rate, LTE can manage the communication with an accuracy higher than 90%, a result that is slightly better than the one reached by mmWaves, when more than 15 bs/km^2 are deployed in the scenario. The reason is that LTE propagation is more robust than when operating at higher frequencies.

As stated before, these results are still pessimistics since `HybridBuildingsPropagationLossModel` is used in the simulation, with a scenario that is not completely suitable for this propagation loss model. Using `FriisPropagationLossModel` would increase even more the PRR reaching results extremely close to 1. This behavior allows to use LTE in services that demands an high reliability such as self-driving cars or alert messaging at low datarates when mmWaves are not available.

Looking at mmWaves results, it can be seen how the technology supports better than LTE the highest application rates, while it ensures a reliability slight lower than LTE for low datarates, since mmWaves suffer more than LTE the effect of blockages (in this case buildings) between transmitter and receiver. The effect of the buildings in the scenario is clear considering the trend of PRR when varying the base station density for both the technologies.

MmWaves' PRR for high datarates when 31 bs/km^2 are deployed stands between 80% and 90%, but the correspondent throughput is acceptable. This shows how mmWaves can be used in contexts in which an high throughput is required but there are no strict requirements in terms of PRR. These services will be enabled mainly by 5G standards and are applications like audio and video streaming in which a PRR of 90% is still acceptable.

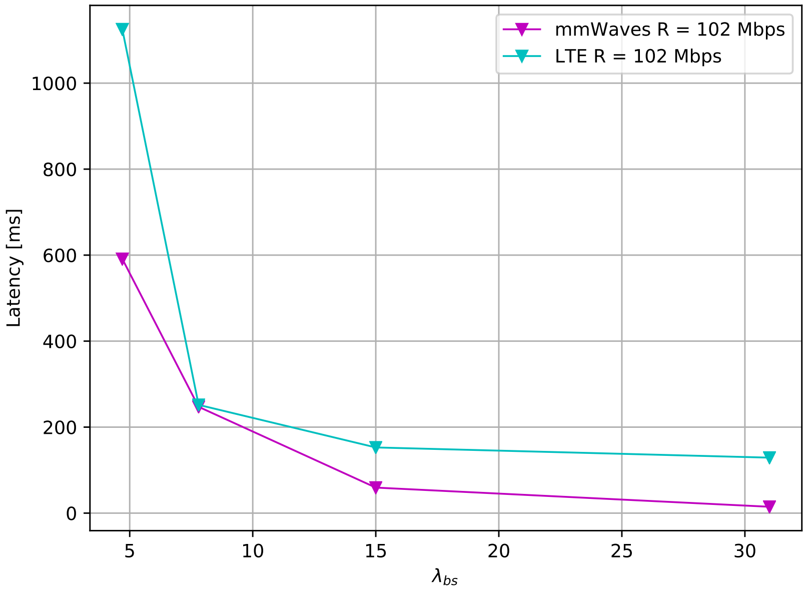

FIGURE 9.14: Average latency vs. base stations density λ_{bs} for different values of the application rate R.

In Fig. 9.14 the latency of the packets correctly received is plotted. Notice that the latency is not defined for the packets that are not received and is calculated as the time from the moment in which the packet is enqueued in the transmission buffer at the transmitter until the moment it is received by the UE. Looking at the plot is clear how, in condition of few base stations deployed in the scenario, the network is not able to ensure a low latency, but it gives instead uncontrollably high measures for both LTE and mmWaves. Increasing the number of base stations in the simulated area, the latency decreases, reaching very low values for high λ_{bs} (i.e. 31 bs/km^2). These results reflect the situation showed in Fig. 9.13 where the PRR is lower for lower base stations densities. In fact, when the Base Station (BS) can not enstablish a good connection with the UE, the packets are enqueued at the transmitter waiting a good channel condition. Once the channel returns in a condition that allows the communication, the packets are sent to the receiver with a consequent high latency.

LTE has a latency higher than mmWaves since a datarate of 100 Mbps is considered and has been shown that LTE can reach up to 75 Mbps in the simulated scenario, increasing the latency of the communication.

