POLITECNICO DI TORINO

Master Degree course in Communications and Computer Networks Engineering

Master Degree Thesis

Vehicular communications: from DSRC to Cellular V2X

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Abstract

Vehicular communication technologies have been increasingly spread in the last decades. They have been studied and deployed, altought they will not find a commercial solution before 2020. The concept of Intelligent Transport System and vehicular networks, alongside the one of smart city, is one of the biggest achievement of technology in the field of vehicular safety, environmental health and commercial convenience. This evolution is brought on by a big technology, that recently made another step.
Cellular V2X is the possibility of a vehicular network to relay (partially or totally) on a cellular network, already deployed, therefore stable, and bring to users several advantages and novelties. Some of these novelties can be found in the coverage itself of the network that can be potentially bigger than the one of DSRC network, the possibility of getting contents and infotainment for the vehicle (connecting to the cellular network), the D2D connectivity among devices that doesn't rely on the network architecture like in the regular infrastructure communication, and so much more.
This thesis work was developed in the V2X Research and Development division team of Magneti Marelli (Torino). It presents in a detailed way all the previously said vehicular communication features, considering the passage from the DSRC, a vehicular technology mainly built on a similar Wi-Fi standard, to the brand new Cellular V2X. The main goal of the thesis was to begin an important study on this topic for the company itself, that will soon take advantage of this technology for its demos.
The last part of the thesis is developed around the simulation of a 4G LTE network with an object based simulator (SimuLTE), studying different parameters for a future deployment of a single network cell that will be used by Magneti Marelli for the first Cellular V2X demonstrations.

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List of Acronyms

Abbreviation	**Acronym**
3GPP	3rd Generation Partnership Project
BS	Base Station
BSS	Basic Service Set
CAM	Cooperative Awareness Messages
CCH	Control Channel
CDMA	Code Division Multiple Access
CSMA/CA	Carrier Sense Multiple Access Collision Avoidance
D2D	Device-to-Device
DENM	Decentralized Environment notification Message
DL	Downlink
DLL	Data link Layer
DSRC	Dedicated Short Range Communications
EDGE	Enhanced Data Rates in GSM
eMBB	Enhanced Mobile Broadband
EPC	Evolved Packet Core
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile Communications
IoT	Internet of Things
ITS	Intelligent Transportation Systems
LTE	Long-Term Evolution
MNO	Mobile Network Operator
MIMO	Multiple Input Multiple Output
MME	Mobile Management Entity
OFMD	Orthogonal Frequency Division Multiplexing
PLMN	Public Land Mobile Network
ProSe	Proximity Service
QoS	Quality of Service

Abbreviation	**Acronym**
RAN	Radio Access Network
SL	Sidelink
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
UE	User Equipment
UICC	Universal Integrated Circuit Card
UL	Uplink
UMTS	Universal Mobile Telecommunications System
USIM	Universal Subscriber Identity Module
UTRA	Universal Terrestrial Radio Access
V2I	Vehicle to Infrastructure
V2N	Vehicle to Network
V2P	Vehicle to Pedestrian
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything
WAVE	Wireless Access in Vehicular Environment

Introduction

This thesis work is meant to explore the world of vehicular communications and in particular the Cellular V2X (vehicle to everything). So much has been studied up to now and with this thesis I have reported in a detailed way what we actually know about this new communication technology.
The thesis was entirely developed in the V2X Research and Development division team of Magneti Marelli (Torino), during an Internship of 6 months. The main goal of the Internship was to begin an important study on this topic for the company, that will soon take advantage of this technology for its demos. After having reviewed articles, 3GPP specifications and many other official documents, my research work was grouping all this information together and expose them as a guide for the company I worked for.
In the following chapters I will introduce the vehicular communications, highlighting the reasons why they are so important for the future of the road safety and how they will be one of the most hot topics in the next decade.
After that, my thesis will be about the introduction of Cellular V2X technology, from the architectural point of view, how to deploy it and build it and, in particular, which other technologies will be based on (i.e. D2D, ProSe, 4G LTE cellular network, 5G). All of these topics will be discussed in separated chapters to highlight their main features and advantages, with respect to previous technologies.
The Cellular V2X will take place of the Dedicated short-range communication technology (DSRC). In chapter 4 I will discuss the main changes, how it will take its place and which advantages the C-V2X will actually bring to the vehicular environment and to the Intelligent Transport System (ITS).
The last chapter represents the practical work I have done for Magneti Marelli, besides the research. Being the C-V2X a technology mainly based on cellular network (4G LTE and its evolved versions), I performed some tests on an LTE network with an object based simulator, SimuLTE (based on OMNeT++). The chapter reports a series of results the company was interested into for a future deployment of a single network cell that will be used by Magneti Marelli for the first Cellular V2X demonstrations.

Chapter 1

Vehicular communications

1.1 Introduction to vehicular networks

When talking about Mobile Ad Hoc Networks (MANETs) we mean a series of computing and communicating devices (nodes) connecting with each others by wireless links, forming an arbitrary graph. In the last decades the main interest was on the idea of smart cities, focusing on bringing this type of networks to high urbanized areas.
Vehicular networks are a particular case of MANETs, named VANETs (Vehicular Ad Hoc Network). This type of networks presents some differences with respect to the MANETs [4]:

- mobility: higher speed of nodes needs to be taken into account. The topology of the network changes really fast and it is somehow predictable
- the network topology changes fast therefore fragmentation can occur
- the resources are not limited by energy, memory or computation capabilities
- the effective network diameter of a VANET is small
- localization is provided by systems such as GNSS
- it poses a number of unique security challenges.

Economic growth has been strongly associated with urbanization, overwhelming cities with vehicles since transportation, generally, and infrastructure, in particular, are large segments of the economy. By 2030, it is expected that around 60% of the global population will live in urban areas charting the growing contribution of cities both to the world economy and to carbon emissions. According to the International Energy Agency (IEA), cities are also the key drivers of global energy demand and greenhouse gas emissions, accounting for around 70% of both. This data reflect negative consequences, such as:

- Environmental/natural resource degradation (smog, polluted waterways, increased energy consumption, and CO_2 emissions).
- Socioeconomic (enormous losses of time in congestions, accidents, and degradation in life quality/deaths).
- Technical consequences (safety compromises, accidents).

These facts reveal inefficiencies related to urban transport, as identified by research communities of both public agencies and private industry and they are the main reasons that pushed forward to the Intelligent Transport System (ITS) [4].

1.2 Intelligent Transport System (ITS)

As mentioned above, the presence of innovative, cost-effective cooperative mobility and automated driving solutions has improved energy efficiency, individual safety and the effectiveness of public and freight transport. These initiatives together constitute the heart of Intelligent Transport Systems (ITS) [5].
By enabling vehicles to communicate with each other via Vehicle to Vehicle (V2V) communication as well as with roadside base stations via Vehicle-to-Infrastructure (V2I) communication, ITS can contribute to safer and more efficient roads.

The general ITS vision is shown on the following figure [6].

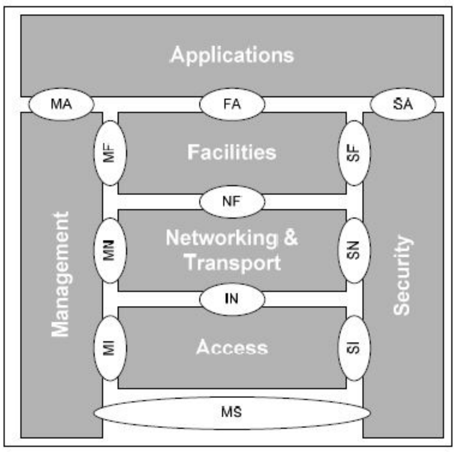

Figure 1.1: General ITS vision [6].

From a complementary perspective, advanced safety systems for both vehicles and pedestrians are established as a most important service requirement in the transportation field, for numerous countries.
Despite the still partial establishment of traffic management/safety systems, there is still a long way to go for maximizing transportation efficiency and safety. Some of the causes that may be identified are [4]:

- The traffic conditions that should be handled by the transportation infrastructure may frequently change. Traffic changes can be sudden or recurring. Sometimes they may be due to the occurrence of emergencies. Traffic is to be assessed in real-time, and communicated to the drivers, in such a way it can be taken into account. Traffic patterns resulting from a learning process should add more accuracy to the messages communicated to the drivers.

- Sudden changes into the traffic are often the direct cause of accidents, again the transport infrastructure is expected to communicate these changes in a timely fashion in order to decrease the risk of accident and therefore casualties which would result in an even worse traffic condition.

- Legacy traffic assessment and management systems are mainly centralized. This means that, in principle, they are unsuitable either for adapting, in short time scales, to context changes, or for supporting cooperation of the relevant services. Currently, the collection of context information, the solution of optimisation problems and the application of reconfiguration decisions is an off-line process, applied in medium (or long) time scales.

- Intelligence embedded in vehicles is still at a low level in terms of their communication capability with external entities (i.e., other vehicles and/or objects of the transportation infrastructure) and there is no assessment in the vehicle of the overall security status that would rely on a correlation of the global traffic condition and the vehicle and driver behaviours.

- There is no direct communication between the traffic infrastructure and the cars about which directions are to avoid or to follow. The drivers are not aware of the traffic conditions in real time and have no mean therefore to behave or adapt accordingly.

1.3 General overview of VANETs

We have already briefly introduced VANETs as particular MANETs networks. In fact as we can read from [5], they operate with little or no permanent infrastructure and they are characterized by high mobility, fixed road networks, predictable speed

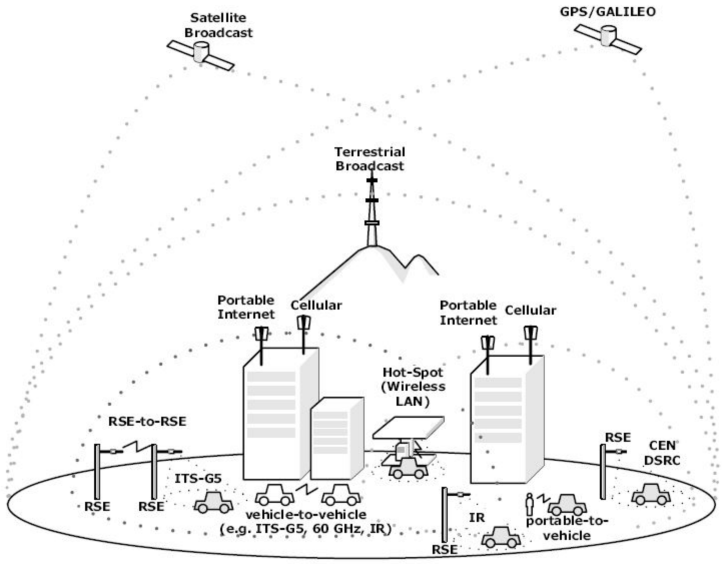

Figure 1.2: Intelligent Transport System city environment view [6].

and traffic patterns in congested conditions, and very few power constraints or storage limitations.
Unlike other communication systems, in which the primary goal is to achieve high message throughput, VANETs aim primarily for communication reliability and fast dissemination.
Communication pathways include [7]:

- **Vehicle-to-vehicle (V2V)**: messages are transmitted between neighboring vehicles. This includes *one-hop* and *multi-hop* messaging scenarios in which vehicles communicate directly with other vehicles or through intermediary vehicles.

- **Vehicle-to-infrastructure (V2I)**: messages are transmitted between vehicles and roadside units located on nearby arterial road intersections or highway on-ramps.

- **Vehicle-to-pedestrian (V2P)**: messages are transmitted between vehicles and pedestrians who send and receive messages via their phones or other wireless devices.

- **Vehicle-to-network (V2N)**: messages are transmitted between vehicles and servers that provide V2N applications.

These vehicular communication networks can help improve safety, the environment, and mobility. For example, V2V and V2I systems use information on

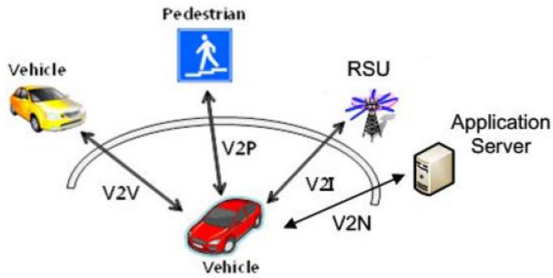

Figure 1.3: Types of V2X applications (V2V, V2P, V2N and V2I) [7].

acceleration and braking behaviours of nearby vehicles to track dangers beyond a driver's line of sight, helping to prevent collisions. With vehicles in communication with each other, *platooning* is possible, which reduces vehicle headways and aerodynamic drag, helping to improve fuel efficiency. V2P systems improve the safety of pedestrians crossing at intersections and facilitate carpooling and ride sharing, by providing people real-time information about their rides. Additionally, the network can also provide useful information, such as route guidance, and even entertainment to passengers and drivers [5].

1.4 Applications for vehicular communications

1.4.1 Road safety-oriented

Vehicular safety remains the major driver for automotive telematics. Message transmission can be triggered periodically or event driven. In the periodic case, preventive safety messages are disseminated to keep drivers informed with details such as forward and opposing vehicle speed, and optimal acceleration and deceleration settings. On the other hand, event-driven messages are delivered occasionally as in the case of a sudden hard breaking vehicle from other nearby vehicles or emergency vehicles such as ambulances.
Moreover, many applications that send event-driven messages are relevant for further vehicles, allowing upstream vehicles to undertake early countermeasures to prevent severe catastrophes such as chain-reaction accidents. The difficulty of course in dissemination of event-driven messages, in particular, is the need to balance speed and security. These messages have latency requirements on the order of 100 *ms* or less so they cannot carry the overhead that might be needed to guarantee security [4].

1.4.2 Environmental

The environmental aspects related to VANETs are increasingly gaining interest. Several procedures can reduce fuel consumption and increase safety for both passenger cars and trucks. Recommended speeds, calculated based on optimal fuel efficiency, can be provided to drivers, who can then choose to adjust their speeds. Studies involving both battery electric and conventional vehicles suggest that significant fuel savings and CO_2 reductions can be achieved by eco-driving, which typically relies on VANETs [4].

1.4.3 Convenience and commercial

Last important advantage that worth mentioning is the convenience and commercial aspect. Non-safety applications in vehicular networks provide secondary benefits for vehicles such as travel time savings and in-car entertainment. Convenience applications can enhance traffic flow and increase the driving experience by sharing traffic information between vehicles and the central traffic control system. These provide drivers with ways to make more informed route choice decisions. They can also supply drivers with important information on parking congestion and rates. Commercial applications provide drivers and their passengers with infotainment content delivery, Web access, and audio and video streaming [4].

1.5 Vehicular communication standards

As already mentioned, the main motivation for vehicular communication systems is safety and eliminating the excessive cost of traffic collisions. According to World Health Organization (WHO), road accidents annually cause approximately 1.2 million deaths worldwide, one-fourth of all deaths caused by injury. Also about 50 million persons are injured in traffic accidents. Besides, a study from the American Automobile Association (AAA) concluded that car crashes cost the United States 300 billion dollar per year.
In general, V2I communications have been implemented based on numerous standards, such as IEEE 802.11n, DSRC and Infrared techniques. They have been widely deployed for road charging applications but the infrastructure cost makes the cost/benefit calculation challenging, demanding significant investment overhead. Further, Wide Area Networking (WAN) technologies such as 2G/GPRS/EDGE, 3G/UMTS/HSPA/HSPA+, and 4G/LTE have also been used for vehicle to back office communication, but these suffer from location accuracy which could be improved by secondary mechanism such as GPS.
On the other hand, the concept of (mostly neighboring) vehicles communicating with each other has been the subject of research and development initiatives for many years. However, the level of adoption of V2V techniques in modern vehicles

has only recently started to increase and it is still far below satisfactory levels.
Lately, through the connectivity available coverage, vehicles have started getting connected to the internet, giving birth to several applications that fall in the realm of V2B (Vehicle-to-Business) communications.
Last but not least, the increasingly rising utilization of smart devices has produced a new generation of mobile apps so that a driver can be connected to his/her vehicle remotely [4].

1.5.1 VANETs architecture and standards

With the term V2X, Vehicle to Everything communication, we intend the possibility for a network of communicating in all possible modes V2V, V2I and V2P. The V2X have been standardized both in US and EU through different architectures, respectively by WAVE (Wireless Access Vehicular Environment) and ETSI (European Telecommunications Standards Institute), both based on dedicated short range communication (DSRC) technology.
The VANETs architecture differs then among the standard in use. Altought there are some basic blocks that we can mention and that characterize the network:

- Road Side Unit (RSU): a fixed access point along the road,
- On Board Unit (OBU): a communication facility situated on the vehicle itself.

The communication from vehicle to infrastructure and viceversa are handled by the RSU that is able to create a wireless link with the vehicle, if the car is under the coverage range of the RSU's antenna. V2V communications can happen outside the coverage area in different ways through the on board unites present in vehicles. V2V and V2I differs among each other in the purpose and the need for infrastructure. V2I needs a centralized network in which the nodes are moving at a high speed (vehicles) so they can create wireless links for a short time. V2I is then used for applications that are not safety-oriented [5].
In the next chapters we will discuss the different standards nowadays present on the market: the DSRC and the cellular V2X (C-V2X) and we will compare them.

1.6 Future trends in vehicular communication

Future vehicular applications in the mass market like infotainment, driver assistance systems and autonomous driving will create a massive communication demand, especially in urban areas. Drivers and autonomous cars will also be supported by an increasingly intelligent roadside infrastructure, such as roadside wireless-enabled detection systems to avoid severe accidents resulting from wrong-way driving.
The key requirements in order to support future communication demands are peak

data rate, cell edge data rate, spectral efficiency, mobility support, cost efficiency, number of simultaneous connections and latency.
A future 5G cellular communication standard should address all these requirements, especially the support of massive MTC. Technical trends in the development of communication networks are device-to-device communication that enables a direct transmission of data between two devices (very interesting for V2V communication) and beam forming to improve the channel quality (also with regard to mobility).
In addition, non-orthogonal multiple access is a candidate for future cellular radio access [4].

1.6.1 Autonomous driving

In general, *autonomous* means having the power for self-governance. There have been several research and development projects dedicated to vehicle autonomy. However, most of them have in fact only been automated (made to be automatic) due to a heavy reliance on artificial hints in their environment, such as magnetic strips. Autonomous control implies good performance under significant uncertainties in the environment for extended periods of time and the ability to compensate for system failures without external intervention. As can be seen from many projects mentioned, it is often suggested to extend the capabilities of an autonomous car by implementing communication networks both in the immediate vicinity (for collision avoidance) and far away (for congestion management). By bringing in these outside influences in the decision process, some would no longer regard the car's behavior or capabilities as autonomous.

In the United States, the National Highway Traffic Safety Administration (NHTSA) has proposed a formal classification system [4]:

- Level 0: The driver completely controls the vehicle at all times.
- Level 1: Individual vehicle controls are automated, such as electronic stability control or automatic braking.
- Level 2: At least two controls can be automated in unison, such as adaptive cruise control in combination with lane keeping. Example: Tesla Model S.
- Level 3: The driver can fully cede control of all safety-critical functions in certain conditions. The car senses when conditions require the driver to retake control and provides a "sufficiently comfortable transition time" for the driver to do so.
- Level 4: The vehicle performs all safety-critical functions for the entire trip, with the driver not expected to control the vehicle at any time. As this vehicle

would control all functions from start to stop, including all parking functions, it could include unoccupied cars.

An alternative classification system based on five different levels (ranging from driver assistance to fully automated systems) has been published by SAE, another automotive standardization body. In SAE's autonomy level definitions, *driving mode* means "a type of driving scenario with characteristic dynamic driving task requirements (e.g., expressway merging, high speed cruising, low speed traffic jam, closed-campus operations, etc.)".
Here the different level from the SAE definition [8]:

- Level 0: Automated system issues warnings and may momentarily intervene but has no sustained vehicle control.
- Level 1 (*hands on*): The driver and the automated system share control of the vehicle. Examples are Adaptive Cruise Control (ACC), where the driver controls steering and the automated system controls speed; and Parking Assistance, where steering is automated while speed is under manual control. The driver must be ready to retake full control at any time. Lane Keeping Assistance (LKA) Type II is a further example of level 1 self driving.
- Level 2 (*hands off*): The automated system takes full control of the vehicle (accelerating, braking, and steering). The driver must monitor the driving and be prepared to intervene immediately at any time if the automated system fails to respond properly. The shorthand "hands off" is not meant to be taken literally. In fact, contact between hand and wheel is often mandatory during SAE 2 driving, to confirm that the driver is ready to intervene.
- Level 3 (*eyes off*): The driver can safely turn their attention away from the driving tasks, e.g. the driver can text or watch a movie. The vehicle will handle situations that call for an immediate response, like emergency braking. The driver must still be prepared to intervene within some limited time, specified by the manufacturer, when called upon by the vehicle to do so. As an example, the 2018 Audi A8 Luxury Sedan was the first commercial car to claim to be capable of level 3 self driving. This particular car has a so-called Traffic Jam Pilot. When activated by the human driver, the car takes full control of all aspects of driving in slow-moving traffic at up to 60 kilometres per hour (37 mph). The function works only on highways with a physical barrier separating one stream of traffic from oncoming traffic.
- Level 4 (*mind off*): As level 3, but no driver attention is ever required for safety, i.e. the driver may safely go to sleep or leave the driver's seat. Self driving is supported only in limited spatial areas (geofenced) or under special circumstances, like traffic jams. Outside of these areas or circumstances, the

vehicle must be able to safely abort the trip, i.e. park the car, if the driver does not retake control.

- Level 5 (*steering wheel optional*): No human intervention is required at all. An example would be a robotic taxi.

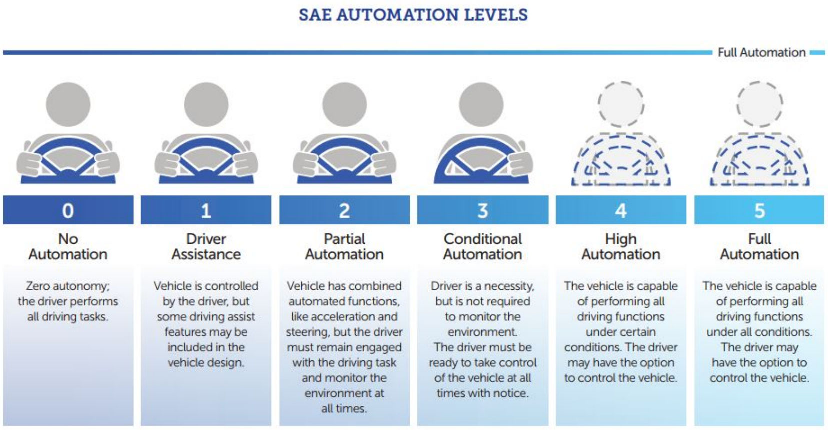

Figure 1.4: Autonomous driving levels, as defined by SAE.

Autonomous driving brings several advantages. It is expected that an increase in the use of autonomous vehicles would make possible such benefits as avoid traffic collisions caused by human driver errors (reaction time, tail gating, rubbernecking, and other forms of distracted or aggressive driving) and increased roadway capacity and reduced traffic congestion due to reduced need for safety gaps and the ability to better manage traffic flow.
Other advantages can be [4]:

1. Relief of vehicle occupants from driving and navigation chores.

2. Higher speed limit for autonomous cars.

3. Removal of constraints on occupants' state in an autonomous car, it would not matter if the occupants were under age, over age, unlicensed, blind, distracted, intoxicated, or otherwise impaired.

4. Reduction of physical space required for vehicle parking, and vehicles will be able to drive where space is not scarce.

5. Reduction in the need for traffic police and premium on vehicle insurance.

6. Reduction of physical road signage. Autonomous cars could receive necessary communication electronically (although physical signs may still be required for any human drivers).

7. Smoother ride.
8. Reduction in car theft, due to the vehicle's increased awareness.
9. Increased ergonomic flexibility in the cabin, due to the removal of the steering wheel and remaining driver interface, as well as no occupant needing to sit in a forward-facing position.
10. Increased ease-of-use of large vehicles such as motorhomes.
11. When used for car-sharing.
12. Reduces total number of cars.
13. Enables new business models such as mobility as a service which aim to be cheaper than car ownership by removing the cost of the driver.
14. Elimination of redundant passengers – the robotic car could drive unoccupied to wherever it is required, such as to pick up passengers or to go in for maintenance.

Autonomous driving has the power to change the world as we know it forever. This change will take place step by step, however, to ensure that the technology fits around how and where people use it.
Today, several vehicle manufacturers use this technology to create semiautonomous cars that make your journey easier and safer, while leaving you fully in control. For example, Mercedes-Benz, Volvo, and BMW have already the all-technologies keeping you a set distance from the car in front and in lane, at speeds up to 100–130 km/h.
The fully autonomous car goes further. It is able to perform all driving functions without supervision of the driver.
In between these two is the highly autonomous car. This technology will give you the option of handing over control?and responsibility?to the car on specific roads. You will be able to use your time as you choose, taking back control to enjoy driving whenever you like [4].

Chapter 2

Cellular V2X

2.1 Introduction

The following chapter will introduce the Cellular V2X starting from the cellular network. It will focus and how it relies with the already existed cellular network and its differences with the latter.
The cellular networks I will present is the fourth generation one (4G) and how this is evolving towards the fifth cellular generation (5G). Discussing about LTE architecture will be indispensable to understand the C-V2X architecture that will be based on the latter.
Similarities and differences between 4G LTE and C-V2X will also be the subject of this chapter and they will make us understand the state of the art of cellular V2X.

2.2 Cellular network evolution: from 4G to 5G

Mobile communication has brought more and more comfort to people everyday. In the last decades, it has evolved from being an expensive technology for a few selected individuals to today's present systems used by the majority of the world's population.
The world has witnessed four generations of mobile-communication systems, each associated with a specific set of technologies and a specific set of supported use cases. The generations and the steps taken between them are used here as background to introduce the main content of this thesis: LTE and cellular V2X networks. In the last part of the chapter I will also introduce the latest generation of cellular network, the 5G, focusing in particular on its ability to serve also as a vehicular network [1].

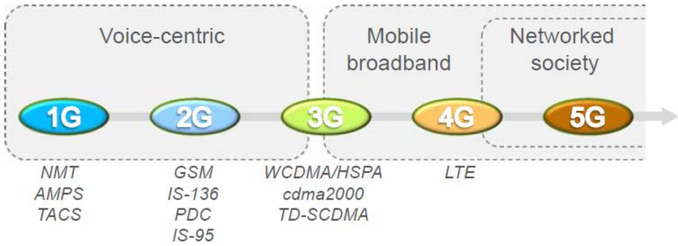

Figure 2.1: Cellular generations [1].

2.2.1 The Third-Generation Partnership Project

The 3rd Generation Partnership Project (3GPP) unites seven telecommunications standard development organizations (ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, TTC), known as *Organizational Partners* and provides their members with a stable environment to produce the Reports and Specifications that define 3GPP technologies.
The project covers cellular telecommunications network technologies, including radio access, the core transport network, and service capabilities - including work on codecs, security, quality of service - and thus provides complete system specifications. The specifications also provide hooks for non-radio access to the core network, and for interworking with Wi-Fi networks.
3GPP specifications and studies are contribution-driven, by member companies, in Working Groups and at the Technical Specification Group level.

The three Technical Specification Groups (TSG) in 3GPP are;

- Radio Access Networks (RAN),
- Services and Systems Aspects (SA),
- Core Network and Terminals (CT).

The Working Groups, within the TSGs, meet regularly and come together for their quarterly TSG Plenary meeting, where their work is presented for information, discussion and approval.
The 3GPP technologies from these groups are constantly evolving through Generations of commercial cellular/mobile systems. Since the completion of the first LTE and the Evolved Packet Core specifications, 3GPP has become the focal point for mobile systems beyond 3G [1].

Although these Generations have become an adequate descriptor for the type of network under discussion, real progress on 3GPP standards is measured by the milestones achieved in particular Releases. New features are *functionality frozen* and are ready for implementation when a Release is completed. 3GPP works on a number of Releases in parallel, starting future work well in advance of the completion of the current Release. Although this adds some complexity to the work of the groups, such a way of working ensures that progress is continuous and stable.

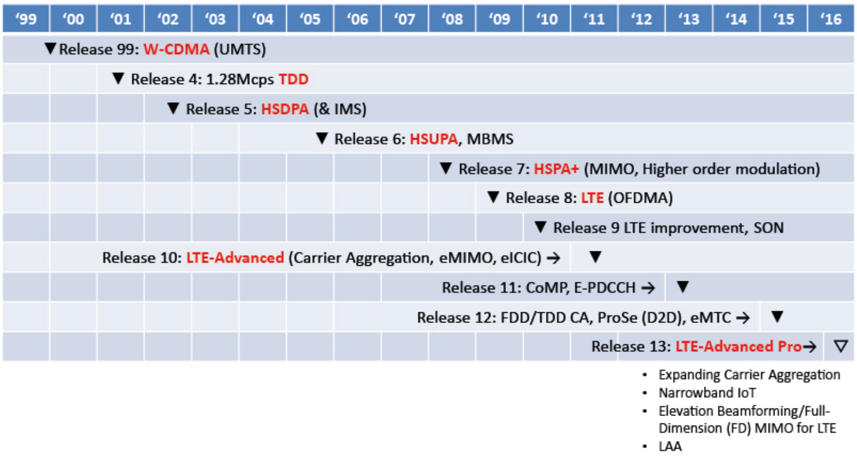

Figure 2.2: Technologies and systems over the most recent 3GPP releases [1].

All of these advances have provided a high degree of continuity in the evolving systems, allowing existing equipment to be prepared for future features and functionality - delivering higher data rates, quality of service and cost efficiencies. Each progressive 3GPP radio access technology aims to reduce complexity and avoid fragmentation of technologies on offer [1].

2.2.2 Fourth Cellular Generation: LTE

LTE stands for *Long Term Evolution* and it was started as a project in 2004 by telecommunication body known as the Third Generation Partnership Project (3GPP). SAE (System Architecture Evolution) is the corresponding evolution of the GPRS/3G packet core network evolution. The term LTE is typically used to represent both LTE and SAE.
LTE evolved from an earlier 3GPP system known as the Universal Mobile Telecommunication System (UMTS), which in turn evolved from the Global System for Mobile Communications (GSM). Even related specifications were formally known as the evolved UMTS terrestrial radio access (E-UTRA) and evolved UMTS terrestrial radio access network (E-UTRAN). First version of LTE was documented in Release 8 of the 3GPP specifications.
A rapid increase of mobile data usage and emergence of new applications such as

Generation	Major Systems Milestones
1G	Analogue technology, from the 1980s onwards. Various technologies were deployed, Nationally or Regionally, including: NMT (Nordic Mobile Telephone), AMPS (Advanced Mobile Phone System), TACS (Total Access Communications System). A-Net to E-Netz, Radiocom 2000. RTMI (Radio Telefono Mobile Integrato), JTACS (Japan Total Access Communications System) and TZ-80n (Source:wikipecha)
2G	First digital systems, deployed in the 1990s introducing voice, SMS and data services. The Primary 2G technologies are: GSM/GPRS and EDGE, CDMAOne, PDC, iDEN, IS-136 or D-AMPS.
3G	The 3G system from 3GPP is based on evolved Global System for Mobile communication (GSM) core networks and the radio access technologies that they support. This has allowed for the maintenance and development of GSM, with the evolution of General Packet Radio Service (GPRS) and Enhanced Data rates for GSM Evolution (EDGE), as well as further developments with the Universal Mobile Telecommunications System (UMTS) and High Speed Packet data Access (HSPA). 3G brought a global vision to the evolution of mobile networks, with the creation of the ITU's family of IMT2000 systems which included EDGE, CDMA2000 1X/EVDO and UMTS-HSPA+ radio access technologies.
3G/4G	LTE and LTE-Advanced have crossed the 'generational boundary" offering the next generalion(s) ofcapabilities. With their capacity for high speed data, significant spectral efficiencies and adoption of advanced radio techniques, their emergence has been the basis for all new mobile systems from Release 8 onwards.It should be noted that LTE-Advanced (From Release 10) is 3GPP's ITU-R IMT-Advanced radio interface. LTE-Advanced is the first true 4G technology to be specified by 3GPP.LTE-Advanced Pro is the name that helps the industry describe what has been achieved with the completion of Release 13. LTE Pro is set to be used by other sectors, beyond telecoms, including Critical Communications (blue light services and other Mission Critical systems), the machine-to-machine or Internet of Things (loT) sector, Transport (Rail, ITS, etc), Education and many other areas. LTE-Advanced Pro is 3GPP's stepping stone to 5G systems.

Table 2.1: Major system milestone overview of the 4 cellular generations [1].

MMOG (Multimedia Online Gaming), mobile TV, Web 2.0, streaming contents have motivated the 3GPP to work on LTE on the way towards fourth-generation mobile.
The main goal of LTE is to provide a high data rate, low latency and packet optimized radio access technology supporting flexible bandwidth deployments. Same time its network architecture has been designed with the goal to support packet-switched traffic with seamless mobility and great quality of service [1] [9].

Spectrum and categories of LTE

The frequency bands where LTE will operate are in both paired and unpaired spectrum, requiring flexibility in the duplex arrangement. For this reason, LTE supports both FDD and TDD operations.
Release 13 of the 3GPP specifications for LTE includes 32 frequency bands for FDD and 12 for TDD. The number of bands is very large and for this reason, the numbering scheme recently had to be revised to become future proof and accommodate more bands. The paired bands for FDD operation are numbered from 1 to 32 and 65 to 66, as shown in table 2.3, while the unpaired bands for TDD operation are numbered from 33 to 46, as shown in table 2.4. Note that the frequency bands defined for UTRA FDD use the same numbers as the paired LTE bands, but are labeled with Roman numerals. Bands 15 and 16 are reserved for definition in Europe, but are not used at the present time [1].

To support different scenarios, which may call for different device capabilities in terms of data rates, as well as to allow for market differentiation in terms of low and high-end devices with a corresponding difference in price, not all devices support all capabilities. Furthermore, devices from an earlier release of the standard will not support features introduced in later versions of LTE. For example, a release-8 device will not support carrier aggregation as this feature was introduced in release 10. Therefore, as part of the connection setup, the device indicates not only which release of LTE it supports, but also its capabilities within the release.
In principle, the different parameters could be specified separately, but to limit the number of combinations and avoid a parameter combination that does not make sense, a set of physical-layer capabilities are lumped together to form a *UE category.*
The categories are summarized in table 2.5 (in simplified form with uplink and downlink categories merged in a single table). Note that, regardless of the category, a device is always capable of receiving single-stream transmissions from up to four antenna ports [1].

Paired Frequency Bands Defined by 3GPP for LTE			
Band	Uplink Range (MHz)	Downlink Range (MHz)	Main Region(s)
1	1920−1980	2110−2170	Europe, Asia
2	1850−1910	1930−1990	Americas, Asia
3	1710−1785	1805−1880	Europe, Asia, Americas
4	1710−1755	2110−2155	Americas
5	824−849	869−894	Americas, Asia
6	830−840	875−885	Japan (only for UTRA)
7	2500−2570	2620−2690	Europe, Asia
8	880−915	925−960	Europe, Asia
9	1749.9−1784.9	1844.9−1879.9	Japan
10	1710−1770	2110−2170	Americas
11	1427.9−1447.9	1475.9−1495.9	Japan
12	698−716	728−746	United States
13	777−787	746−756	United States
14	788−798	758−768	United States
17	704−716	734−746	United States
18	815−830	860−875	Japan
19	830−845	875−890	Japan
20	832−862	791−821	Europe
21	1447.9−1462.9	1495.9−1510.9	Japan
22	3410−3490	3510−3590	Europe
23	2000−2020	2180−2200	Americas
24	1626.5−1660.5	1525−1559	Americas
25	1850−1915	1930−1995	Americas
26	814−849	859−894	Americas
27	807−824	852−869	Americas
28	703−748	758−803	Asia/Pacific
29	N/A	717−728	Americas
30	2305−2315	2350−2360	Americas
31	452.5−457.5	462.5−467.5	Americas
32	N/A	1452−1496	Europe
65	1920−2010	2110−2200	Europe
66	1710−1780	2110−2200	Americas
67	N/A	738−758	Europe

Figure 2.3: LTE spectrum of paired frequency bands [1].

Main features and advantages of LTE

The main features of LTE are related to improvement of the network data rate. It will bring up to 50 times performance improvement and much better spectral efficiency to cellular networks. The new data rates are 300 Mbps peak downlink and 75 Mbps peak uplink. In a 20MHz carrier, data rates beyond 300 Mbps can be achieved under very good signal conditions. LTE is an ideal technology to support high date rates for the services such as voice over IP (VOIP), streaming multimedia, videoconferencing or even a high-speed cellular modem [9].

Unpaired Frequency Bands Defined by 3GPP for LTE		
Band	**Frequency Range (MHz)**	**Main Region(s)**
33	1900–1920	Europe, Asia (not Japan)
34	2010–2025	Europe, Asia
35	1850–1910	(Americas)
36	1930–1990	(Americas)
37	1910–1930	–
38	2570–2620	Europe
39	1880–1920	China
40	2300–2400	Europe, Asia
41	2496–2690	United States
42	3400–3600	Europe
43	3600–3800	Europe
44	703–803	Asia/Pacific
45	1447–1467	Asia (China)
46	5150–5925	Global

Figure 2.4: LTE spectrum of unpaired frequency bands [1].

UE Categories (Simplified Description)						
		Downlink			**Uplink**	
Category	**Release**	**Peak Rate (Mbit/s)**	**Maximun Number of MIMO Layers**	**Maximum Modulation**	**Peak Rate (Mbit/s)**	**Maximum Modulation**
M1	13	0.2	1		0.14	
0	12	1	1	64QAM	1	16QAM
1	8	10	1	64QAM	5	16QAM
2	8	50	2	64QAM	25	16QAM
3	8	100	2	64QAM	50	16QAM
4	8	150	2	64QAM	50	16QAM
5	8	300	4	64QAM	75	64QAM
6	10	300	2 or 4	64QAM	50	16QAM
7	10	300	2 or 4	64QAM	100	16QAM
8	10	3000	8	64QAM	1500	64QAM
9	11	450	2 or 4	64QAM	50	16QAM
10	11	450	2 or 4	64QAM	100	16QAM
11	12	600	2 or 4	256QAM optional	50	16QAM
12	12	600	2 or 4	256QAM optional	100	16QAM
13	12	400	2 or 4	256QAM	150	64QAM
14	12	400	2 or 4	256QAM	100	16QAM
15	12	4000	8	256QAM		

Figure 2.5: LTE categories classification [1].

LTE main features are [9]:

- it uses both Time Division Duplex (TDD) and Frequency Division Duplex (FDD) mode. In FDD uplink and downlink transmission used different frequency, while in TDD both uplink and downlink use the same carrier and are separated in Time;
- it supports flexible carrier bandwidths, from 1.4 MHz up to 20 MHz as well as both FDD and TDD. LTE designed with a scalable carrier bandwidth from 1.4 MHz up to 20 MHz which bandwidth is used depends on the frequency band and the amount of spectrum available with a network operator;
- all LTE devices have to support (MIMO) Multiple Input Multiple Output transmissions, which allow the base station to transmit several data streams over the same carrier simultaneously;
- all interfaces between network nodes in LTE are now IP based, including the backhaul connection to the radio base stations. This is a great simplification compared to earlier technologies that were initially based on E1/T1, ATM and frame relay links, with most of them being narrowband and expensive;
- Quality of Service (QoS) mechanism have been standardized on all interfaces to ensure that the requirement of voice calls for a constant delay and bandwidth, can still be met when capacity limits are reached;
- It is compatible with GSM/EDGE/UMTS systems utilizing existing 2G and 3G spectrum and a new spectrum. Supports hand-over and roaming to existing mobile networks.

Main advantages of LTE are:

- *high throughput*: high data rates can be achieved in both downlink as well as uplink.
- *Low latency*: Time required to connect to the network is in range of a few hundred milliseconds and power saving states can now be entered and exited very quickly;
- Frequency Division Duplex (FDD) and Time Division Duplex (TDD) can be both used on same platform;
- *superior end-user experience*: Optimized signaling for connection establishment and other air interface and mobility management procedures have further improved the user experience. Reduced latency (to 10 ms);

- LTE will also support seamless connection to existing networks such as GSM, CDMA and WCDMA;
- *Plug and play*: the user does not have to manually install drivers for the device. Instead system automatically recognizes the device, loads new drivers for the hardware if needed, and begins to work with the newly connected device;
- *simple architecture*: because of this low operating expenditure (OPEX) is possible.

LTE Quality of Service

LTE architecture supports hard QoS requirements, with end-to-end quality of service and guaranteed bit rate (GBR) for radio bearers. Just as Ethernet and the internet have different types of QoS, for example, various levels of QoS can be applied to LTE traffic for different applications. Because the LTE MAC is fully scheduled, QoS is a natural fit.
Evolved Packet System (EPS) bearers provide one-to-one correspondence with RLC radio bearers and provide support for Traffic Flow Templates (TFT). There are four types of EPS bearers [9]:

- GBR Bearer resources permanently allocated by admission control
- Non-GBR Bearer no admission control
- Dedicated Bearer associated with specific TFT (GBR or non-GBR)
- Default Bearer Non GBR, catch-all for unassigned traffic

OFDM technology

Orthogonal frequency-division multiplexing (OFDM), is a frequency-division multiplexing (FDM) scheme used as a digital multi-carrier modulation method.
To overcome the effect of *multipath fading* problem present in UMTS, LTE uses *Orthogonal Frequency Division Multiplexing* (OFDM) for the downlink that is to transmit the data from the base station to the terminal over many narrow band carriers of 180 KHz each instead of spreading one signal over the complete 5MHz career bandwidth. Indeed OFDM uses a large number of narrow sub-carriers for multi-carrier transmission to carry data.
OFDM meets the LTE requirement for spectrum flexibility and enables cost-efficient solutions for very wide carriers with high peak rates. The basic LTE downlink physical resource can be seen as a time-frequency grid, as illustrated in the figure below. The OFDM symbols are grouped into *resource blocks*. The resource blocks have a

Versione name	3GPP Release	3GPP Category	Latency
LTE	Rel. 8 - 9	from 1 to 5	20 ms
LTE Advanced	Rel. 10 - 11 - 12	from 6 to 8 from 9 to 12 from 13 to 16	10 ms
LTE Advanced Pro	Rel. 13 - 14	from 17 to 19	less than 2 ms
Cellular V2X	Rel. 14	from 17 to 19	less than 2 ms
5G New Radio (phase 1)	Rel 15	-	less than 2 ms
5G New Radio (phase 2)	Rel. 16	-	1 ms

Table 2.2: Comparison between LTE versions, Cellular V2X and the brand new 5G technology for release, category and latency.

Versione name	Licensed/Unlicensed spectrum	Peak data rate
LTE	licensed	100 Mbit/s in DL 50 Mbit/s in UL
LTE Advanced	licensed	1 Gbit/s in DL 500 Mbit/s in UL
LTE Advanced Pro	licensed and unlicensed	more than 3 Gbit/s in DL more than 1 Gbit/s in UL
Cellular V2X	licensed and unlicensed	more than 3 Gbit/s in DL more than 1 Gbit/s in UL
5G New Radio (phase 1)	licensed and unlicensed	from 1 to 10 Gbit/s in DL and UL
5G New Radio (phase 2)	licensed and unlicensed	up to 20 Gbit/s in DL up to 10 Gbit/s in UL

Table 2.3: Comparison between LTE versions, Cellular V2X and the brand new 5G technology for spectrum type and peak data rate.

total size of 180kHz in the frequency domain and 0.5 ms in the time domain. Each 1 ms Transmission Time Interval (TTI) consists of two slots (Tslot) [9].

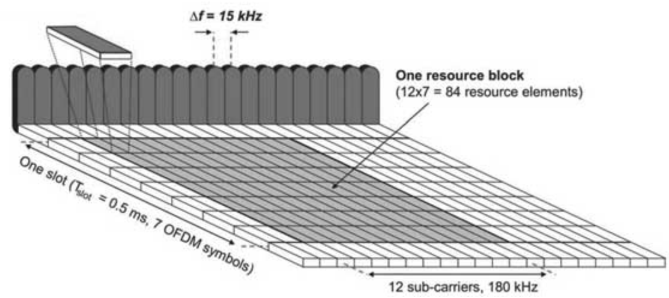

Figure 2.6: Orthogonal frequency-division multiplexing in LTE [9].

Each user is allocated a number of so-called resource blocks in the time/frequency grid. The more resource blocks a user gets, and the higher the modulation used in the resource elements, the higher the bit-rate. Which resource blocks and how many the user gets at a given point in time depend on advanced scheduling mechanisms in the frequency and time dimensions. The scheduling mechanisms in LTE are similar to those used in HSPA, and enable optimal performance for different services in different radio environments.

Some of the main advantages of this technique are listed below.

- The primary advantage of OFDM over single-carrier schemes is its ability to cope with severe channel conditions (for example, attenuation of high frequencies in a long copper wire, narrowband interference and frequency-selective fading due to multipath) without complex equalization filters.
- Channel equalization is simplified because OFDM may be viewed as using many slowly-modulated narrowband signals rather than one rapidly-modulated wideband signal.
- The low symbol rate makes the use of a guard interval between symbols affordable, making it possible to eliminate inter symbol interference (ISI).
- This mechanism also facilitates the design of single frequency networks (SFNs), where several adjacent transmitters send the same signal simultaneously at the same frequency, as the signals from multiple distant transmitters may be combined constructively, rather than interfering as would typically occur in a traditional single-carrier system.

Despite the many advantages, OFDM has also some drawbacks such as high peak-to-average ratio and it is sensitive to frequency offset, hence to Doppler-shift as well.

2.2.3 Fifth Cellular Generation: 5G

The fifth cellular Generation represents the latest effort of telecommunication community to evolve from the already well performing 4G network. It is important for the porpouse of vehicular network to introduce this cellular network, because as I will talk about in the next chapters, it will be fully compatible with the C-V2X vehicular network and it will help to improve the latter one in the future.
The industry is already well on the studying towards the next generation of mobile communication, commonly referred to as fifth generation or 5G. 3GPP has, in fact, been working on Release 15 and 16 since some years, the so-called 5G phase 1 and phase 2, and they will soon freeze it.
In essence, 5G should be seen as a platform enabling wireless connectivity to all kinds of services, existing as well as future not-yet-known services and thereby taking wireless networks beyond mobile broadband. Connectivity will be provided essentially *anywhere*, *anytime* to *anyone* and *anything*. The term networked society is sometimes used when referring to such a scenario where connectivity goes beyond mobile smartphones, having a profound impact on the society [1].