9.3 Discussion of the results

Summing up the results obtained in this work, the outcomings reflect the expected performance of the simulated technologies.

In the first scenario, the results show how WAVE offers low-rate and short-range connectivity, but it embeds desirable features for future 5G vehicular networks in terms of reliable communication and low latency. Given these features, this technology can be leveraged in the next generation cellular networks integrating it with other promising novel technologies such as mmWaves to design a network suitable for every type of service. V2V communication in a similar scenario can be indeed offered also by mmWaves, at the cost of using more expansive hardware due to mmWaves' frequency bands and with an higher computational cost since mmWaves uses directional antennas, thus an high-precision beam tracker is needed to connect directly two vehicles. Moreover, since WAVE works at lower frequencies, is less affected from blockages, making the communication even more reliable in a dense urban scenario.

Given these results, WAVE technology can be used in most of the safety applications of vehicular networks described in Chapter 3, since, besides emergency vehicle signal preemption and the V2I part of cruise control applications, they require a coverage of 500 meters at large, a range that can be reached by WAVE increasing the transmission power of the antennas or the channel bandwidth, and a low rate communication (in the order of tens of kbps).

In the second scenario, mmWaves show a great improvements to nowadays cellular networks performance in terms of throughput and latency, even if they are affected by high blockage sensitivity. This technology, in general, can be used in throughput-demanding services that does not requires a very high reliability (i.e. audio and video streaming) and can be supported by LTE in case the conditions of the channel do not allow a stable link between transmitter and receiver. LTE ensures an high reliability when datarates under 100 Mbps are used, eNodeB offers a larger coverage with respect to mmWaves' gNodeB coverage and can rely on a capillary network of infrastructures deployed in the world. For both technologies, an high density of base stations is needed in a dense urban scenario, even if in general LTE works at a lower frequency so is more robust to NLOS communications.

Moreover, given the omnidirectional antennas used for LTE, a frequency reuse policy have to be designed to avoid inter-cell interference when considering an urban scenario, mmWaves did not suffer this problem since the antenna beam is directional.

Looking at the applications that will be offered in the next generation of cellular network, in particular the one described in Chapter 3, LTE is the most suitable technology for the applications in which a V2I communication is needed and an high PRR is expected such as emergency vehicle signal preemption and the V2I part of cruise control applications, while mmWaves are the only technology able to support user applications such as video and audio streaming or in-vehicle massive online games where some loss is accepted and an extremely high datarate is required.

In general, where WAVE and mmWaves can not be used, LTE can be used as support technology, at the cost of an higher complexity and a V2I communication if the support is required by WAVE, or an higher latency and a lower maximum achievable throughput if instead the requiring technology is mmWaves.

Chapter 10

Conclusion and future work

In this work, IEEE 802.11p/WAVE, LTE and mmWaves have been investigated with a view to the future vehicular networks applications. Three different scenarios have been taken into account:

- a V2V scenario in which WAVE is used to communicate between two vehicles in a highway-like environment;
- a V2I scenario in which a vehicle communicates with the closer infrastructures in an urban-like environment, using LTE or mmWaves;
- a V2I highway scenario where a user communicates with the closer gNodeB using only mmWaves.

These scenarios showed how the three technologies used have different limits and can offer different services, the future researches have the task to integrate these technologies in order to design a complex network able to ensure the best QoS to every user.

This work can be extended simulating more advanced protocols like TCP and the same scenarios but with more than one user, in order to consider the throughput experienced by UE in a real network and not only the cell capacity.

A typical scenario in which these technologies can be investigated is a realistic ad-hoc urban scenario using mobility traces generated with a third-party software like Simulation or Urban MObility (SUMO). In this case the real performance of these protocols can be assessed and a more accurated parametrization can be done for the scenario-dependant NS3 models (e.g. `HybridBuildingPropagationLossModel` for LTE).

Moreover, mmWave module for NS3 can be extended to support end-to-end simulation of Integrated Access and Backhaul (IAB) at mmWaves [49][50]. The research field this work is part of is still largely unexplored and deserves further investigation to design valuable systems to be physically realized in the next generation of cellular networks.

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Chapter 11

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