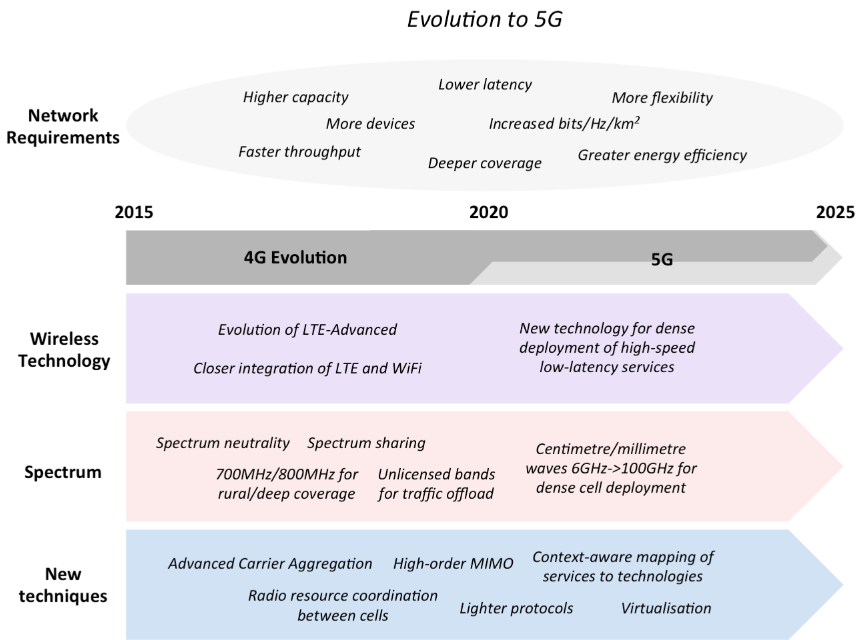

Figure 2.7: Scheme of the evolution to 5G [1].

5G spectrum

Wireless networks are composed of cell sites divided into sectors that send data through radio waves.

Fourth-generation LTE wireless technology provides the foundation for 5G. Unlike 4G, which requires large, high-power cell towers to radiate signals over longer distances, 5G wireless signals will be transmitted via large numbers of small cell stations located in places like light poles or building roofs. The use of multiple small cells is necessary because the millimeter wave spectrum – the band of spectrum between 30 GHz and 300 GHz that 5G relies on to generate high speeds – can only travel over short distances and is subject to interference from weather and physical obstacles, like buildings [10].

Previous generations of wireless technology have used lower-frequency bands of spectrum. To offset millimeter wave challenges relating to distance and interference, the wireless industry is also considering the use of lower-frequency spectrum for 5G networks so network operators could use spectrum they already own to build out their new networks. Lower-frequency spectrum reaches greater distances but has lower speed and capacity than millimeter wave, however [10].

Country	**Low frequency band**	**High frequency band**
Finland	3.4 - 3.8 GHz	26.5 - 27.5 GHz
France	3.46 - 3.8 GHz	26 GHz
Germany	3.4 - 3.8 GHz	26 - 27.5 GHz
Ireland	3.4 - 3.8 GHz	26 GHz
Italy	3.6 - 3.8 GHz	26.5 - 27.5 GHz
Russia	3.4 - 3.8 GHz	26 GHz
Spain	3.4 - 3.8	26.5 - 27.5 GHz
United Kingdom	3.4 - 3.6, 3.6 to 3.8 GHz (in 2019)	26.5 - 27.5 GHz

Table 2.4: Spectrum for 5G [1].

5G main features

The followings are the main characteristics of 5G [1].

- *Massive system capacity.*
  Traffic demands for mobile-communication systems are predicted to increase dramatically. To support this traffic in an affordable way, 5G networks must deliver data with much lower cost per bit compared with the networks of today. Furthermore, the increase in data consumption will result in an increased energy footprint from networks. 5G must therefore consume significantly lower energy per delivered bit than current cellular networks. The exponential increase in connected devices, such as the deployment of billions of wirelessly

connected sensors, actuators and similar devices for massive machine connectivity, will place demands on the network to support new paradigms in device and connectivity management that do not compromise security. Each device will generate or consume very small amounts of data, to the extent that they will individually, or even jointly, have limited impact on the overall traffic volume. However, the sheer number of connected devices seriously challenges the ability of the network to provision signaling and manage connections.

- *Very high data rates everywhere.*
  An important capability is the data rate that can actually be provided under real-life conditions in different scenarios.5G should support data rates exceeding 10 Gbps in specific scenarios such as indoor and dense outdoor environments. Data rates of several 100 Mbps should generally be achievable in urban and suburban environments. Data rates of at least 10 Mbps should be accessible almost everywhere, including sparsely populated rural areas in both developed and developing countries. For more details about data rate see table 2.3.

- *Very low latency.*
  Very low latency will be driven by the need to support new applications. Some envisioned 5G use cases, such as traffic safety and control of critical infrastructure and industry processes, may require much lower latency compared with what is possible with the mobile-communication systems of today. To support such latency-critical applications, 5G should allow for an application end-to-end latency of 1ms or less, although application-level framing requirements and codec limitations for media may lead to higher latencies in practice. Many services will distribute computational capacity and storage close to the air interface. This will create new capabilities for real-time communication and will allow ultra-high service reliability in a variety of scenarios, ranging from entertainment to industrial process control. Table 2.3 contains the latency values of 5G phase 1 and phase 2.

- Ultra high reliability and availability.
  In addition to very low latency, 5G should also enable connectivity with ultra-high reliability and ultra-high availability. For critical services, such as control of critical infrastructure and traffic safety, connectivity with certain characteristics, such as a specific maximum latency, should not merely be typically available. Rather, loss of connectivity and deviation from quality of service requirements must be extremely rare. For example, some industrial applications might need to guarantee successful packet delivery within 1 ms with a probability higher than 99.9999 percent.

- *Very low device cost and energy consumption.*
  Low-cost, low-energy mobile devices have been a key market requirement

since the early days of mobile communication. However, to enable the vision of billions of wirelessly connected sensors, actuators and similar devices, a further step has to be taken in terms of device cost and energy consumption. It should be possible for 5G devices to be available at very low cost and with a battery life of several years without recharging.

- *Energy-efficient network*.
  While device energy consumption has always been prioritized, energy efficiency on the network side has recently emerged as an additional KPI, for three main reasons: Energy efficiency is an important component in reducing operational cost, as well as a driver for better dimensioned nodes, leading to lower total cost of ownership. Energy efficiency enables off-grid network deployments that rely on medium-sized solar panels as power supplies, thereby enabling wireless connectivity to reach even the most remote areas. Energy efficiency is essential to realizing operators' ambition of providing wireless access in a sustainable and more resource-efficient way. The importance of these factors will increase further in the 5G era, and energy efficiency will therefore be an important requirement in the design of 5G wireless access.

Usage scenarios for IMT-2020

With a wide range of new use cases being one principal driver for 5G, ITU-R has defined three usage scenarios that form a part of IMT vision recommendation. Inputs from the mobile industry and different regional and operator organizations were taken into the IMT-2020 process in ITU-R WP5D, and were synthesized into the three scenarios [1]:

- Enhanced mobile broadband (EMBB): With mobile broadband today being the main driver for use of 3G and 4G mobile systems, this scenario points at its continued role as the most important usage scenario. The demand is continuously increasing and new application areas are emerging, setting new requirements for what ITU-R calls enhanced mobile broadband. Because of its broad and ubiquitous use, it covers a range of use cases with different challenges, including both hot spots and wide-area coverage, with the first one enabling high data rates, high user density and a need for very high capacity, while the second one stresses mobility and a seamless user experience, with lower requirements on data rate and user density. The enhanced mobile broadband scenario is in general seen as addressing human-centric communication.

- Ultra-reliable and low-latency communications (URLLC): This scenario is intended to cover both human and machine-centric communication, where the latter is often referred to as critical machine-type communication (C-MTC).

It is characterized by use cases with stringent requirements for latency, reliability and high availability. Examples include vehicle-to-vehicle communication involving safety, wireless control of industrial equipment, remote medical surgery, and distribution automation in a smart grid. An example of a human-centric use case is 3D gaming and "tactile internet", where the low latency requirement is also combined with very high data rates.

- Massive machine-type communications (M-MTC): This is a pure machine-centric use case, where the main characteristic is a very large number of connected devices that typically have very sparse transmissions of small data volumes that are not delay sensitive. The large number of devices can give a very high connection density locally, but it is the total number of devices in a system that can be the real challenge and stresses the need for low cost. Due to the possibility of remote deployment of M-MTC devices, they are also required to have a very long battery life time.

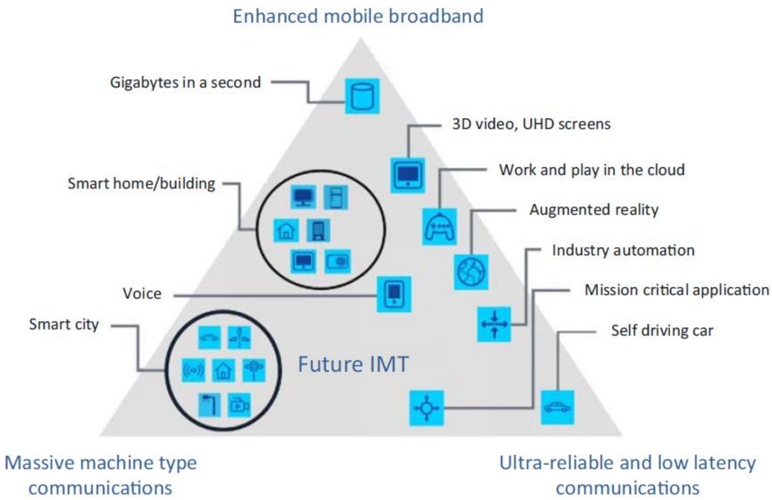

Figure 2.8: IMT-2020 use cases and mapping to usage scenarios [1].

Capabilities of IMT-2020

As part of the development the framework for the IMT-2020 as documented in the IMT vision recommendation, ITU-R defined a set of capabilities needed for an IMT-2020 technology to support the 5G use cases and usage scenarios identified through the inputs from regional bodies, research projects, operators, administrations, and other organizations. There are a total of 13 capabilities, where eight were selected as key capabilities. Those eight key capabilities are illustrated through two spider web diagrams in figure 2.9.

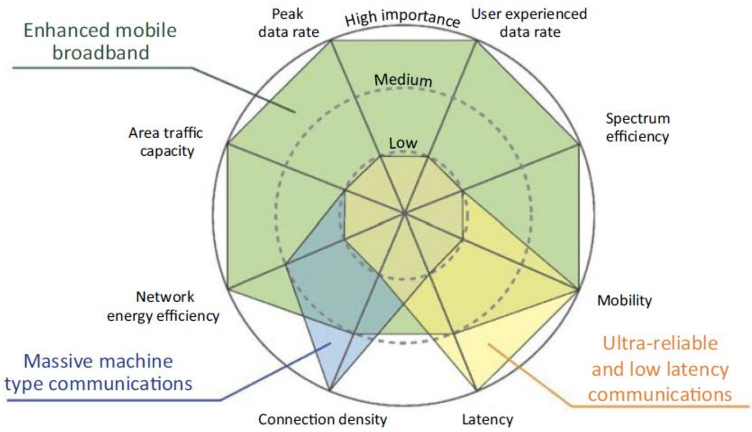

Figure 2.9: Relation between key capabilities and the three usage scenarios of ITU-R [1].

Figure 2.9 illustrates the key capabilities together with indicative target numbers intended to give a first high-level guidance for the more detailed IMT-2020 requirements that are now under development. As can be seen the target values are partly absolute and partly relative to the corresponding capabilities of IMT-advanced. The target values for the different key capabilities do not have to be reached simultaneously, and some targets are to a certain extent even mutually exclusive.
Peak data rate is a number which always has a lot of focus, but it is in fact quite an academic exercise. ITU-R defines peak data rates as the maximum achievable data rate under ideal conditions, which means that the impairments in an implementation or the actual impact from a deployment in terms of propagation, and so on does not come into play. It is a dependent key performance indicator (KPI) in that it is heavily depending on the amount of spectrum available for an operator deployment. Apart from that, the peak data rate depends on the peak spectral efficiency, which is the peak data rate normalized by the bandwidth:

$$Peak\ data\ rate = System\ bandwidth \cdot Peak\ spectral\ efficiency \tag{2.1}$$

Since large bandwidths are really not available in any of the existing IMT bands below 6 GHz, it is expected that really high data rates will be more easily achieved at higher frequencies. This leads to the conclusion that the highest data rates can be achieved in indoor and hot-spot environments, where the less favorable propagation properties at higher frequencies are of less importance.
The user-experienced data rate is the data rate that can be achieved over a large coverage area for a majority of the users. This can be evaluated as the 95th percentile from the distribution of data rates between users. It is also a dependent

capability, not only on the available spectrum but also on how the system is deployed. While a target of 100 Mbit/s is set for wide area coverage in urban and suburban areas, it is expected that 5G systems could give 1 Gbit/s data rate ubiquitously in indoor and hot-spot environments.
Spectrum efficiency gives the average data throughput per Hz of spectrum and per cell, or rather per unit of radio equipment (also referred to as transmission reception point, TRP). It is an essential parameter for dimensioning networks, but the levels achieved with 4G systems are already very high. The target was set to three times the spectrum efficiency target of 4G, but the achievable increase strongly depends on the deployment scenario. Area traffic capacity is another dependent capability, which depends not only on the spectrum efficiency and the bandwidth available, but also on how dense the network is deployed:

$$Area\,Traffic\,Capacity = Spectrum\,efficiency \cdot TRP\,density \tag{2.2}$$

By assuming the availability of more spectrum at higher frequencies and that very dense deployments can be used, a target of a 100-fold increase over 4G was set for IMT-2020. Network energy efficiency is, as already described, becoming an increasingly important capability. The overall target stated by ITU-R is that the energy consumption of the radio access network of IMT-2020 should not be greater than IMT networks deployed today, while still delivering the enhanced capabilities. The target means that the network energy efficiency in terms of energy consumed per bit of data therefore needs to be reduced with a factor at least as great as the envisaged traffic increase of IMT-2020 relative to IMT-advanced. These first five key capabilities are of highest importance for the enhanced mobile broadband usage scenario, although mobility and the data rate capabilities would not have equal importance simultaneously. For example, in hot spots, a very high user-experienced and peak data rate, but a lower mobility, would be required than in wide-area coverage case. Latency is defined as the contribution by the radio network to the time from when the source sends a packet to when the destination receives. It will be an essential capability for the URLLC usage scenario and ITU-R envisions that a 10-fold reduction in latency from IMT advanced is required.
Mobility is in the context of key capabilities only defined as mobile speed, and the target of 500 km/h is envisioned in particular for high-speed trains and is only a moderate increase from IMT-advanced. As a key capability, it will however also be essential for the URLLC usage scenario in case of critical vehicle communication at high speed and will then be of high importance simultaneously with low latency. Note that mobility and high user-experienced data rates are not targeted simultaneously in the usage scenarios [1].

2.3 Network architecture: from LTE to C-V2X

This section contains a brief overview of the architecture of the LTE radio-access network (RAN) and the associated core network (CN), the descriptions of the RAN user plane and control plane protocols and a detailed overview of the more recent C-V2X architecture.
Since the LTE cellular network is indispensable to build the C-V2X network, I will introduce the 4th Generation of cellular network first and then the cellular Vehicle-to-Everything network.

2.3.1 LTE architecture

The high-level network architecture of LTE is comprised of following three main components [9]:

1. the User Equipment (UE),
2. the Evolved UMTS Terrestrial Radio Access Network (E-UTRAN),
3. the Evolved Packet Core (EPC).

The Evolved Packet Core communicates with packet data networks in the outside world such as the internet, private corporate networks or the IP multimedia subsystem. The interfaces between the different parts of the system are denoted Uu, S1 and SGi as shown below:

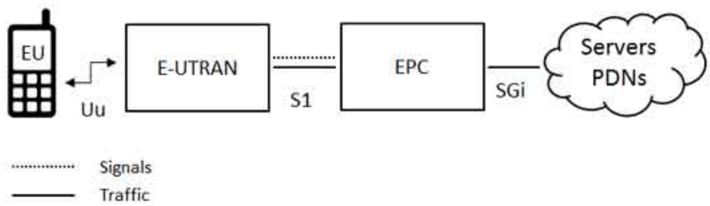

Figure 2.10: Evolve packet core connections and interfaces [9].

In networking context, a *plane* is one of three integral components of a telecommunications architecture. These three elements, the data plane, the control plane and the management plane, can be thought of as different areas of operations. Each plane carries a different type of traffic and is conceptually (and often in reality) an overlay network (a telecommunications network that runs independently on top of another one, although supported by its infrastructure) [11].
The *data plane* (sometimes also called user plane, forwarding plane, carrier plane or bearer plane) carries the network user traffic. The *control plane* carries signaling

traffic. Control packets originate from or are destined for a router. The *management plane*, which carries administrative traffic, is considered a subset of the control plane.
In conventional networking, all three planes are implemented in the firmware of routers and switches. Software-defined networking (SDN) decouples the data and control planes, removes the control plane from network hardware and implements it in software instead, which enables programmatic access and, as a result, makes network administration much more flexible.
Moving the control plane to software allows dynamic access and administration. A network administrator can shape traffic from a centralized control console without having to touch individual switches. The administrator can change any network switch's rules when necessary – prioritizing, de-prioritizing or even blocking specific types of packets with a very granular level of control.

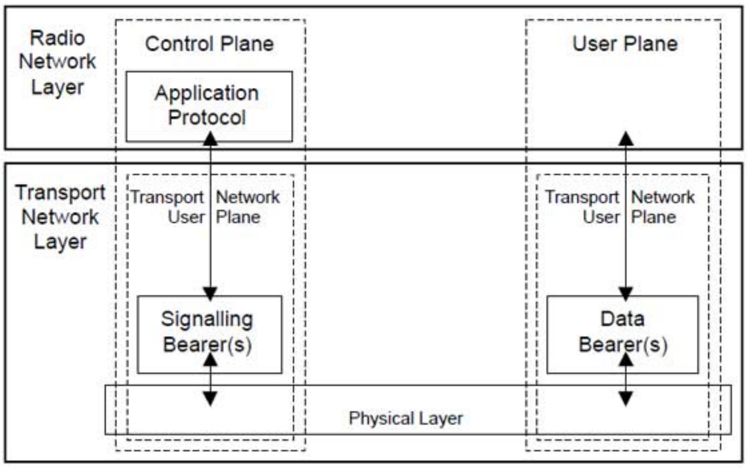

Figure 2.11: LTE radio protocol architecture highlighted with data plane, control plane and management plane [9].

User Equipment (UE)

User equipment is defined as a device used directly by an end-user to communicate. It can be of different types: a hand-held telephone, a laptop computer equipped with a mobile broadband adapter, a vehicle equipped with a mobile broadband adapter or any other device.
It is roughly similar to the mobile station (MS) in the GSM system and it connects the end-user to the eNodeB as specified in the 3GPP and ETSI standards [9].
The radio interface between the UE and the Node B is called Uu, as we can see from figure 2.10.
Later, in chapter 5, when I will talk about UE it will stand for a vehicle equipped

with a circuit and an eSIM (a SIM that is built within the circuit) able to communicate with the cellular network and connect the vehicle to the network itself.

Evolved Packet Core (EPC)

The EPC of LTE is a radical evolution from the GSM/GPRS core network used for GSM and WCDMA/HSPA. EPC supports access to the packet-switched domain only, with no access to the circuit-switched domain. It consists of several different types of nodes, some of which are briefly described in the following and illustrated in the figure below [9].

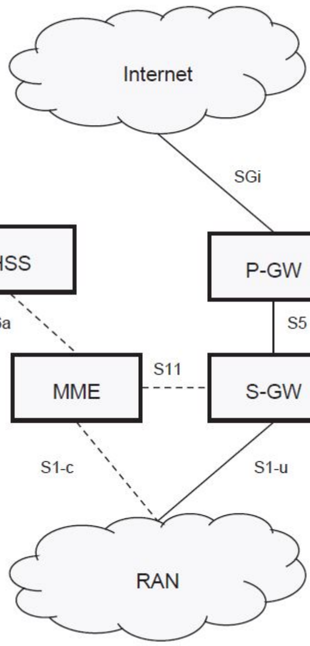

Figure 2.12: Core network architecture [9].

The mobility management entity (MME) is the control plane node of the EPC. Its responsibilities include connection/release of bearers to a device, handling of IDLE to ACTIVE transitions, and handling of security keys. The functionality operating between the EPC and the device is sometimes referred to as the non-access stratum (NAS), to separate it from the access stratum (AS) which handles functionality operating between the device and the RAN.
The serving gateway (S-GW) is the user-plane node connecting the EPC to the LTE RAN. The S-GW acts as a mobility anchor when devices move between eNodeBs, as well as a mobility anchor for other 3GPP technologies (GSM/GPRS and HSPA). Collection of information and statistics necessary for charging is also handled by the S-GW.

The packet data network gateway (PDN gateway, P-GW) connects the EPC to the internet. Allocation of the IP address for a specific device is handled by the P-GW, as well as quality of service (QoS) enforcement according to the policy controlled by the PCRF. The P-GW is also the mobility anchor for non-3GPP radio-access technologies, such as CDMA 2000, connected to the EPC.
In addition, the EPC also contains other types of nodes such as policy and charging rules function (PCRF) responsible for QoS handling and charging, and the home subscriber service (HSS) node, a database containing subscriber information. There are also some additional nodes present with regard to network support of multimedia broadcast multicast services (MBMS).
It should be noted that the nodes discussed earlier are logical nodes. In an actual physical implementation, several of them may be very well combined. For example, the MME, P-GW, and S-GW could be combined into a single physical node [9] [1].

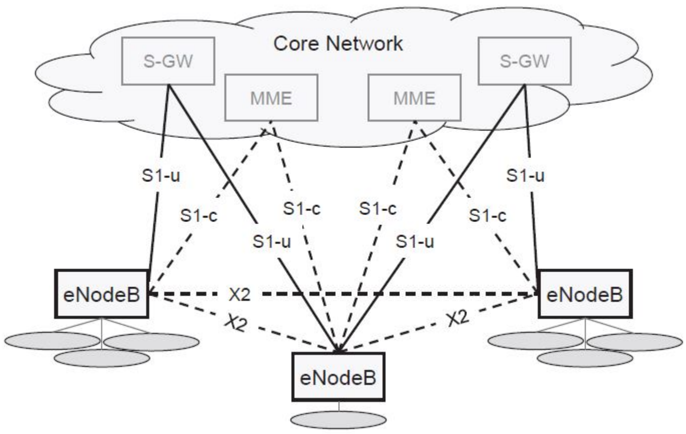

Figure 2.13: Radio access network interfaces [9].

E-UTRAN and role of the eNodeB

The LTE radio access network uses a flat architecture with a single type of node: the *eNodeB*. The eNodeB is responsible for all radio-related functions in one or several cells. It is important to note that an eNodeB is a logical node and not a physical implementation. One common implementation of an eNodeB is a three-sector site, where a base station is handling transmissions in three cells. Although other implementations can be found as well, such as one baseband processing unit to which a number of remote radio heads are connected. One example of the latter is a large number of indoor cells, or several cells along a highway, belonging to the same eNodeB. Thus, a base station is a possible implementation of, but not the same as, an eNodeB.
As can be seen from the previous figure, the eNodeB is connected to the EPC by

means of the S1 interface, more specifically to the S-GW by means of the S1 user plane part, S1-u, and to the MME by means of the S1 control plane part, S1-c. One eNodeB can be connected to multiple MMEs/S-GWs for the purpose of load sharing and redundancy.
The X2 interface, connecting eNodeBs to each other, is mainly used to support active mode mobility. This interface may also be used for multi-cell radio-resource management (RRM) functions such as inter-cell interference coordination (ICIC). The X2 interface is also used to support lossless mobility between neighboring cells by means of packet forwarding.
The interface between the eNodeB to the device is known as the Uu interface. Unless dual connectivity is used, a device is connected to a single eNodeB at a time. There is also a PC5 interface defined for direct device-to-device communication. This topic will be further describe in the following chapters, in particular, with respect to the D2D communication between vehicles in a cellular V2X network [1]. A complete list of all interfaces is provided in the section 2.3.6.

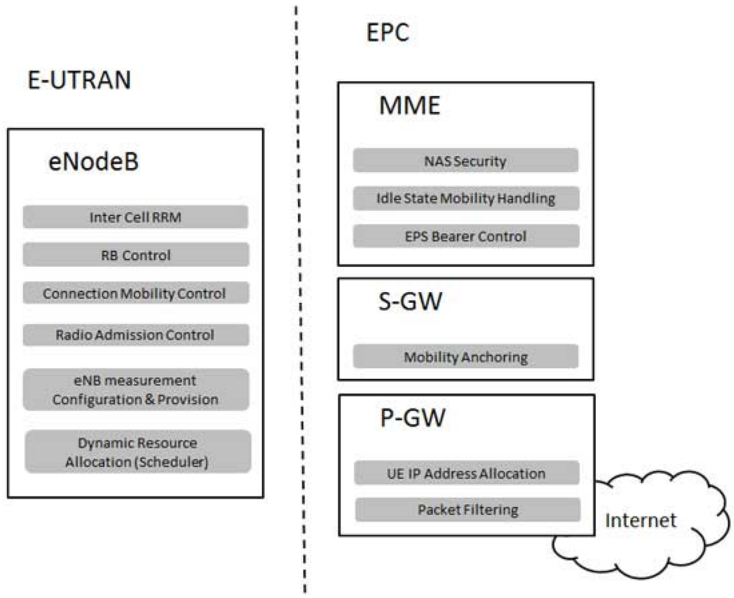

Figure 2.14: Functional split between the E-UTRAN and the EPC [9].

Roaming architecture

A network run by one operator in one country is known as a Public Land Mobile Network (PLMN) and when a subscribed user uses his operator's PLMN then it is said Home-PLMN. Roaming allows users to move outside their home network and using the resources from other operator's network. This other network is called Visited-PLMN.

A roaming user is connected to the E-UTRAN, MME and S-GW of the visited LTE network. However, LTE/SAE allows the P-GW of either the visited or the home network to be used (see figure 2.15).

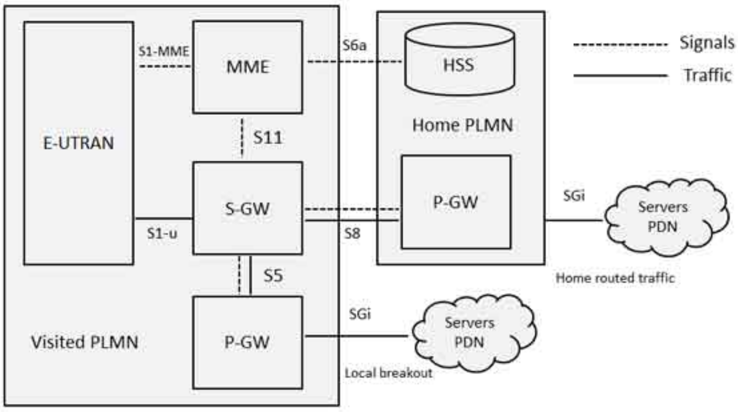

Figure 2.15: LTE roaming architecture [9].

The home network's P-GW allows the user to access the home operator's services even while in a visited network. A P-GW in the visited network allows a *local breakout* to the Internet in the visited network.
The interface between the serving and PDN gateways is known as S5/S8. This has two slightly different implementations, named S5 if the two devices are in the same network, and S8 if they are in different networks. For mobiles that are not roaming, the serving and PDN gateways can be integrated into a single device, so that the S5/S8 interface vanishes altogether [9].

2.3.2 Introduction to Cellular V2X

In June 2017, 3GPP completed the standardisation of Cellular Vehicle-to-Everything (C-V2X) technology in the Release 14 of its standard. Based on LTE, this cellular technology is designed to connect vehicles to each other, to roadside infrastructure, to other road-users and to cloud-based services.
The main reason of choosing C-V2X over other technologies is the numerous advantages that it will bring to the smart cities of the future in terms of safety, connectivity and development of cooperative intelligent transport systems (C-ITS) that reduce congestion and pollution and enhance travel. It will help cities to become smarter and support increasingly automated transport systems that are safer and more efficient than today's networks.
Some of the promised advantages by this brand new technology are [12]:

- Leverage the comprehensive coverage of secure and well-established LTE networks;

- enable highly reliable, real-time communication at high speeds and in high-density traffic;
- support both short-range and long-range transmissions between vehicles and roadside infrastructure;
- it is part of the roadmap to 5G connectivity. C-V2X is designed to be fully compatible with forthcoming 5G mobile technologies, meaning investments in infrastructure and modules today will be future-proof.

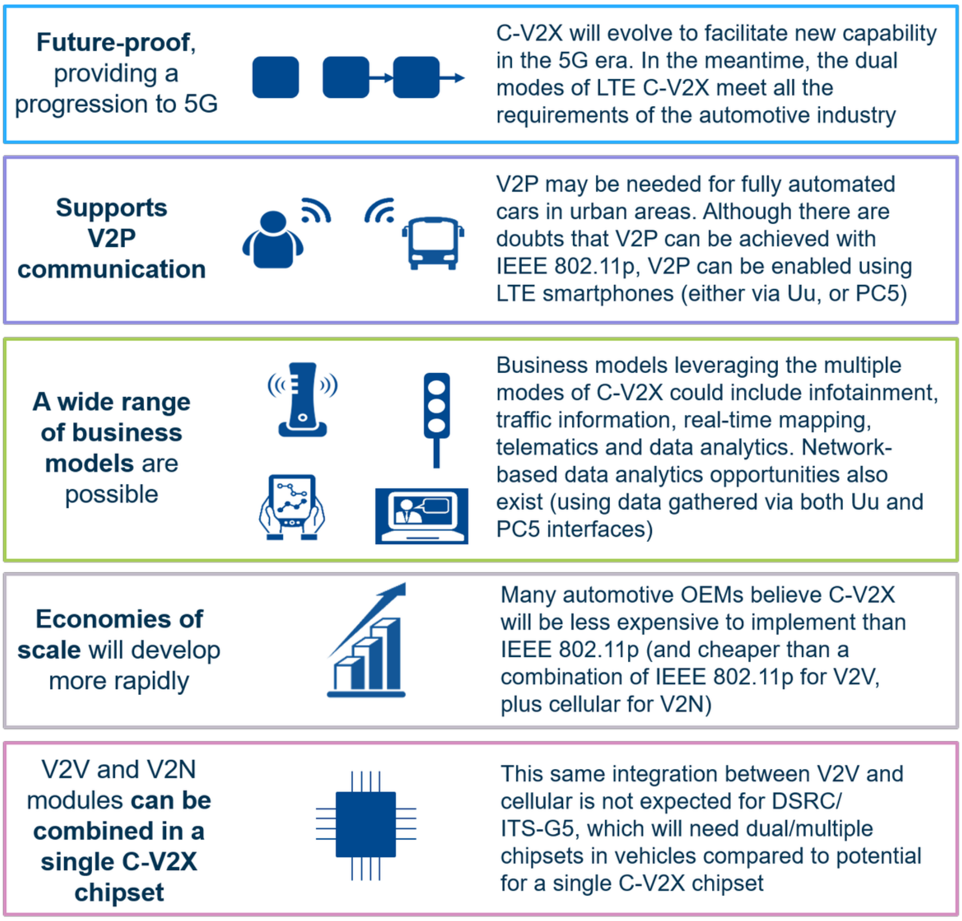

Figure 2.16: Main advantages of C-V2X [12].

Road safety is the key word around the V2X world, but there are much more improvements that are worth mentioning [12].

- *Platooning*: The formation of a convoy in which the vehicles are much closer together than can be safely achieved with human drivers, making better use of road space, saving fuel and making the transport of goods more efficient.

- *Co-operative driving*: Vehicles can use C-V2X to work together to minimise the disruption caused by lane changes and sudden braking.
- *Queue warning*: Roadside infrastructure can use C-V2X to warn vehicles of queues or road works ahead of them, so they can slow down smoothly and avoid hard braking.
- *Avoiding collisions*: Each vehicle on the road could use C-V2X to broadcast its identity, position, speed and direction. An on-board computer could combine that data with that from other vehicles to build its own real-time map of the immediate surroundings and alert the driver to any potential collisions.
- *Hazards ahead warning*: C-V2X can be used to extend a vehicle's electronic horizon, so it can detect hazards around a blind corner, obscured by fog or other obstructions, such as high vehicles or undulations in the landscape.
- *Increasingly autonomous driving*: Along with other sensors and communications systems, C-V2X will play an important role in enabling vehicles to become increasingly autonomous.
- *Collecting road tolls*: designed to reduce congestion and the impact of motor transport on the environment

2.3.3 Cellular V2X architecture

C-V2X architecture strictly relies on an already existed cellular architecture (LTE architecture or further LTE architecture versions as LTE Advanced or LTE Advanced Pro) but introducing some new functional entities that I will investigate in deep details in the following sections.
C-V2X can support a wider range of capabilities than earlier dedicated vehicle connectivity solutions, which are generally based on a Wi-Fi variant, 802.11p. C-V2X employs two complementary transmission modes to enable a very broad range of driving safety features. These two modes are namely over the PC5 and over LTE-Uu interfaces. LTE-Uu can be unicast and/or Multimedia Broadcast Multicast Service (MBMS). These two operation modes may be used by a UE independently for transmission and reception. For instance, a UE can use MBMS for reception without using LTE-Uu for transmission. A UE may also receive V2X messages via LTE-Uu unicast downlink [2].
For both operation modes, there are some fundamental principles to take in consideration especially when building a C-V2X network.

- The interface between V2X Application Servers and the methods of the exchange of messages between V2X Application Servers is out of scope of 3GPP.

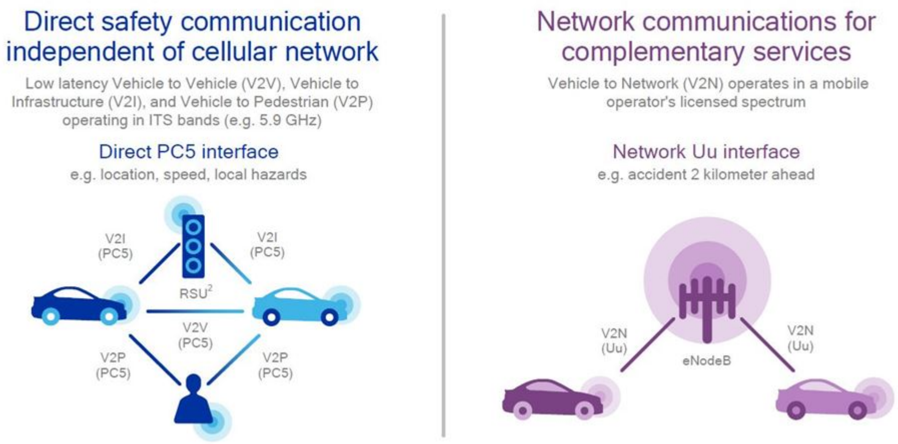

Figure 2.17: C-V2X modes of operation. Image courtesy of Qualcomm.

- ProSe discovery feature is not required for V2X Services.
- An RSU is not an architectural entity, but an implementation option. This is achieved by collocating a V2X application logic/server with some entities of the 3GPP system.

It is important to note that:

- ProSe discovery feature can be used by a V2X supporting UE, but that is up to UE implementation and not to the protocol itself;
- ProSe discovery feature service is subject to regional regulations, lawful interception requirements apply to V2X Services;
- an RSU is not an architectural entity, but an implementation option. This is achieved by collocating a V2X application logic/server with some entities of the 3GPP system.

In figure 2.18 we can observe the overall architecture of V2X system and how it integrates with the LTE architecture. Most of the functional blocks are kept as in 4G architecture. There are some new fundamental blocks such as *V2X Control Function* and *V2X Application Server* and other minor blocks that will be discussed in the following sections [2].

2.3.4 Multimedia Broadcast Multicast Services

The term Multimedia Broadcast Multicast Services (MBMS) has already been mentioned and it deserves a separate description because of its importance in the LTE networks and consequently in the C-V2X one.

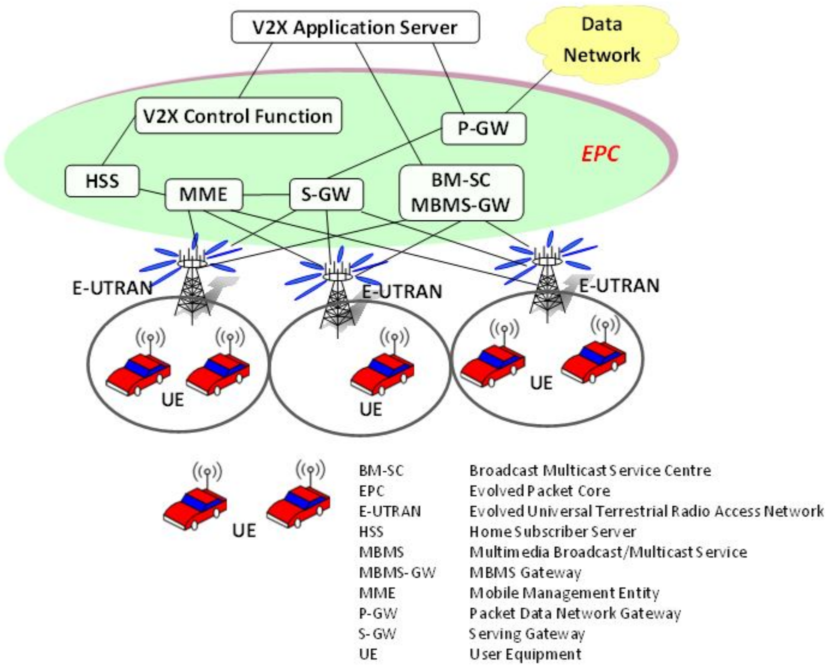

Figure 2.18: Overall cellular V2X architecture. Image courtesy of The 3G4G Blog.

Multimedia Broadcast Multicast Services (MBMS) is a point-to-multipoint interface specification for existing and upcoming 3GPP cellular networks, which is designed to provide efficient delivery of broadcast and multicast services, both within a cell as well as within the core network. For broadcast transmission across multiple cells, it defines transmission via single-frequency network configurations. when transmissions are delivered through an LTE (Long Term Evolution) network the specification can be referred as Evolved Multimedia Broadcast Multicast Services (eMBMS). eMBMS is also known as LTE Broadcast [13].

As we see from figure 2.19, there are four main network components responsible for Multimedia Broadcast Multicast Services.
The *Broadcast multicast service center (BMSC)* is located at the core of the network, managing the interface with content providers including billing and the content to be transmitted over the wireless network.
MBMS gateway (MBMS-GW) is a logical element that delivers MBMS traffic using IP-multicast reaching multiple cell sites in a single transmission.
Multi-cell/multicast coordination entity (MCE) is responsible for the administration of radio resources for MBMS to all radios that are part of the MBMS service area.
The mobility management entity (MME) which performs the MBMS session control

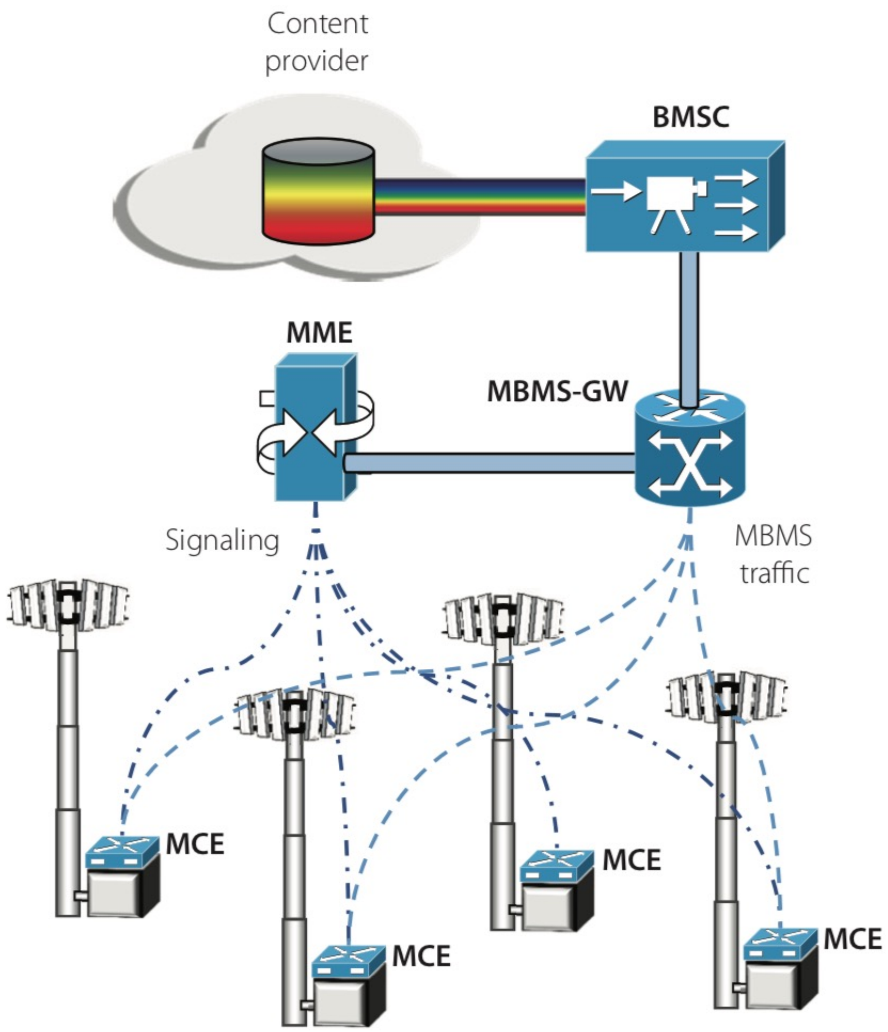

Figure 2.19: MBMS network architecture [13].

signaling including session start, update, and stop, as well as delivering additional MBMS information to the MCE including QoS and MBMS service area.
MBMS provides broadcast multimedia services through the LTE network combining unicast (PDSCH) and multicast (PMCH) services in LTE radio the same LTE frame [13].

2.3.5 C-V2X functional entities

The main functional entities of the C-V2X architecture are [2]:

- V2X Control Function
- V2X Application Server
- MME
- BM-SC
- MBMS-GW
- UE

The *V2X Control Function* is the logical function that is used for network related actions required for V2X. According to the standard there is only one logical V2X Control Function in each PLMN that supports V2X Services. If multiple V2X Control Functions are deployed within the same PLMN (for example for load reasons), then the method to locate the specific V2X Control Function (through a database lookup, etc.) is not defined by the standard specification.
V2X Control Function is used to provision the UE with necessary parameters in order to allow the V2X communication. Its implementation is then fundamental for the overall architecture.
It is used to provision the UEs with PLMN specific parameters that allow the UE to use V2X in the specific PLMN. It is also used to provision the UE with parameters that are needed when the UE is *not served by EUTRAN* (e.g. the UE is out of network coverage). It may also be used to obtain V2X USDs for UEs to receive MBMS based V2X traffic, through V2 reference point from the V2X Application Server [2].

The *V2X Control Function Discovery* in a specific HPLMN happens through interaction with the Domain Name Service function. The FQDN of a V2X Control Function in the Home PLMN may either be pre-configured in the UE, provisioned by the network or self-constructed by the UE, i.e. derived from the PLMN ID of the HPLMN). The IP address of a V2X Control Function in the Home PLMN may also be provisioned to the UE [2].

The *V2X Application Server* is another important actor in the Vehicle-to-Everything communication. His role is normally to deliver and receive data to/from the UE over Unicast or MBMS. Altought it supports also other features and capabilities [2]:

- Receiving uplink data from the UE over unicast.
- Delivering data to the UE(s) in a target area using Unicast Delivery and/or MBMS Delivery.
- Mapping from geographic location information to appropriate target MBMS SAI(s) for the broadcast.

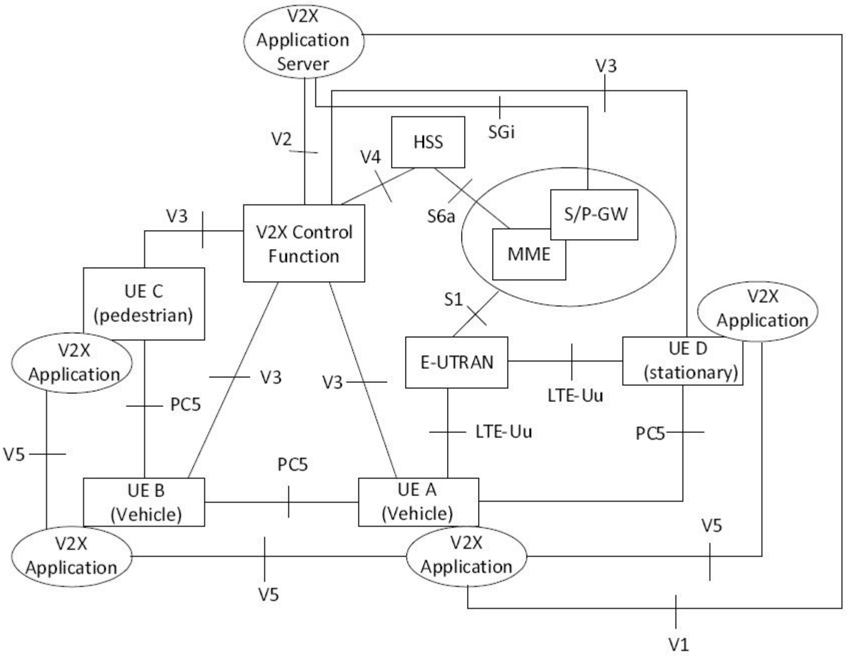

Figure 2.20: Non-roaming reference architecture for PC5 and LTE-Uu based V2X communication [2].

- Mapping from geographic location information to appropriate target 3GPP ECGI(s) for the broadcast.
- Mapping from UE provided ECGI to appropriate target MBMS SAI(s) for the broadcast.
- Providing the appropriate ECGI(s) and/or MBMS SAI(s) to BM-SC.
- Pre-configured with Local MBMS information (e.g. IP multicast address, multicast source (SSM), CTEID).
- Pre-configured with Local MBMS's IP address and port number for the user-plane.
- Sending Local MBMS information to the BM-SC.
- Requests BM-SC for allocation/de-allocation of a set of TMGIs.
- Requests BM-SC for activating/deactivating/modifying the MBMS bearer.
- Providing the V2X USDs for UE to receive MBMS based V2X traffic to V2X Control Function.

The *UE* in a C-V2X network is a vehicle that is user by end-user (the driver) to communicate with other vehicles equipped with the same technology.
The UE may support the following functions [2]:

- Exchange of V2X control information between UE and the V2X Control Function over the V3 reference point.
- Procedures for V2X communication over PC5 reference point and/or LTE-Uu reference point.
- Configuration of parameters for V2X communication (e.g., destination Layer-2 IDs, radio resource parameters, V2X Application Server address information, mapping between service types and V2X frequencies). These parameters can be pre-configured in the UE, or, if in coverage, provisioned by signaling over the V3 reference point from the V2X Control Function in the HPLMN.
- Provided with V2X USDs for receiving MBMS based V2X traffic via existing MBMS service announcement mechanisms, or provisioned from V2X Control Function, or provisioned from the V2X Application Server via V1 reference point.
- Provisioned with V2X Server USDs for receiving V2X Application Server information via MBMS.

The *Mobility Management Entity (MME)*, in case the V2X architecture is deployed, performs the following functions [2]:

- obtains subscription information related to V2X as part of the subscription data;
- provides indication to the E-UTRAN about the UE authorization status on V2X use.

In case of V2X the *BM-SC* performs the following functions [2]:

- Receives Local MBMS information from V2X Application Server.
- Sends Local MBMS information to the MBMS-GW.

In case of V2X the *MBMS-GW* performs the following functions [2]:

- If receiving Local MBMS information from the BM-SC, skipping the allocation procedure for IP multicast distribution, e.g., allocating an IP multicast address.

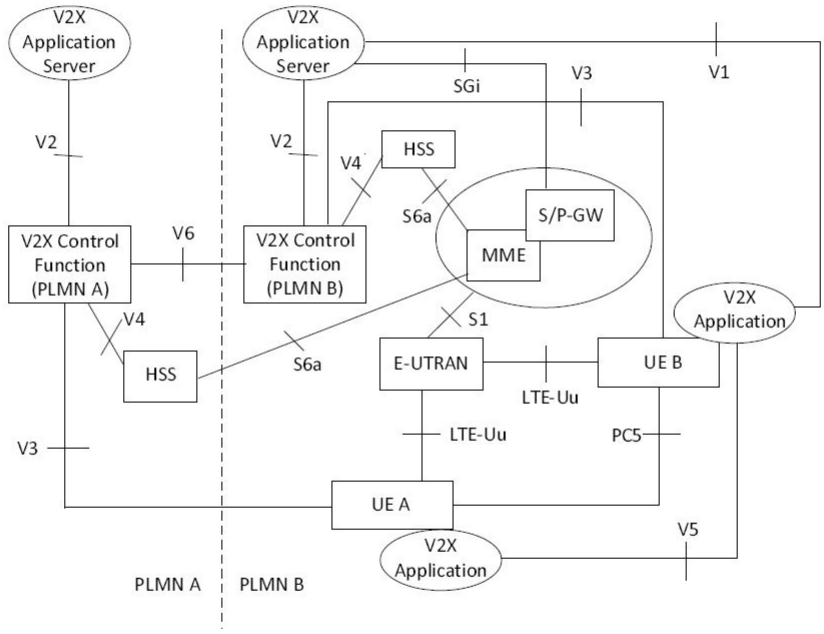

Figure 2.21: Roaming reference architecture for PC5 and LTE-Uu based V2X communication [2].

2.3.6 C-V2X interfaces

Table 2.5 represents a complete list of all interfaces present in the LTE Advanced cellular network. As we have already said the C-V2X network can use and exploit ProSe features (technology available for LTE networks) [3]. The actual interfaces names could be different in the C-V2X standard architecture, altought they have the same role and they can be considered equal.
For a complete comparison, please refere to figure 3.3 in chapter 3.

2.3.7 C-V2X communications overview

The basic principles of *service authorization* for V2X communications over PC5 reference point [2]:

1. the UE gets authorization to use V2X communications over PC5 reference point on a per PLMN basis in the serving PLMN by the V2X Control Function in the HPLMN,

2. the V2X Control Function in the HPLMN requests authorization information from the V2X Control Function of the serving PLMN,

3. the V2X Control Function in the HPLMN merges authorization information

Interface	Description
PCI	It is the interface between the UE ProSe application and the ProSe Application Server. It is used to provide the level signalling requirements definition.
PC2	It is the interface between the ProSe Application Server and the ProSe Function. It is used to define the interaction between ProSe Application Server and ProSe functionality. The ProSe Function use this interface to supports EPC-level discovery by the following functionalities: - Storage of a list of applications that are authorized to use EPC-level ProSe Discovery. - Exchange of signalling with 3rd party Application Servers for application registration and identifier mapping.
PC3	The reference point between the UE and the ProSe Function. It is based on IP protocol and used for the ProSe Direct Discovery authorisation and to define the authorisation policy per PLMN for ProSe Direct Discovery and communication between UE and ProSe Function.
PC4a	The reference point between the HSS and ProSe Function. It is responsible to manage the subscription information and access authorisation for ProSE Direct Discovery and ProSE Direct Communication. The PC4a interface is based on Diameter protocol. Over The PC4a interface, Diameter messages over the PC4a interface shall make use of SCTP IETF RFC 4960.
PC5	ProSe UEs are interconnected with each other by means of PC5 interface that is based on "ProSE protocol" that is used for handling ProSe Direct Discovery.
PC6	The reference point between two ProSe Functions located in different PLMNs. This interface is used for the ProSe service and ProSe Direct Discovery requests authorization.
PC7	Interconnected the visited ProSe Function and the home ProSe Function. It is used to control ProSE service authorisation in the home ProSe Function.

Table 2.5: Interfaces and Reference Points for D2D architecture under LTE Advanced network. The D2D technology can be used in a cellular V2X network over the PC5 interface [2] [3].

from home and serving PLMNs and informs the UE of the final authorization information,

4. the V2X Control Function in the VPLMN or HPLMN may revoke the authorization at any time. The V2X Control Function in the HPLMN shall be notified when authorization is revoked by the VPLMN.

The authorization to use V2X services is very important in this kind of network because if absent or revoked it can be the cause of a UE of not joining the network itself.
Besides the Authorization policy there are also some radio parameters that are requested for when the UE is not served by E-UTRAN. They includes the radio parameters with Geographical Area(s) and an indication of whether they are *operator managed* or *non-operator managed*. These radio parameters (e.g. frequency bands) are defined by standard. The UE uses the radio parameters to perform V2X communications over PC5 reference point when not served by E-UTRAN only if the UE can reliably locate itself in the corresponding Geographical Area. Otherwise, the UE is not authorized to transmit. Whether a frequency band is operator managed or non-operator managed in a given Geographical Area is defined by local regulations.
For V2X communication over PC5, the operator may pre-configure the UEs with the required provisioning parameters for V2X Communication, without the need for the UEs to connect to the V2X Control Function to get this initial configuration. In this way the UE get the authorization to use V2X services immediatly and can communicate outside the network coverage over PC5 interface.
Additional information may be provisioned to the UE for the use of V2X communications over LTE-Uu reference point, for example for unicast or MBMS [2].

Transmission/reception over PC5 reference point

The PC5 reference point is used by the UE to communicate in a V2X network, specifically for transmission and reception of V2X messages. Messages types depends on the standard in use (for example ETSI) and the kind of application (V2I, V2V, I2V, V2N).
PC5 communication supports roaming and inter-PLMN operations. As I have previously said V2X communication over PC5 reference point is supported when the UE is served by E-UTRAN and also when the UE is not served by E-UTRAN (out of coverage situation).
The V2X communication over PC5 reference point is a type of ProSe Direct Communication (further details about ProSe are provided in chapter 3) with the following characteristics [2]:

- the V2X communication over PC5 reference point is connectionless, and there is no signaling over PC5 control plane for connection establishment;

- V2X messages are exchanged between UEs over PC5 user plane;
- both IP based and non-IP based V2X messages are supported.
- for IP based V2X messages, only IPv6 is used.

Transmission/reception over LTE-Uu reference point

The LTE-Uu reference point is used for the transmission and reception of V2X messages. The V2X message transmission and reception can be via unicast, while the V2X message reception can be via MBMS [2].

A UE needs to discover the V2X Application Server(s), when V2X communication over LTE-Uu operation mode is used. The V2X Application Server address information may be configured on the UE or provisioned via V3 interface.
When the configuration contains the FQDN(s), the UE shall perform DNS to resolve the address(es) of the V2X Application Server. The UE may use the configured V2X Application Server information only in the designated geographical area. When the UE changes serving PLMN or crosses configured geographic areas, it should perform address resolution again.
For a network that has deployed broadcast mechanisms (MBMS for instance) additional information to assist V2X Application Server discovery can be provided via the MBMS broadcast channel. When a UE has the configuration for receiving V2X Application Server information via MBMS, it can perform the procedures to obtain additional local V2X Application Server information.
Multiple V2X Application Servers may be involved in the V2X communication, each providing particular V2X services and/or serving a particular geographical region. Therefore, the V2X Application Server address information can contain multiple servers' information. When multiple V2X Application Servers are configured, the application layer will choose the proper V2X Application Server to use.
When localized V2X Application Servers are deployed, Anycast may be used to conceal the server change from the UE. In this case, a FQDN is configured for a large region, e.g. the entire PLMN, and the UE only needs to resolve it once to an Anycast address. The PDN GW or LGW is responsible for routing the traffic to the appropriate local V2X Application Servers based on Anycast address [2].

Figure 2.22 represents the procedures for receiving V2X Application Server information via MBMS.

1. When a UE desires V2X communications via LTE-Uu, it attaches to the serving PLMN if it has not done so.
2. If the UE has configuration for receiving V2X Application Server information via MBMS, it receives the local Service Information from the corresponding

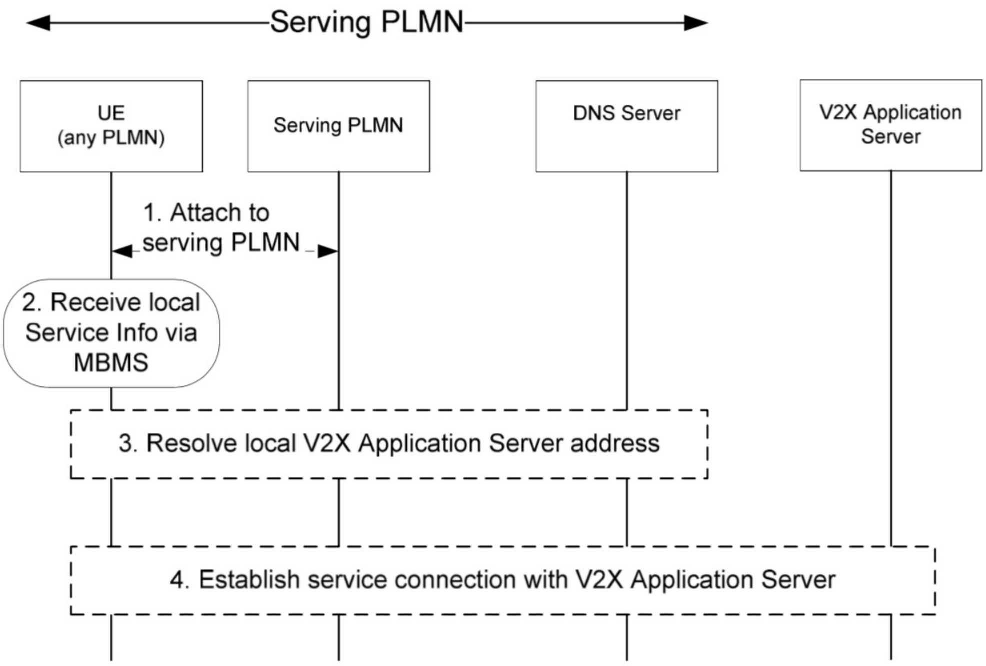

Figure 2.22: V2X Application Server discovery using broadcast [2].

broadcast traffic channel. The local Service Information includes the address information of the local V2X Application Servers, e.g. the FQDNs of the servers. In addition, the local Service Information may include the V2X USD for the corresponding V2X Application Servers, if MBMS downlink is to be used.

3. Based on the information received from step 2, the UE obtains the local V2X Application Server address, e.g. via a query of the DNS with the received FQDN.

4. The UE may establish connection with the V2X Application Server for the service, e.g. obtaining the V2X USD if it is not provided in step 2 to allow the UE to receive V2X messages over MBMS.

Subscription to V2X services

The user's profile in the HSS contains the subscription information to give the user permission to use V2X services. At any time, the operator can remove the UE subscription rights for V2X services from user's profile in the HSS, and revoke the user's permission to use V2X services [2].
The following subscription information is defined for V2X services:

1. whether the UE is authorized to perform V2X communication over PC5 reference point as Vehicle UE, Pedestrian UE, or both,
2. UE-PC5-AMBR for V2X communication over PC5 reference point,
3. the list of the PLMNs where the UE is authorized to perform V2X communication over PC5 reference point.

The HSS provides 1) and 2) to MME as subscription information and the MME provides 1) and 2) to eNodeB as part of the UE context information.
The HSS provides 3) to V2X Control Function [2].

Chapter 3

D2D for Cellular V2X

3.1 Introduction to D2D

In this chapter I will mainly focus on D2D technology for vehicular networks introduced by Cellular V2X. This technology, already present in LTE, is highly exploited by this new vehicular network. Altought, in order to do so it is necessary to observe closely the device-to-device communications principles.
D2D (device-to-device) communications are direct communications between devices in short range proximity without the support (or total support) of any network infrastructure. As the location-based communications, D2D communications benefit from the geographical and radio proximity of devices in order to establish a direct link between them for a local data exchange. Basically, devices could be any device equipped with a D2D technology suitable for short range communication (e.g. Bluetooth, Wi-Fi Direct), such as smartphones, tablets, laptops, network printers, cameras, or even connected vehicles.
In the LTE networks, D2D is a new communication mode that gives the user device a different role in the network and even more network capabilities than what it used to have in the past. The device is no longer a passive node in the communication process, but it is rather an active network node that can perform some network functions like *relaying*, *routing* and *cooperation* with its D2D neighbours [14].

3.2 Technologies and use cases

3.2.1 Technologies

D2D communications already exists since a decade within mobile services and they are based on some well-known short range technologies, such as Bluetooth and Wi-Fi Direct.
While these technologies are not suitable for future generation of mobile networks

mainly because of their range limitations, LTE-based D2D services, instead, are becoming the new trend. These new services use a new LTE short range radio called *LTE Direct* in the device. Therefore, LTE Direct is a D2D technology that uses licensed LTE spectrum for proximal discovery of friends, services, offers, and other relevant data.
The ultra-low latency in the communication is surely one of the main benefits of D2D and it is due to a shorter signal traversal path. Wireless technologies like Bluetooth, WiFi Direct and LTE Direct (defined by the Third Generation Partnership Project from Release 12) can be used to enable D2D communication and they differ mostly in the data rates, distance between 1-hop devices, device discovery mechanisms and typical applications.
For instance, Bluetooth 5 supports a maximum data rate of 50 Mbps and a range of 240 meters, WiFi Direct allows up to 250 Mbps rate and 200 meters range, while LTE Direct provides rates up to 13.5 Mbps and a range of 500 meters [14].
In table 3.1 and 3.2 we can see the main differences between the most used D2D technologies [14].

D2D connectivity will make operators more flexible in terms of offloading traffic from the core network, increase spectral efficiency and reduce the energy and the cost per bit.

3.2.2 Use cases

Significant attention has been dedicated to device-to-device services recently. Mobile operators and Telecommunication industrials present multiple attractive in use cases of new services, from public/commercial services to more specific fields like public safety and military. A list of the main use cases can be observed in table 3.3 [14].

Commercial activity are deeply involved in several D2D use cases, for example Social Proximity Services. Vehicular network represents one of the many Public Safety Services. More detailed D2D features/use cases are enlisted below [14].

- *Local data services*
  D2D communication can support local data services very efficiently through Unicast, Groupcast and Broadcast transmissions.

- *Information sharing*
  UEs can leverage D2D links to transfer files, audios and videos with higher data rates and lower energy than those in conventional cellular channels. They facilitate streaming services like Google Chromecast, IPTV, etc. by forming clusters and groupcasting data within a cluster. They also aid in other proximity services like public safety. D2D links can operate unimpeded in a disaster-hit area where all BSs (base stations) are paralyzed.

	Wi-Fi Direct	Bluetooth
Range (nominal)	50 m	10 m
Scalability	Fair (current), Good (evolved)	Fair (v2.1 - v3.0), Good (v4.0)
Discovery energy consumption	Fair with reduced exchange of management frames (evolved)	High (up to v.3.0), Low(v.4.0)
Reliability	Sometimes poor due to asynchronous channel scan (current), potentially good except in high load (evolved)	Good for Bluetooth v4.0 due to dedicated advertising channels
Security	Natively weak - discovery is unencrypted and no trusted authentication of device identification	Same as Wi-Fi Direct
Interoperability	Potentially good but potential issue with legacy device	Good for dual-mode v4.0. Poor for "v4.0 only" devices, issues with legacy devices
Market (expected)	More than 2 billion shipments in 2016, but some dependency on full support for stack at OS level	More than 2 billion shipments of dual mode v4.0 and 1 billion single mode v4.0 devices in 2015

Table 3.1: Comparison of the main D2D technologies (I) [14].

	LTE Direct
Range (nominal)	50 to 500 m
Scalability	Potentially very good
Discovery energy consumption	Potentially low due to dedicated resources and synchronous operation
Reliability	Potentially good due to dedicated discovery resources
Security	Potentially strong with cellular network-enabled authentication of device identification
Interoperability	Potential issue with discovery between devices from different operators
Market (expected)	Currently unclear time to market, probably not before 2020

Table 3.2: Comparison of the main D2D technologies (II) [14].

- *Data and computation offloading*
  A device with a good Internet connectivity can act as a hotspot to which data is offloaded/cached from the BS and from which other devices may download data using D2D links. UEs having poor processing power or low energy budgets may also offload computation-heavy tasks to nearby more capable UEs using D2D links. Considerable research has gone into design of offloading techniques.

Use case category	Applications
Commercial and Social Proximity Services: An evolution of LBS services through hyper-local and dynamic proximity data.	Discovery-centric services: Context-aware applications, Social networking applications, location enhancement applications, Social gaming, and smart cities services... Communication-centric services: content and video sharing services
Public safety services based on group and relay communications: Secure services used on specific D2D enabled devices and deployed on a dedicated non-public network	Direct communication between public safety agents in or outside network coverage: push-to-talk, group communication, priority handling... Dedicated network access sharing for out of coverage devices through peer-to-peer connections to nearby in-coverage devices.
Services for network capabilities enhancement	Offloading services: offload of local data traffic or video/voice call traffic. Multi-hop access services: Internet connection sharing through devices acting as relays, Connectivity extension to heterogeneous networks (UE acting as a gateway to a Sensor network, UE in a vehicle acting as a cooperative relay to a vehicular network infrastructure, etc.)

Table 3.3: D2D use cases classification [14].

- *Coverage extension*
  A UE X (e.g., at the cell edge or in a disaster-hit area) may encounter poor signal quality while connecting to the BS. A UE Y close to it that has, however, a better link to the BS may act as a relay for it. Thus a D2D link X - Y followed by a cellular link Y - BS connects X to the BS.

- *Machine-to-machine (M2M) communication*
  M2M communication is an enabling technology for Internet of Things (IoT). It involves autonomous connectivity and communication among devices ranging from embedded low-power devices to powerful compute-rich devices. D2D connections can be used to establish M2M communication in IoT since they

afford ultra low latency and hence, real-time responses. A particular application is vehicle-to-vehicle (V2V) communication where D2D links can be utilized to share information between neighbouring vehicles quickly and offload traffic efficiently. They can also be used for vehicle-to-infrastructure and vehicle-to-pedestrian communication. C-V2X exploits the D2D M2M communication for V2V, V2I and V2P.

3.2.3 D2D modes

D2D working modes represents one of the largest research topic about D2D. For years mobile operators put their interests on them and developed mainly 2 communication modes. Two modes are available: the D2D *distributed mode* and the D2D *network-assisted mode* [15].

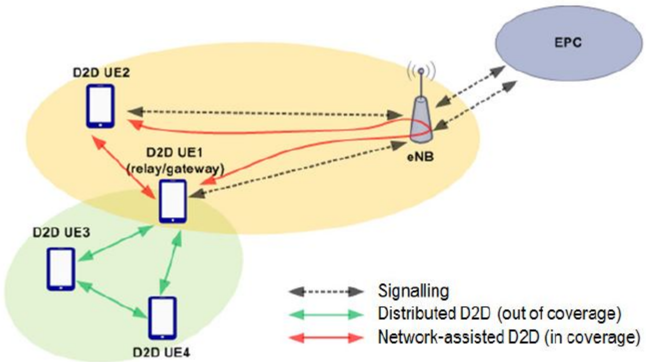

Figure 3.1: D2D communication modes [15].

In the distributed mode the devices are organized in a completely distributed and self-organizing network without the control of any network infrastructure. Usually, the communications between the devices in this mode are out of coverage. Devices are preconfigured to use a specific D2D radio band that is licensed by a mobile operator for this usage. This mode is generally used in situations where the network coverage is unavailable (e.g. rescuing operation in caves, earthquake, tsunami, network failure and general public safety situation).
Considered as the next evolution of TETRA networks, it is commonly dedicated to Public safety services using protected radio frequencies and special devices that are configured to work in the D2D distributed mode.
As depicted in figure 3.1, a network infrastructure is involved in the control of D2D communications in network-assisted mode. This results in either a fully-controlled scheme or a loosely controlled scheme. The D2D network-assisted fully-controlled

scheme implies a total control from the operator on the D2D communication establishment process. In the loosely-controlled scheme, the network infrastructure partially intervene in the D2D communication establishment process such as for users authentication, authorization or service registration. Besides, in a D2D network-assisted mode, devices are under the network coverage and may use a licensed or an unlicensed band according to the operator policy and legislation [15].

3.2.4 D2D communication mechanisms

In a D2D communication, we distinguish two main phases: the *discovery phase*, in which a device discovers other devices in its surrounding, and a *data communication phase* in which D2D peers setup a D2D link for the data exchange [16].

D2D discovery

The D2D discovery phase can be done in a direct way or assisted by the network. Therefore, 2 approaches are possible [16].

- *Direct discovery approach*
  According to the 3GPP standard on Proximity-based Services (ProSe), two direct discovery models were identified: the *I'm here* model (A) and the *who is there? /are you there?* model (B). In addition, a device performs the direct discovery of its surrounding according to a discovery role: the announcing role in which the device is in an active discovery mode and announces its presence and the service it is offering, and the monitoring role in which the device is more in a passive mode and only monitors from its surrounding specific information and services related to its fields of interest.
  The Direct discovery approach has the advantage of flexibility and scalability as it profits from the local radio and positioning information of the devices to discover their neighbourhood in a more efficient way. The radio resources for this discovery mode can be either allocated by the network (from the eNodeB) if the devices are under the network coverage, or preconfigured on specific devices (for example in public safety devices) if the devices are out of the network coverage.

- *Centralized discovery approach*
  This approach has been considered in some research studies and mostly by the ProSe standard. It involves at least one or more network entities in the discovery procedure. It is an operator business oriented approach for the D2D discovery that highlights particularly the role of the mobile operator as a provider of context and proximity information in the discovery phase. Thanks to the wider vision of the mobile operator on the overall traffic and on the user device mobility context, centralized discovery approaches aim at exploiting

mobile operator core network assets about devices micro/macro mobility in order to provide a more accurate and efficient discovery information. It is to note that this discovery approach exceeds the basic definition of D2D as an infrastructure-less communication between two devices. Nevertheless, it is considered as one alternative discovery model for Proximity Services by the 3GPP.

D2D data communication

After the D2D discovery phase, D2D peers need to establish a communication link for data exchange. When the establishment of such a link is triggered by the network in order to reduce the network overload. This process is known as *offloading* and is defined as the fact of using alternative access technologies than the cellular one to exchange data between mobile devices. Similarly to the D2D discovery phase, the offloading can be done using two approaches [16].

- *Direct D2D offloading*: the data are routed between the devices directly using the D2D radio interface and does not cross the network infrastructure.
- *Controlled D2D offloading*: the data are routed between D2D devices using an optimized data path (e.g. through the eNodeB).

Based on these two offloading schemes, the data communication between devices could be *Best-Effort* (no QoS support, connectionless links) or *QoS-enabled* (establishment of dedicated LTE data bearers).
In a classic LTE communication, data flows between two devices are setup through the establishment of data bearers. A data bearer is composed of a radio bearer between the device and the eNodeB, an EPC (Evolved Packet Core) bearer between the eNodeB and the Core network and packet filters in the devices. The establishment of a data bearer consists on the setup of a PDN (Packet Data Network) connection with the PDN Gateway and the allocation of an IP address for the communicating devices.
In a D2D Direct communication scheme, the establishment of LTE data bearers between devices may not be needed; the data are exchanged directly on the radio link between the devices and only MAC layer addressing is used to identify the source and the destination of the data packets [16].

3.3 3GPP Proximity-based Services (ProSe)

What I will focus now will be the LTE Direct D2D because, as we already mentioned, this is the base of the D2D mechanism used for C-V2X and to make communicate vehicles among theirself. In the following section a state of the art of the

standardized LTE Direct service will be given.
I will provide a description of the ProSe architecture basic features, components and procedures, mainly those related to ProSe Direct Discovery and Direct Communication in non-roaming scenario with a single PLMN.

3.3.1 Coverage scenarios

In 3GPP Release 12, completed on-time in March 2015, device-to-device communication, or ProSe communication, is limited to the public safety usage. According to the associated requirements, ProSe communication has to work in regions, where network coverage cannot be guaranteed. Therefore, ProSe communication is specified for the following scenarios (figure 3.2) [15].

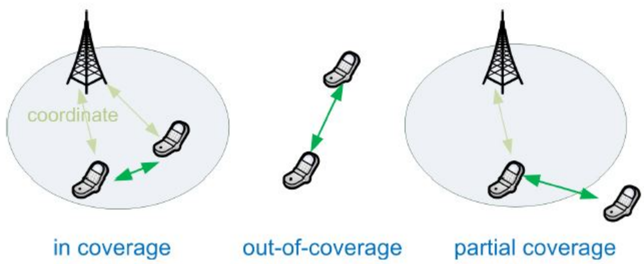

Figure 3.2: Coverage scenarios for ProSe communication [15].

In the *in coverage* scenario, the network controls the resources used for ProSe communication. It may assign specific resources to a transmitting UE, or may assign a pool of resources the UE selects from. This way, interference with the cellular traffic is avoided and in addition the ProSe communication may be optimized.
For the *out-of-coverage* case such a control is not possible. The UE uses resources which are preconfigured, either in the mobile device or in the USIM of the UICC card. However, the term out-of-coverge has to be interpreted carefully. It does not mean that there is no coverage at all. It rather means that there is no coverage on the frequency used for ProSe direct communication, although the UE might be in coverage on a different carrier for cellular traffic.
A special case is represented by the *partial coverage* case. The UE out-of-coverage uses the preconfigured values, whereas the UE in coverage gets its resources from the eNodeB. A careful coordination between the network and the preconfigured values is necessary in order to enable communication and to limit the interference to UEs at the cell boundary near an out-of-coverage UE [15].

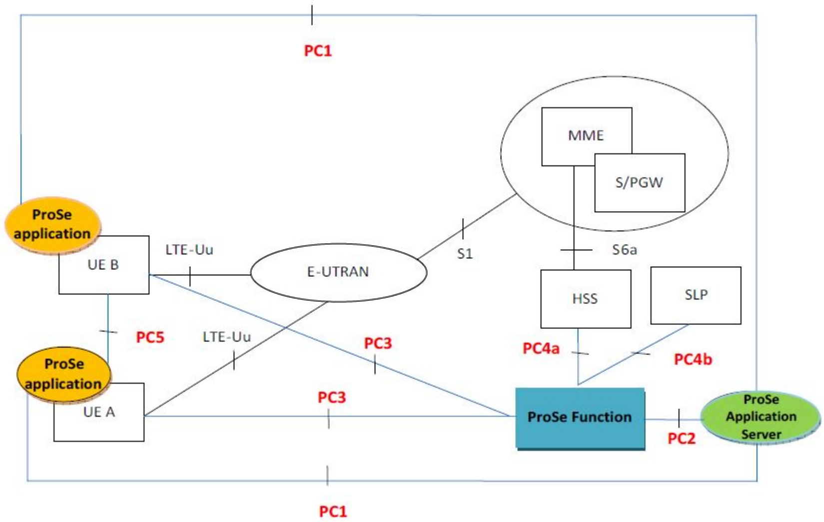

Figure 3.3: ProSe non-roaming reference architecture [16].

3.3.2 ProSe architecture

First introduced in Release 12 of the 3GPP, ProSe (Proximity Services) is a D2D technology that allows LTE devices to detect each other and to communicate directly. We can define it as a set of new features and mechanisms introduced as enhancements to the Evolved Packet System (EPS) architecture to support Proximity-based Services in 4G and future 5G networks. The ProSe enablers for the support of LTE-based D2D services consist mainly of the following features [14]:

- *ProSe Direct discovery*: this function defines the procedures and mechanisms used to identify ProSe-enabled UEs that are in proximity using E-UTRAN. It corresponds to the D2D direct discovery which could be performed according to two discovery models: the model A *I'm Here* and the model B *who is there? /are you there?*.

- *EPC-level ProSe Discovery*: this function defines the procedures and mechanisms used to identify ProSe-enabled UEs that are in proximity using EPC. It corresponds to network-assisted D2D discovery in the fully-controlled scheme.

- *ProSe Direct communication*: this function consists on the procedures and mechanisms that enable the establishment of communication paths between two or more ProSe-enabled UEs who are in direct communication range. The ProSe Direct Communication path could use E-UTRAN or WLAN. The direct communication through E-UTRAN is currently dedicated by the standard to Public Safety cases.

- *ProSe UE-to-Network relay*: this function consists on the procedures and mechanisms to implement for a ProSe-enabled UE that is in E-UTRAN coverage to serve as a network relay for one or more ProSe-enabled UEs that are out of E-UTRAN coverage. This function is currently dedicated by the standard to Public safety usages.

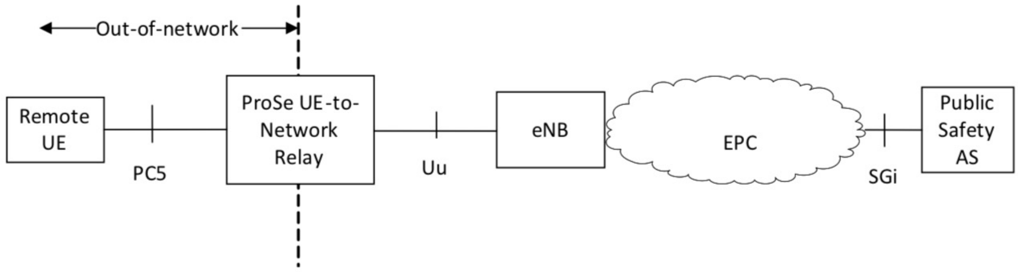

Figure 3.4: ProSe UE-to-Network Relay [16].

In figure 3.3 we can see the ProSe non-roaming architecture in which only the home PLMN is considered. The main logical components are coloured and they are:

- the ProSe Function,
- the ProSe Application Server,
- the ProSe Application.

We can note the similarity with the C-V2X non-roaming architecture. The latter one is analogous to the ProSe architecture and it takes the main elements and adapt them for a vehicular communication network [14].

The ProSe Function

As seen in figure 3.3, the ProSe architecture introduces a new entity in the EPC called ProSe Function. The ProSe Function is a User plane level server entity which main role is to provide ProSe configuration and authorization to ProSe-enabled UEs and to manage the ProSe context of the UEs, similarly to the V2X Control Function. It is located outside the EPC and is connected to its different entities by the mean of reference points called *PCx*. These reference points define the protocol and the set of information to exchange between the ProSe function and the UEs and between the ProSe function and EPC entities. The PCx interfaces in figure 3.3 are described in details in table 2.5 and they are the same interfaces presented in the C-V2X architecture [14].

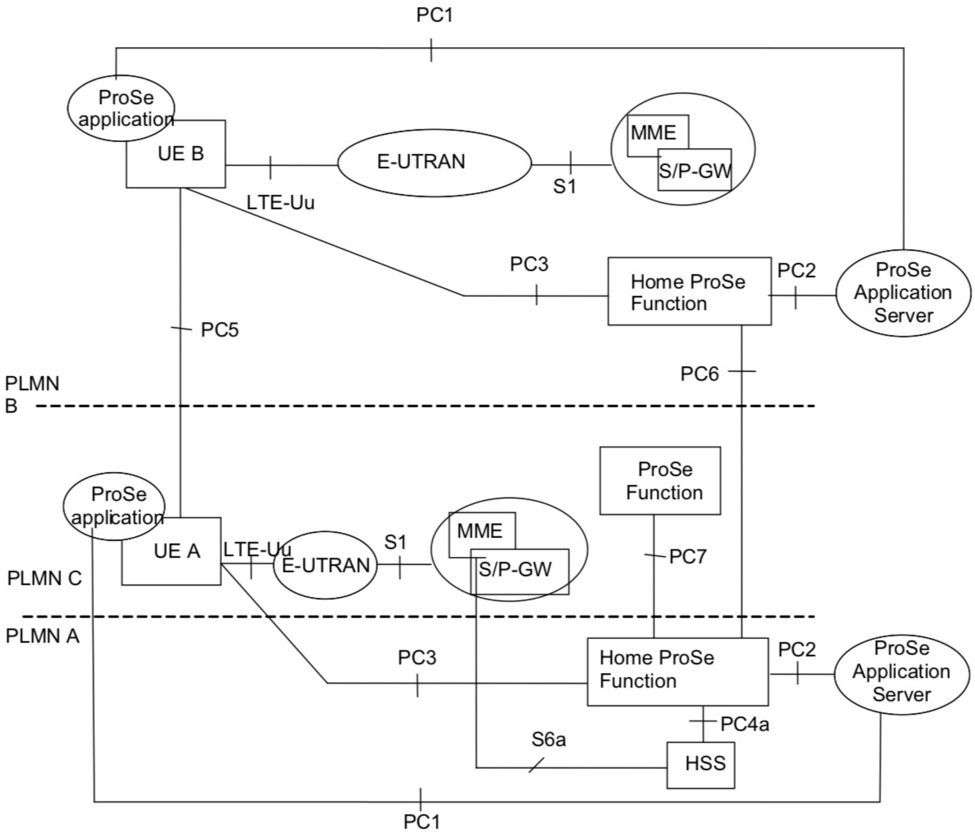

Figure 3.5: ProSe roaming reference architecture [16].

The 3GPP standard establishes one ProSe function per PLMN. It is the central entity that allows or not a ProSe-enabled UE to use a specific ProSe application. It is also the unique gateway to the ProSe Application server.

Several new interfaces have been introduced. From the UE point of view, the most important ones are the PC5 interface between two UEs and the PC3 interface between each UE and the ProSe Function.
For Release 12, the PC5 is a one-to-many communication interface, meaning that it is specified for group communication. From a higher layer point of view, this is reflected in the assignment of destination IDs, which are always group IDs.
Using the PC3 interface, the UE contacts the ProSe Function. The IP address of the the ProSe Function might be preconfigured (hard-coded) in the device. The alternative is, that the device identifies the IP address of the ProSe Function via DNS look-up. To contact the ProSe Function the device has to establish an RRC connection with the network. For the information exchange between the UE and the ProSe Function IP messages are used, HTTP Request and Response message, with its related syntax [16].

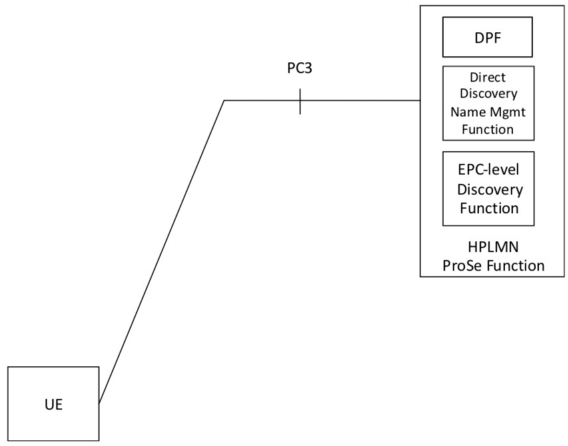

Figure 3.6: UE to ProSe Function interfaces for each sub-function [16].

From the ProSe Function the UE receives information for network related actions. This includes service authorization and provisioning of PLMN specific information. The authorization is always done on a per PLMN basis. However, the UE is not required to be registered in the PLMN in which it wants to do ProSe communication. The UE contacts the ProSe Function in its HPLMN, which in turn requests authorization information from the ProSe Function in the local PLMN. The authorization also comprises the information, whether and where the UE is allowed to perform ProSe communication when it is out-of-coverage [16].
In the PLMN specific information provisioning, the ProSe Function sends the following parameters to the UE:

- security parameters,
- group IDs,
- group IP multicast addresses, including the indication whether the UE shall use IPv4 or IPv6 for the group,
- radio resource parameters for usage in out-of-coverage scenarios.

It is always true that for public safety UEs these parameters may be preconfigured in the UE or UICC. If they are defined in both, the parameters from the UICC have precedence.

3.3.3 ProSe Service Authorization

The *ProSe authorization procedure* consists on giving or not to a ProSe-enabled UE the authorization to use a specific ProSe feature (e.g. ProSe Direct Discovery or

ProSe Direct Communication) based on its ProSe context information in the ProSe function or its ProSe subscriber information stored in the HSS.
A configuration phase in which the ProSe function provides certain ProSe information to the UE precedes this procedure. Such information are the authorization information for a list of PLMNs where the UE is authorized to perform ProSe direct discovery or Prose direct communication or both, in addition to information regarding out-of-coverage operations.
After the ProSe configuration, the UE perform ProSe service authorization with the ProSe function. The UE gets the service authorization for ProSe Direct Discovery or ProSe Direct Communication or both, with a given validity time, from the ProSe Function of the Home PLMN. The service authorization procedure is executed in the following cases [16].

- Before starting the setup of ProSe Direct Discovery or ProSe Direct Communication if the UE has no valid authorization information.
- When the UE already engaged in a ProSe Direct Discovery or ProSe Direct Communication changes its registered PLMN and has no valid authorization information for the new registered PLMN.
- When the service authorization expires.

The authorization procedure is made using *over IP* mechanisms and only IP connectivity is required to allow the UE to access the ProSe Function.

3.3.4 ProSe Direct Discovery

The *ProSe Direct discovery*, as described in 3GPP specification, consists on the exchange of discovery messages directly over the air between the UEs using the wireless LTE-direct interface. There are two types of ProSe Direct Discovery: open and restricted. Open direct discovery is performed when there is no explicit permission that is needed from the UE being discovered, whereas restricted direct discovery only takes place with explicit permission from the UE that is being discovered.
ProSe Direct Discovery can be a standalone service enabler that could for example use information from the discovered UE for certain applications in the UE that are permitted to use this information, for instance "find a taxi nearby" or "find me a coffee shop". Additionally, depending on the information obtained, the ProSe Direct Discovery can be used for subsequent actions such as initiating a ProSe Direct Communication. In order to enable a ProSe direct discovery service between two UEs, a service setup phase is required. This phase is needed in order to provision the UEs with the necessary credentials (e.g. ProSe application Codes and Filters) to use on the air interface for the direct discovery [16].

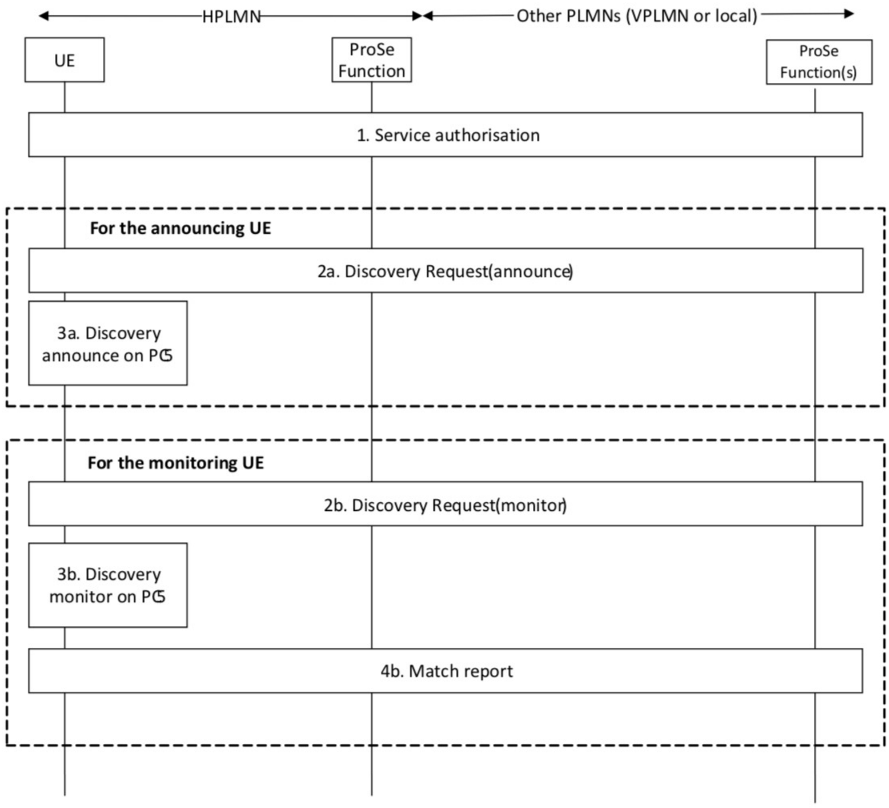

Figure 3.7: Overall procedure for ProSe Direct Discovery [16].

3.3.5 The PC5 protocol

PC5 is the protocol defined by the 3GPP specification ProSe standard for the ProSe Direct Discovery and it is used to define the format of direct discovery messages. The PC5 protocol is connection-less and no IP layer encapsulation is used: PC5 messages are sent directly over the MAC layer that handles source and destination address resolution [14].
ProSe-enabled UEs engaged in a Prose direct discovery procedure could have different roles according to the discovery model (model A or model B) and the type of direct discovery (open or restricted). Discovery models and roles are listed and explained in the table 3.4.

3.3.6 ProSe direct communication

The second main feature of ProSe architecture is the *ProSe direct communication*. It consists on defining the protocols and procedures that allow establishing a communication data path between two or more ProSe-enabled UEs that might have previously performed a ProSe direct discovery phase.

Discovery model	Discovery role	Role description	Applicable discovery type
Model A	Announcing UE	The device is in an active discovery mode and announces certain information that could be use by UEs in proximity that has the permission to discover.	Open and restricted discovery
	Monitoring UE	The UE is in a passive mode and monitors certain information/services of interest that are announced in its surrounding by announcing UEs.	
Model B	Discoverer UE	The UE transmits a request containing certain information about what it is interested to discover.	Restricted discovery only
	Discoverer UE	The UE that receives the request message can respond with some information related to the discoverer's request.	

Table 3.4: Prose Direct Discovery models and roles [16].

For this feature 3 different schemes have been proposed: ProSe one-to-one direct communication, ProSe one-to-many direct communication and ProSe UE-to-Network relay communication [14]. More generally, these schemes can be performed in two different modes:

- *Network independent direct communication.* This mode of operation does not require any network assistance to authorize the connection between the UEs. The communication is performed by using only UEs local functions and information. This mode is applicable only to pre-authorized ProSe-enabled Public Safety UEs and regardless of whether the UEs are served or not by E-UTRAN. It can take place to both ProSe one-to-one and one-to-many direct communication.

- *Network authorized direct communication.* This mode of operation always requires network assistance by the EPC to authorize the connection between the UEs. This mode is applicable to ProSe one-to-one direct communication and when both UEs are served by E-UTRAN. Only applicable to Public Safety UEs when only one UE is served by E-UTRAN.

The purpose of ProSe direct communication is mainly the offloading of EPC-based communication sessions to more appropriate ProSe communication paths based on the proximity information of the UEs and some other network criteria, such as: system-specific conditions (e.g. backhaul link, supporting links or EPC performance), cell-specific conditions (e.g. cell loading), ProSe and EPC Path conditions (e.g. communication range, channel conditions and achievable QoS) [14].

ProSe communication data paths

Considering the already known classic communication data path (through the eNodeB and the PDN-GW), ProSe has added two new communication data paths (see figure 3.8).

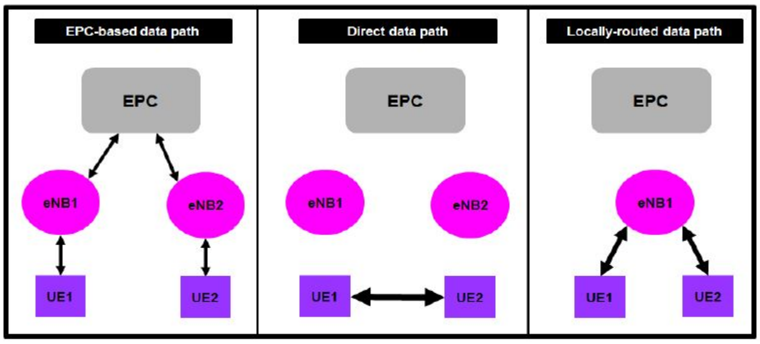

Figure 3.8: EPC-based data path vs. ProSe communication data paths [14].

With the direct data path the data is carried over direct links between the UEs, through to the PC5 interface and protocol).
The Locally-routed data path, instead, is locally-routed via one or more eNode without going through the PDN-GW [14].

ProSe communication control paths

Control paths have been used by ProSe on the previous mentioned scenario of figure 3.8. Different are the cases, as we see from figure 3.9.

1. UEs are served by different eNodeBs under network coverage. When the UEs involved in the ProSe Communication are served by different eNodeBs and are under network coverage, the system can decide to perform ProSe Communication using control information exchanged between the UE, eNodeB and the EPC (e.g. session management, authorization, security) as shown

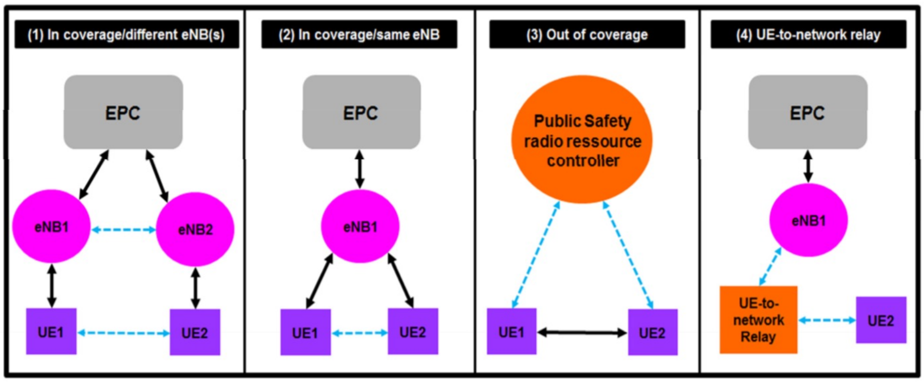

Figure 3.9: Control path schemes for ProSe communication [14].

by the solid arrows in (1) of figure 3.9. In this configuration, the eNodeBs may coordinate with each other through the EPC or communicate directly for radio resource management as shown by the dashed arrow between the eNodeBs. The UEs can in addition exchange control signalling via the ProSe Communication path as shown by the dashed arrow between UE1 and UE2 in the same figure.

2. UEs are served by the same eNodeB under network coverage. When the UEs involved in the ProSe Communication are served by the same eNodeB and are under network coverage, the system can decide to perform ProSe Communication using control information exchanged between the UE, eNodeB and the EPC (e.g, session management, authorization, security) as shown by the solid arrows in (2) of figure 3.9, or exchange control signalling via the ProSe Communication path as shown by the dashed arrow in the same figure.

3. UEs are out of the network coverage. If network coverage is not available, the control path can exist directly between Public Safety UEs, as shown with the solid arrow in (3) of figure 3.9. In this configuration, the Public Safety UEs can rely on pre-configured radio resources to establish and maintain the ProSe Communication. Alternatively, a Public Safety Radio Resource Management Function, which can reside in a Public Safety UE, can manage the allocation of radio resources for Public Safety ProSe Communication as shown with the dashed arrows in the same figure.

4. UE-to-Network relay. If network coverage is available to a subset of the UEs, one or more Public Safety UEs may relay the radio resource management control information for other UEs that do not have network coverage (see (4) of figure 3.9) [16].

ProSe one-to-one direct communication

ProSe One-to-one Direct Communication is defined in the ProSe standard as the establishment operation of a secure layer-2 link (e.g. MAC layer link) over the PC5 interface between two UEs. This mode of communication implies that each UE has a Layer-2 ID for unicast communication that is included in the Source Layer-2 ID field of every frame that it sends on the layer-2 link, and in the Destination Layer-2 ID of every frame that it receives on the layer-2 link. The layer-2 link for ProSe one-to-one Direct Communication is identified by the combination of the Layer-2 IDs of the two UEs. This means that the UE can engage in multiple layer-2 links for ProSe one-to-one Direct Communication using the same Layer-2 ID [16].

ProSe one-to-many direct communication

ProSe One-to-many Direct Communication is defined in the ProSe standard as the multicast communication between one ProSe-enabled UE and a set or a group of ProSe-enabled UEs. According to the standard, this communication mode is reserved only to ProSe-enabled Public Safety UEs and, when authorized, to UEs under E-UTRAN coverage or to UEs outside of E-UTRA coverage. ProSe One-to-many Direct Communication has the following characteristics:

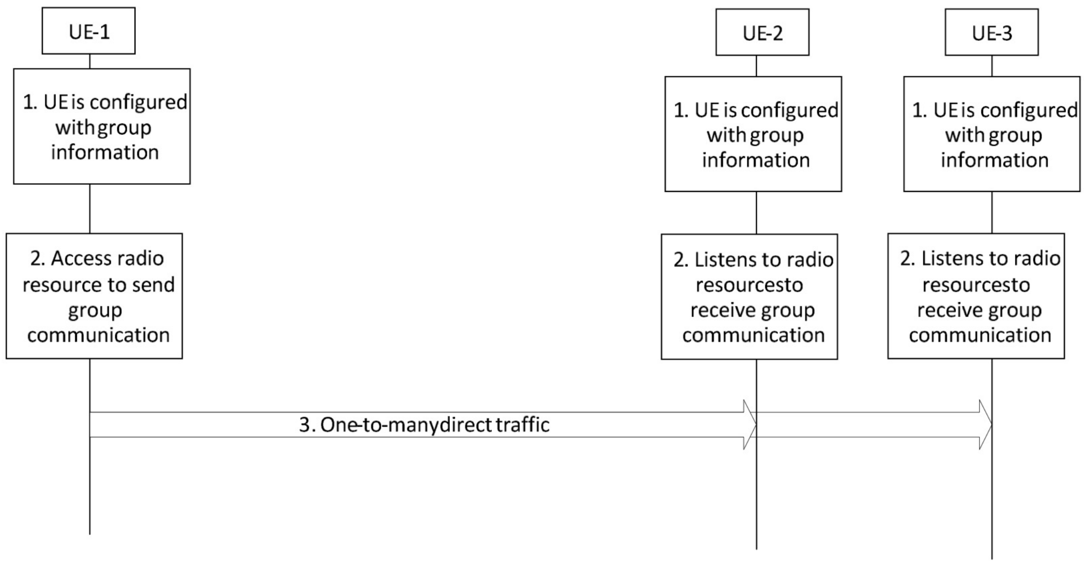

Figure 3.10: One-to-many ProSe Direct Communication transmission [16].

- The communication is connectionless: there is no signalling over PC5 control plane.

- The radio layer provides a user plane communication service for transmission of IP packets between UEs engaged in direct communication.
- Members of a group share a secret from which a group security key may be derived to encrypt all user data for that group.
- Authorization for ProSe one-to-many Direct Communication is configured in the UE by the ProSe Function using PC3 reference point.
- ProSe-enabled UE configuration parameters such as ProSe Group IP multicast addresses, ProSe Group IDs, Group security material, radio related parameters, are configured in the UE [16].

Chapter 4

C-V2X vs DSRC: technology comparison

4.1 Introduction

This chapter will introduce the DSRC vehicular communication technology and compare it with the Cellular V2X.
DSRC technology is the first real big result in the field of vehicular communication and its overall technology is mainly based on short-range standards that will be discussed in the chapter. To fully understand why cellular V2X represents the future of vehicular communication it is important to have a full overview of the DSRC technology and highlight the main advantages and changes of C-V2X with respect to it.

4.2 DSRC overview

Dedicated short-range communications (DSRC) is also known as *wireless access in vehicular environment* (WAVE). It is defined as a communication technology designed for automotive used, specifically for vehicular communication systems, that corresponds to a set of protocols.
In the United States, the Federal Communications Commission has allocated 75 MHz of spectrum in the 5.9 GHz band for DSRC use, while Europe and Japan have allocated their own spectrum band and system design [17].

In the USA, DSRC includes seven licensed channels that are shared between public safety and private applications. Unlike standard 802.11 where each channel is 20 MHz wide, the channels in 802.11p are 10 MHz to make the signal more robust against fading (with an option to use 20 MHz by combining two 10 MHz channels). At the physical layer, IEEE 802.11p (the approved standard to add wireless access

Country/Region	Frequency Bands (MHz)
ITU-R (ISM band)	5725-5875
Europe	5795-5815, 5855/5875-5905/5925
USA	902-928, 5850-5925
Japan	5770-5850; 715-725
Australia	*None*

Table 4.1: Spectrum Allocation for WAVE/DSRC Applications.

in vehicular environments to IEEE 802.11 and considered then for DSRC) is similar to 802.11a/g, based on orthogonal frequency division multiplexing modulation. 802.11p differentiates itself from normal 802.11 with a unique ad hoc mode, random MAC addresses for privacy preservation, and IPv6 for routing in the network layer. The unique ad hoc mode enables 802.11p nodes to communicate outside the context of a basic service set in a highly mobile environment where authentication and association are not defined in 802.11p PHY/MAC but rather handled by the upper layer or the station management entity. This reduces the delay (typically a few seconds) incurred in an initial first-frame exchange in which the communication timing between two vehicles may be short, especially if the vehicles are traveling in opposing directions.
In addition, IEEE 802.11p includes the enhancement of priority classes based on 802.11e and power control based on 802.11h. Prioritization and quality of service for safety timecritical messages in VANET are addressed with enhanced distributed channel access (EDCA) with different contention window size.
DSRC/WAVE provides a flexible architecture with multiple protocol stacks above the network layer (for example, TCP, UDP, and WAVE short message in the transport layer). The standard for DSRC/WAVE uses IEEE 802.11p in the lower layers (physical and MAC) and IEEE 1609 in the upper layers (1609.1 for application services, 1609.2 for security services, 1609.3 for networking services, and 1609.4 for multichannel and EDCA mechanisms), as shown in figure 4.1 [5].

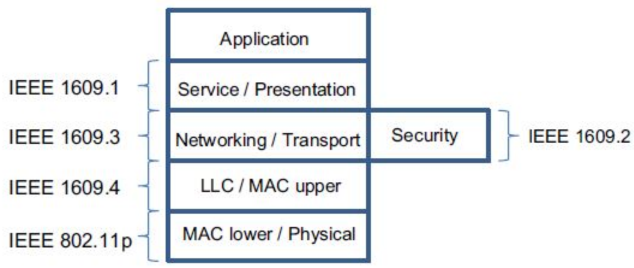

Figure 4.1: Dedicated short-range communication standards.

4.2.1 DSRC technology architecture

DSRC/WAVE is the only wireless technology that can potentially meet the extremely short latency requirement for road safety messaging and control. The unique feature of low latency secures the role of DSRC, as an essential communication technology, in future CALM networks (communications access for land mobiles, a family of network that will make use of other wide spread technology such as cellular, satellite, WLAN and so on) that will make use of multi- radios on multi-bands. However, the current DSRC solutions are not fully field proven. There are significant DSRC-related social and technical challenges that have to be dealt with before large-scale deployment [17].
There are two classes of devices in a WAVE system:

- on-board unit (OBU),
- roadside unit (RSU).

They are equivalent to the mobile station (MS) and base station (BS) in the cellular systems respectively. Two classes of communications are possible for the OBUs and RSUs:

- vehicle to vehicle (V2V),
- vehicle to infrastructure (V2I).

While a MS in the cellular environment normally communicates with another MS via the BS, the OBU in a vehicle normally directly communicates with other OBUs within the radio coverage area. This direct V2V communication reduces the message latency and *low latency* is an essential requirement for safety applications such as collision avoidance.
Another difference is that an OBU is more likely to be embedded and connected with other electronic systems of the vehicle via in-vehicle networking such as controller area network (CAN) and FlexRay, while a MS is normally detached from the CAN. In addition to improving safety, WAVE networks can play major roles in travel plan, traffic management, navigation, fleet and asset management, environment monitoring, logistics, congestion and emission reduction, toll collection, smart parking, emergency services and a wide range of other location-based services [17].

4.2.2 Regulatory requirements

In US, 75 MHz of spectrum in the 5.9 GHz frequency band has been allocated for DSRC applications. Out of the 75 MHz spectrum, 5 MHz is reserved as the guard band and seven 10 MHz channels are defined as in shown in figure 4.2. The available spectrum is configured into 1 control channel (CCH) and 6 service channels (SCHs) [17].

The CCH is reserved for carrying high-priority short messages or management data, while other data are transmitted on the SCHs. The pair of channels (channel 174 and 176, and channel 180 and 182) can be combined to form a single 20 MHz channel, channel 175 and 181 respectively. The channel number (CN) is derived by counting the number of 5 MHz spectrum in the frequency band from 5000 MHz to the center frequency f (CN) of the channel CN, i.e.,

$$f(CN) = 5000 + 5CN\ (MHz). \tag{4.1}$$

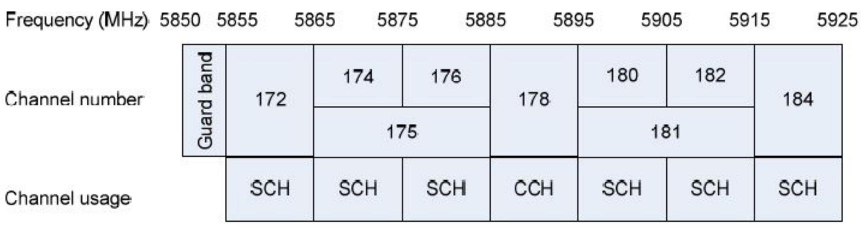

Figure 4.2: The DSRC frequency allocation in the USA [17].

In terms of transmitter (TX) power, four classes of devices have been defined whose maximum TX power ranges from 0 dBm to 28.8 dBm. The associated coverage distance by a single radio link depends on the channel environment, the TX power and the modulation and coding schemes (MCS) used. This distance may range from 10m to 1km. The details of OBU and RSU TX limits of equivalent isotropically radiated power (EIRP) also depend on the operating CN and applications.
It is worth noting that the DSRC regulatory requirements in many parts of the world are in the process of being finalized. There is a chance that similar spectrum allocation and requirements will be adopted world wide for DSRC applications. Spectrum harmonization is desirable for global inter-operability and low-cost DSRC services [17].

4.2.3 DSRC/WAVE messages

The set of messages used in WAVE is composed by:

- *Basic safety messages (BSMs).* These are used in multiple safety applications in each vehicle. These applications are largely independent of each other, but all make use of the incoming stream of BSMs from surrounding (nearby) vehicles to detect potential events and dangers. In the basic system defined by the SAE J2735 standard, each moving vehicle updates and sends its own BSM every 100 ms. Other nearby devices (typically vehicles but potentially also RSUs) detect this broadcast and process it as they see fit, i.e. running whatever safety applications they wish;

- *Roadside alert (RSA) messages.* These are the messages used in various traveller information applications. For instance, an Emergency Vehicle Alert message is used to inform mobile users of nearby emergency operations. The types of data in the roadside alert messages can include information such as travel delays, incident and diversion data, construction messages, and other data that the traffic management centre (TMC) may wish to deliver to drivers;

- *Probe vehicle messages (PVMs).* These are used by multiple applications. Vehicles gather data on road and traffic conditions at intervals. The probe data provides information on traffic conditions, weather, and road surface conditions;

- *Signal phase and time (SPAT) messages.* SPAT messages are used to convey the current status of one or more signalized intersections. Along with map messages (see below), the receiver of such messages can determine the state of the signal phasing and when the next expected phase will occur. It will be used from applications that notify to the driver which would be the best speed to be kept to overcome the traffic light (e.g., in the context of GLOSA – Green Light Optimal Speed Advice);

- *Map messages.* Map data messages are used to convey many types of geographic road information. Currently, its primary use is to convey one or more intersection lane geometry maps within a single message [18].

4.2.4 DSRC/WAVE Standards

Collectively the IEEE 1609 family, IEEE 802.11p and the Society of Automotive Engineers (SAE) form the key parts of the currently proposed WAVE protocol stack. The WAVE protocol architecture with its major components is shown in figure 4.3, and they are summarized as follows [17].

- IEEE P1609.0 *Draft Standard for Wireless Access in Vehicular Environments (WAVE) - Architecture.*

- IEEE 1609.1 *Trial Use Standard for Wireless Access in Vehicular Environments (WAVE) - Resource Manager.*

- IEEE 1609.2 *Trial Use Standard for Wireless Access in Vehicular Environments (WAVE) - Security Services for Applications and Management Messages.*

- IEEE 1609.3 *Trial Use Standard for Wireless Access in Vehicular Environments (WAVE) - Networking Services.*
- IEEE 1609.4 *Trial Use Standard for Wireless Access in Vehicular Environments (WAVE) - Multi-Channel Operations.*
- IEEE P1609.11 *Over-the-Air Data Exchange Protocol for Intelligent Transportation Systems (ITS).*
- IEEE 802.11p Part 11: *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications – Amendment: Wireless Access in Vehicular Environments.*

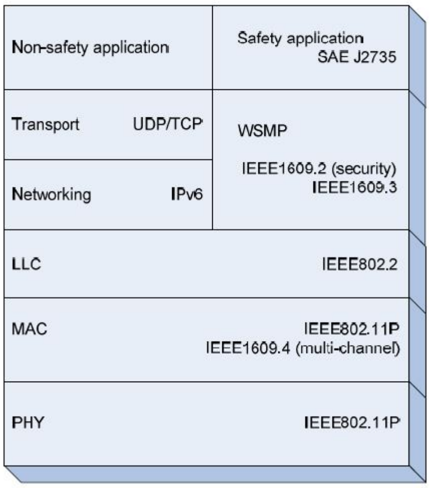

Figure 4.3: The WAVE Protocol Stack and Its Associated Standards.

Table 4.2 enlists the main parameters of WAVE and Wi-Fi, highlighting the main differences between them [17].

4.2.5 ETSI ITS communications architecture and protocol stack

The *European Telecommunication Standards Institute (ETSI) Intelligent Transport Systems (ITS) Technical Committee (TC)*, established in 2007, is responsible for Cooperative ITS (C-ITS) standards development, interoperability and conformance testing. The standardization activity is European-focused but recognized worldwide. The ETSI ITS standard defines four ITS stations (ITS-S) sub-systems (personal, vehicle, roadside and central) which communicate in an ITS environment [19].

Parameters	**WAVE**	**Wi-Fi**
Frequency band	5.9 GHz	5/2.4 GHz
Channel bandwidth	10 MHz	20 MHz
Supported data rate (Mbps)	3,4.5,6,9,12,18,24 and 27	6,9,12,18,24,36, 48 and 54
Modulation	Same as Wi-Fi	BPSK, QPSK, 16QAM and 64QAM
Channel coding	Same as Wi-Fi	Convolutional coding rate: $\frac{1}{2}$, $\frac{2}{3}$ and $\frac{3}{4}$
No. of Data Subcarriers	Same as Wi-Fi	48
No. of Pilot Subcarriers	Same as Wi-Fi	4
No. of Virtual Subcarriers	Same as Wi-Fi	12
FTT/IFFT Size	Same as Wi-Fi	64
FTT/IFFT Interval	6.4 μs	3.2 μs
Subcarrier spacing	0.15625 MHz	0.3125 MHz
CP Interval	1.6 μs	0.8 μs
OFDM Symbol Interval	8 μs	4 μs

Table 4.2: Comparison between WAVE and Wi-Fi OFDM parameters [17].

ETSI ITS V2X communication is based on ITS-G5 access layer technology and allows 6-12 Mbps default data rates in a 10 MHz radio channel. It uses Institute for Electrical and Electronics Engineers (IEEE) 802.11 physical and data link layers (IEEE 802.11 MAC plus ANSI/IEEE 802.2 Logical Link Control). Three dedicated ITS bands are defined in the 5.9 GHz frequency range – G5A (road safety), G5B (non-safety), G5D (future). Due to short-lived V2X communication links, data exchange is enabled without the need for association or authentication. Apart from the detailed radio communication requirements in the 5.9 GHz ITS band, protocols and message specifications, the standard also defines the following C-ITS applications and corresponding use cases: road safety, traffic control and efficiency, fleet and freight management and location-based services.
The ITS communications architecture is based on the Open System Interconnection (OSI) model extended for ITS, as shown in figure 4.4. The higher layers are intended to be access technology agnostic to allow forward compatibility. The protocol stack is defined for basic ITS-S functionality and includes the following layers:

- Applications layer – support for road safety, traffic efficiency, infotainment and other use cases;
- Facilities layer – applications, information services and session support, e.g., Global Positioning System (GPS) positioning, state monitoring (car engine,

lights), messages and time management;

- Networking and transport layer – protocols for data delivery and routing between ITS stations (e.g., IPv6 support, handover between access technologies, etc.);

- Access layer – internal and external ITS-S communication using various media (ITS-G5, Wi-Fi, Ethernet, Cellular, Bluetooth, GPS, etc.);

- Management entity – configuration of ITS-S station and cross-layer information exchange;

- Security entity – privacy and security services [19].

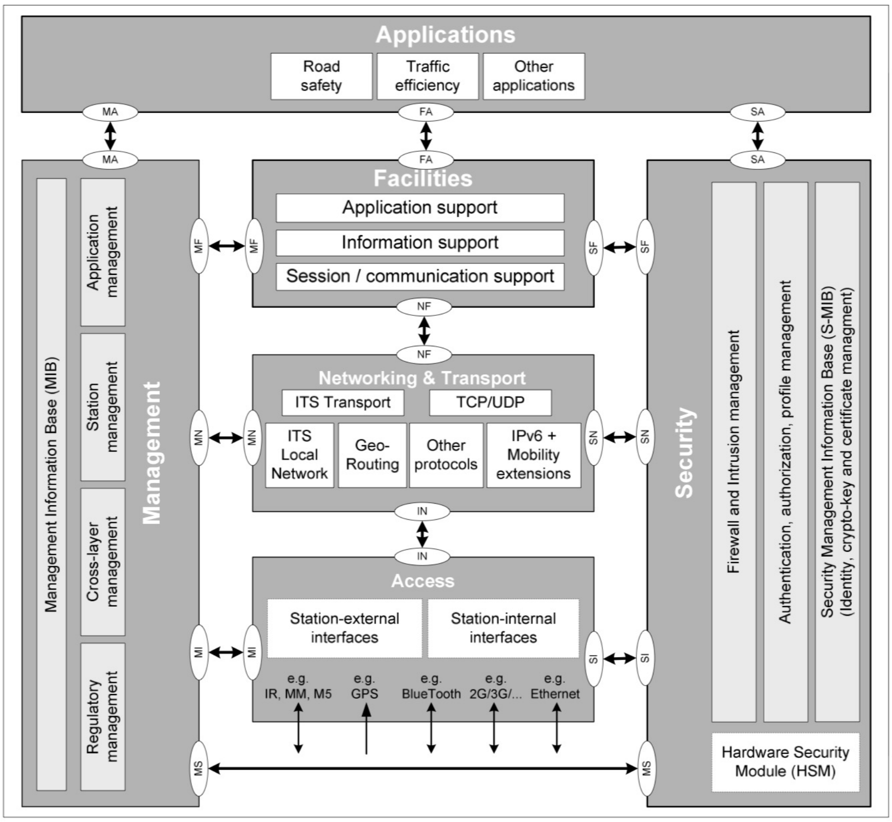

Figure 4.4: Examples of possible elements in the ITS station reference architecture [19].

4.3 Comparison of vehicular network technologies

IEEE 802.11p is the standard that supports ITS applications in VANETs. Easy deployment, low-cost, mature technology, and the capability to natively support V2V communications in ad-hoc mode are among its advantages. Nonetheless, this technology suffers from scalability issues, unbounded delays, and lack of deterministic Quality of Service (QoS) guarantees. Furthermore, due to its limited radio range and without a pervasive roadside communication infrastructure, 802.11p can only offer intermittent and short-lived V2I connectivity. The above-mentioned concerns motivate the recent increasing interest in Long Term Evolution (LTE) as a potential access technology to support communications in vehicular environments and the introduction of Cellular V2X.
C-V2X presents several differences with respect to previous V2X technology as DSRC. Going deeply into its advantages and disadvantages is surely something will make us understand its strong points and why it has been chosen as the vehicular communication of the future [20].

Several wireless technologies have been analyzed as candidates to support the mentioned applications through V2V and V2I communications. In agreement with the CALM (Communications Access for Land Mobiles) guidelines, the ITS station reference architecture proposed in ETSI specifications leverages the complementary strengths of distributed short- range networks (e.g., IEEE 802.11p, and its European counterpart ITS-G5, Wi-Fi) and centralized cellular technologies, among which LTE is the most promising one.
The main candidate access technologies have different characteristics and can match the vehicular application requirements, more or less effectively. Table 4.3 summarizes them [20].

4.3.1 Advantages of C-V2X

Multiple reasons put LTE (C-V2X), as an evolved cellular network, as the main protagonist for vehicular communication networks. The following is a list of the main advantages that this technology will bring to VANETs [12].

- *Coverage and Mobility.* LTE will rely on a capillary deployment of eNodeBs organized in a cellular network infrastructure offering wide area coverage. This would solve the 802.11p issue of poor, intermittent, and short-lived connectivity and would make LTE particularly indicated for V2I communications even at high node speeds. The LTE infrastructure exploitation would also represent a viable solution to bridge the network fragmentation and extend the connectivity in those scenarios where direct V2V communications cannot

Feature	**Wi-Fi**	**802.11p**	**UMTS**	**LTE**	**LTE-A**
Channel width	20 MHz	10 MHz	5 MHz	1.4, 3, 5, 10, 15, 20 MHz	Up to 100 MHz
Frequency band(s)	2.4 GHz, 5.2 GHz	5.86-5.92 GHz	700-2600 MHz	700-2690 MHz	450 MHz- 4.99 GHz
Bit rate	6-54 Mbps	3-27 Mbps	2 Mbps	Up to 300 Mbps	Up to 1 Gbps
Range	Up to 100 m	Up to 1 km	Up to 10 km	Up to 30 km	Up to 30 km
Capacity	Medium	Medium	Low	High	Very High
Coverage	Intermittent	Intermittent	Ubiquitous	Ubiquitous	Ubiquitous
Mobility support	Low	Medium	High	Very high (up to 350 km/h)	Very high (up to 350 km/h)
QoS support	Enhanced Distributed Channel Access (EDCA)	Enhanced Distributed Channel Access (EDCA)	QoS classes and bearer selection	QCI and bearer selection	QCI and bearer selection
Broadcast/ Multicast support	Native broadcast	Native broadcast	Through MBMS	Through eMBMS	Through eMBMS
V2I support	Yes	Yes	Yes	Yes	Yes
V2V support	Native (ad hoc)	Native (ad hoc)	No	No	Potentially, through D2D
Market penetration	High	Low	High	Potentially high	Potentially high

Table 4.3: Main wireless technologies candidates for vehicular communications [20].

be supported due to low car density (off-peak hours, rural scenarios, etc.) or to challenging propagation conditions (e.g., corner effect due to building obstructions at road intersections).

- *Market penetration.* Higher penetration rate is expected to be achieved by LTE compared to 802.11p. The LTE network interface will be integrated in common user devices like smartphones, so that passengers would be accustomed to be connected to the Internet through these devices also while on the road.
- *Capacity.* LTE offers high downlink and uplink capacity (see chapter 2 for more details about LTE data rate) that potentially supports several vehicles per cell. Such data rates values are higher than 802.11p, which offers a data rate up to 27 Mbps [12].

Table 4.4 summurizes some of the advantages of C-V2X with respect to the DSRC technology based on 802.11p standard.

	C-V2X: PC5	**802.11p**	**C-V2X: PC5 advantage**
Synchronization	Synchronous	Asynchronous	Spectral Efficiency. Synchronization enables time division multiplexing (TDM) and lowers channel access overhead.
Resource Multiplexing Across Vehicles	FDM and Time Division Multiplexing (TDM) possible	TDM Only	Frequency Division Multiplexing allows for larger link budget and therefore longer range - or more reliable performance at the same range.
Channel Coding	Turbo	Convolutional	Coding gain from turbo codes leads to longer range - or more reliable performance at the same range.
Retransmission	Hybrid Automatic Repeat Request (HARDQ)	No HARDQ	Leads to longer range - or more reliable performance at the same range.
Waveform	SC-FDM	OFDM	Allows for more transmit power with the same power amplifier. Leads to longer range or more reliable performance at the same range.
Resource Selection	Semi-persistent transmission with relative energy-based selection	CSMA-CA	Optimizes resource selection with selection of close to best resource with no contention overheads. By contrast 802.11p protocol selects the first "good enough" resource and requires contention overhead.

Table 4.4: Main C-V2X advantages over 802.11p standard technology for DSRC.

C-V2X has a number of technical advantages over 802.11p-based alternatives, as summarised in table 4.4. Together, these advantages equate to a significantly

higher link budget and system performance, enabling range, Doppler (speed) and reliability advantages over 802.11p. C-V2X has a higher spectral efficiency, enabling it to serve more road users within a given chunk of spectrum. Hence, C-V2X can provide higher levels of safety to more road users than alternative technologies.
Ad hoc networks relying only on direct communications between vehicles can become inefficient if the number of hops becomes significant, due to the protocol overhead. A practical limit tends to be five hops. However, if there is an active antenna system located in the front and rear of a car, the number of hops can be doubled.
As well as offering superior direct communications, C-V2X offers a higher degree of security than 802.11p for all operating modes. Mobile operators secure all traffic travelling to and from their networks, which can be supplemented with Public Key Infrastructure (PKI) encryption services [12].

4.3.2 Evolution from DSRC to C-V2X

One of the first evolution in the cellular V2X network, with respect to the DSRC one, is the architecture of the Road Side Unite (RSU). The RSU can now be implemented in two different ways. With reference to the architectural reference models, the RSU can receive V2X messages via SGi, PC5 or LTE-Uu interface depending on implementation option.

Figure 4.5 shows a UE-type RSU, which combines a UE with the V2X application logic [2].

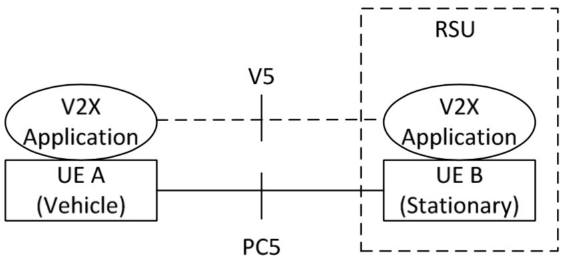

Figure 4.5: RSU includes a UE and the V2X application logic [2].

Figure 4.6 shows one example of eNB-type RSUs. In this example, the RSU comprises an eNB, a collocated L-GW, and a V2X Application Server.

Another deployment option is the one regarding the localization of the MBMS system. In current MBMS system, the BM-SC, MBMS-GW and MME are located in the Core Network. The backhaul delay between the BM-SC and the eNodeB is non-negligible when calculating the end-to-end delay, especially when MBMS is used to delivery downlink V2X messages in the V2X system. To minimize the latency, possible deployment can consider the following options:

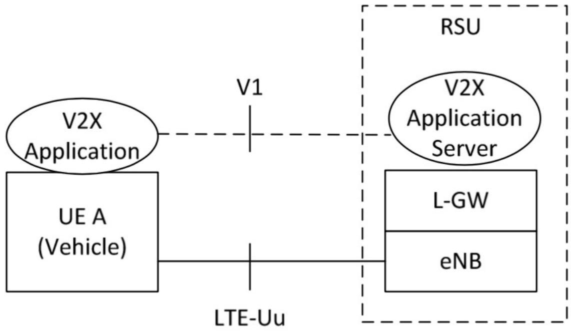

Figure 4.6: RSU includes an eNB, L-GW and a V2X Application Server [2].

- To move the MBMS CN functions (e.g. BM-SC, MBMS-GW) closer to the eNB.
- To move the user plane of MBMS CN functions (BM-SC, MBMS-GW) closer to the eNodeB [2].

4.3.3 Role of 5G alongside C-V2X

C-V2X is designed to be fully compatible with 5G, meaning investments in infrastructure and modules today won't be made obsolete for a long time to come. C-V2X technology will be further refined and its capabilities expanded with Release 15 of the 3GPP standards, due in June 2018, and Release 16 in June 2019 [12].
The deployment of commercial 5G networks from 2020 onwards based on the 3GPP standards will enhance C-V2X in several different ways. In the 5G era, C-V2X will be able to support:

- Very precise positioning and ranging to support cooperative and automated driving.
- High throughput and low-latency connectivity to enable the exchange of raw or processed data gathered through local sensors or live video images.
- High throughput to build local, dynamic maps based on camera and sensor data; which can then be distributed at street intersections. For example, C-V2X could be used to supply a driver or an on-board computer with a bird's eye view of an intersection or see-through capability when driving behind a truck.
- Very low latency and high reliability to support high-density platooning.

Moreover, 5G will be able to support very large numbers of simultaneous connections in a small geographic area, enabling each vehicle to gather more information about its immediate surroundings [12].

4.4 Conclusions

For road operators, automakers and mobile operators, C-V2X offers multiple technical and economic advantages over other dedicated vehicle connectivity technologies. Unlike the alternatives, C-V2X can support a very broad range of use cases spanning safety, navigation and integrated transport systems. One of the main advantages of using a cellular system is that it can address all V2X applications in an end-to-end manner with the same technology. That makes it very scalable and future-proof. Moreover, as part of the 3GPP standards family, C-V2X has the support of a broad and global ecosystem, while providing a clear evolution path from LTE to 5G [12].
Despite several documents, such as [12], stand that Cellular V2X represents a better alternative than the DSRC, we have to remind that the Dedicated Short Range Communication is a stable technology that is been already commercialised. Therefore several tests have been done on it and the results were satisfying. This technology can work and despite all the limitations with respect to V2X, it si a valid choice for a first ITS deployment.
Cellular V2X is potentially a great technology that offers much more features and opportunities that DSRC, but in this particular moment of its history it lacks of tests and demonstrations that stands its reliability. Surely C-V2X will be the main character of the next decades and most of the efforts will be on studying it and its potential problems, in a way to solve them and bring it into commercialisation.

Chapter 5

Cellular network simulation with SimuLTE

5.1 Introduction

SimuLTE can help us simulate LTE network scenarios in presence or not of the D2D technology. The same technology will be very important for cellular V2X future vehicular communication standard and it will permit the vehicles (UEs) to communicate among theirself without relying on the network infrastructure (eNodeB).
In this simulation we want to highlight the latency (or the delay) of a standard packet (varying the size) sent by the UE to another UE and the packet losses during a total 50 seconds of simulation time. During the experiment several configurations of packet sizes and absence/presence of network disturbances will be taken into account.
Another interesting index could be the CQI (Channel Quality Index) that will tell us the quality of the channel without relying on the signal to noise ratio.
After doing this we can see what happens if we have the presence of more couples of UEs communicating among theirself, so in case of network overloading.
All the scenarios of this experiment are taken from the simple assumption of using one LTE cell and not multicell. This is because it is more useful to see the behavior in a simple scenario to understand the main quality and features.

5.2 The OMNeT++ framework

SimuLTE is based on the OMNeT++ simulation framework, which can be used to model several things (not only networks). We focus only on the aspects of OMNeT++ which are more relevant to understanding SimuLTE.
The basic OMNeT++ building blocks are *modules*, which can be either simple or compound. Modules communicate through messages, which are usually sent and

received through a connection linking the modules' gates, which act as interfaces. A network is a particular compound module, with no gates to the outside world, which sits at the top of the hierarchy. Connections are characterized by a bit rate, delay and loss rate, and cannot bypass module hierarchy: with reference to figure 5.1, simple module 3 cannot connect to 2, but must instead pass through the compound module gate. Simple modules implement model behaviour.
Although each simple module can run as an independent coroutine, the most common approach is to provide them with event handlers, which are called by the simulation kernel when modules receive a message. Besides handlers, simple modules have an initialization function and a finalization function, often used to write results to a file at the end of the simulation. The kernel includes an event queue, whose events correspond to messages (including those a module sends to itself).
OMNeT++ allows one to keep a model's implementation, description and parameter values separate. The implementation (or behaviour) is coded in C++. The description (i.e., gates, connections and parameter definition) is expressed in files written in Network Description (NED) language. Moreover a modular development is favoured by allowing inheritance of both module description and behaviour. The parameter values are written in initialization (INI) files. NED is a declarative language, which exploits inheritance and interfaces, and it is fully convertible (back and forth) into XML. NED allows one to write parametric topologies, e.g. a ring or tree of variable size. NED files can be edited both textually and graphically (through a Graphic User Interface, GUI), switching between the two views at any time. INI files contain the values of the parameters that will be used to initialize the model. For the same parameter, multiple values or intervals can be specified.
As far as coding is concerned, OMNeT++ is integrated into Eclipse, thus it comes with an IDE which facilitates development and debugging. In fact, modules can be inspected, textual output of single modules can be turned on/off during execution, and the flow of messages can be visualized in an animation, all of which occurs automatically. Events can be logged and displayed on a time chart, which makes it easy to pinpoint the causes or consequences of any given event.

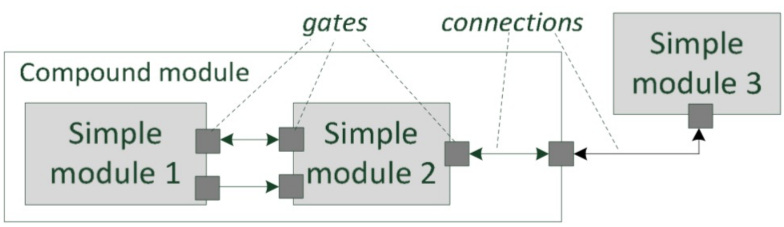

Figure 5.1: OMNeT++ module connection [21].

As for simulation workflow automation, OMNeT++ clearly separates models (i.e., C++ and NED files) from studies. Studies are generated from INI files, by automatically making the Cartesian product of all the parameter values and, possibly, generating replicas of the same instance with different seeds for the random number generators. Note that the IDE allows one to launch and manage multiple runs in parallel, exploiting multiple CPUs or cores, so as to reduce the execution time of a simulation study.
Finally, data analysis is rule-based: the user only needs to specify the files and folders he wants to extract data from, and the recipe to filter and/or aggregate data. The IDE automatically updates and re-draws graphs when simulations are rerun or new data become available [21] [22].

5.3 Overview of SimuLTE

SimuLTE simulates the data plane of the LTE/LTE-A Radio Access Network and Evolved Packet Core.
SimuLTE allows simulation of LTE/LTE- A in Frequency Division Duplexing (FDD) mode, with heterogeneous eNodeBs (macro, micro, pico etc.), using omnidirectional and anisotropic antennas, possibly communicating via the X2 interface. Realistic channel models, MAC and resource scheduling in both directions are supported. In the current release, the Radio Resource Control (RRC) is not modelled. The general structure of the three main nodes is shown in figure 5.2. SimuLTE implements eNodeBs and UEs as com- pound modules. These can be connected with each other and with other nodes (e.g. routers, applications, etc.) in order to compose networks. The Binder module is instead visible by every other node in the system and stores information about them, such as references to nodes. It is used, for instance, to locate the interfering eNodeBs in order to compute the inter-cell interference perceived by a UE in its serving cell. UE and eNB are further composed of modules. Every module has an associated description file (.ned) defining its structure, and may have a class definition file (.cpp, .h) which implements the module functionalities.
The UDP and TCP modules, taken from the INET package, implement the respective transport layer protocols, and connect the LTE stack to TCP/UDP applications. As figure 5.2 shows, TCP and UDP applications (TCP App and UDP App) are implemented as vectors of N modules, thus enabling multiple applications per UE. Each TCP/UDP App represents one end of a connection, the other end of which may be located within another UE or anywhere else in the topology. SimuLTE comes with models of real-life applications (e.g., VoIP and Video on Demand), but any other TCP/UDP-based OMNeT++ application can also be used. The IP module is taken from the INET package as well. In the UE it connects the Network Interface Card (NIC) to applications that use TCP or UDP. In the

eNodeB it connects the eNB itself to other IP peers (e.g., a web server), via PPP (Point-To-Point Protocol).
The NIC module, implements the LTE stack. It has two connections: one between the UE and the eNB and one with the LTE IP module. It is built as an extension of the IWirelessNic interface defined in the INET library, so as to be easily plugged into standard scenarios. This allows one among other things to build hybrid connectivity scenarios, e.g. with nodes equipped with both Wi-Fi and LTE interfaces. Each of the NIC submodules on the left side represents one or more parts of the LTE protocol stack, which is common to the eNB as well. The only module in the UE that has no counterpart in the eNB is the Feedback Generator, which creates channel feedbacks that are then managed by the PHY module. The communication be- tween modules takes place only via message exchange, thus each action starts from a message handler. Cross module calls are used only in the form of getter/setter functions. This allows us to maintain a strong control over the interactions between modules, thus limiting possible buggy behaviours [21] [22].

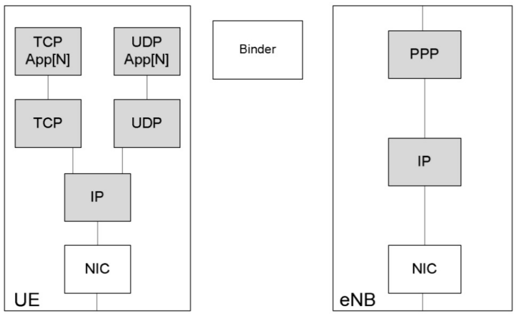

Figure 5.2: UE and eNodeB module structure. Shaded modules are taken from the INET framework [21].

5.4 Network parameters

In SimuLTE the network parameters are already provided and set through an xml file named `config_channel.xml` in which all useful parameters are given. We can see them from the table 5.1.

These parameters are not supposed to be changed cause they constitute a model that was studied for a city scenario. This model has a path loss model, a fading model and it can give the fading and the shadowing disturbances if we decide to simulate them in the network.
SimuLTE allows us only to change the carrier frequency and the number of resource blocks assigned in Downlink and Uplink from the ini file. The ini file contains all the possible network configuration and it is our tool to manipulate the scenarios

Parameter	Value
Carrier frequency	2 GHz
Bandwidth	5 MHz (25 Resource Blocks)
Path loss model	ITU Urban Macro
Fading model	Jakes
UE Tx Power	26 dB
Noise figure	5 dB
Cable loss	2 dB
Simulation time	50 s

Table 5.1: Network parameters used for our simulations.

and obtain different results. Changing parameters is supposed to be done from the ini file and not from the xml file. If, for example, we decide to change the carrier frequency (operation that is possible to do), we have to be careful not to go too much far from 2 GHz because it would change the entire model.
Changing model is an operation very long and hard to do because it requires studying of the actual scenario in which we simulate and data records that have to be collected and put together. This operation cannot be done for our purpose, but we can rely on the already provided model that follows a urban scenario with high buildings and disturbances.
Other parameters that can be changed from the ini file are the maximum power allowed in the channel (now fixed to 10 W) and the number of resource blocks (a concept that is fundamental in LTE environment).
For our experiment I have used the parameters reported in the table 5.1.

5.5 Preparation of the simulation tools

The first step to successfully install SimuLTE is to install OMNeT++ and the INET Framework.
OMNeT++ is C++ simulation library that provides all the elements to build network simulations. OMNeT++ will provide also a graphic GUI (Eclipse-based) environment to code and run our simulation [23].
The INET Framework is an open source model library to build most of the wired network simulations using the OMNeT++ environment. It provides protocols, agents and other models for researchers and students working with communication networks. INET is especially useful when designing and validating new protocols, or exploring new or exotic scenarios [24].
Having installed OMNeT++ first and INET after we can istall SimuLTE. As previously described, SimuLTE is a powerful simulation tool enabling complex system

level performance-evaluation of LTE and LTE Advanced networks (3GPP Release 8 and beyond) for the OMNeT++ framework. It is indispensable if we want to simulate LTE networks with real scenarios [25].
The official website of OMNeT++ and SimuLTE will provide all the instructions to install the tools. Once having installed OMNeT++ is easy to include SimuLTE as a new project in the Workspace and start using it.
SimuLTE has already configured several scenarios that can interested or not: D2D simulations, classic eNodeB infrastructure simulations. Everything is already created (modules, basic network structure and main parameters) so the user will only edit the parameters inside the configuration file (ini file). This file coded in C++ contains all the instruction for the network simulation we are gonna build and run.
For our purpose I choose the D2D folder in which SimuLTE has already built different simulations: single pair switching mode, eNodeB mode, multi pair mode (all of them in TCP and UDP). The user has then to choose the simulation is intended to run and modify some of the main parameters:

- position of the eNodeB
- position of the User equipments
- velocity of the User Equipments (if it is moving)
- network parameters (see section 4 for more details)
- presence of disturbances in the channel (fading and shadowing)
- used protocol to communicate (TCP or UDP)
- size of the sent packets [25].

It is important to understand that SimuLTE provides all the main structure of the network that we are not supposed to modify. We edit only the network parameters and build our scenario.

5.6 About our experiment

I set up our experiment in 2 different scenarios and then compared them. What we are interested into is comparing the results of a D2D scenario, in which 2 vehicles (we treat them as 2 simple User Equipments), can communicate with the D2D technology as far as the distance permits this and then switch to the normal communication with eNodeB, and another scenario in which there is no D2D and the communication only relies on the eNodeB infrastructure.
In both experiment our couple of vehicles will use a VoiP application to communicate, once with UDP and then with TCP. For the different nature of these 2

protocols we are expecting different results.
The main results we are interested into are the latency (delay) of the packets to reach the destination on the base of distance and number of packet losses (frame losses). We will also observe the CQI, as already mentioned before, as it is seen from the eNodeB.

5.7 Switching mode D2D–eNodeB in UDP

The switching mode is the scenario in which the communication between 2 UEs starts in D2D (without relying on the eNodeB) and ends without the D2D technology because the UEs are moving. In our set-up the 2 UEs are vehicles starting from the same points in coordinates and moving with linear motion (constant velocity at 10 m/s) in opposite direction to each other. Going further from each other the Sidelink (the D2D link) becomes weaker until it will be gone and we will have the switching mode. In this moment the 2 UEs will be handled by the eNodeB until the end of the simulation.
This scenario will be repeated also for TCP and we will get the same type of results and do a comparison.
It is useful to say that the coordinates of a point in the network in the OMNeT++ environment are given not in GPS coordinates but in an xyz reference system. For our set-up the z=0 always (we didn't set the amplitude to keep the scenario simple). The position of the eNodeB is fixed and at the beginning and it coincides with the one of the 2 UEs as we can observe from the following pictures. The reason of this stands in the fact that SimuLTE can generate automatically the graphs of the most interesting parameters (packet delay, packet loss...etc) in function of the simulation time. In this way it is then easy to calculate the distance between the 2 UEs if we are interested in it.

5.7.1 Delay and packet loss

It is important to say that with the network model set by SimuLTE, as we already mentioned in the second section, fading and shadowing are disturbing the signal and making varying the delay and the CQI. In this case we want to highlight the effects of the mode switching so we have disabled them. Our experiment is then ideal.
It is also important to precise that OMNeT++ is able to produce different simulations for the same situation in a random way. Every simulator has this ability and it is important to repeat the same simulation several times when we attempt to collect data about an experiment. In this case the graphs I will plot represent a single simulation and they are useful to observe the behaviour in time of the interested value and not the average of the value itself. Requesting a stable average

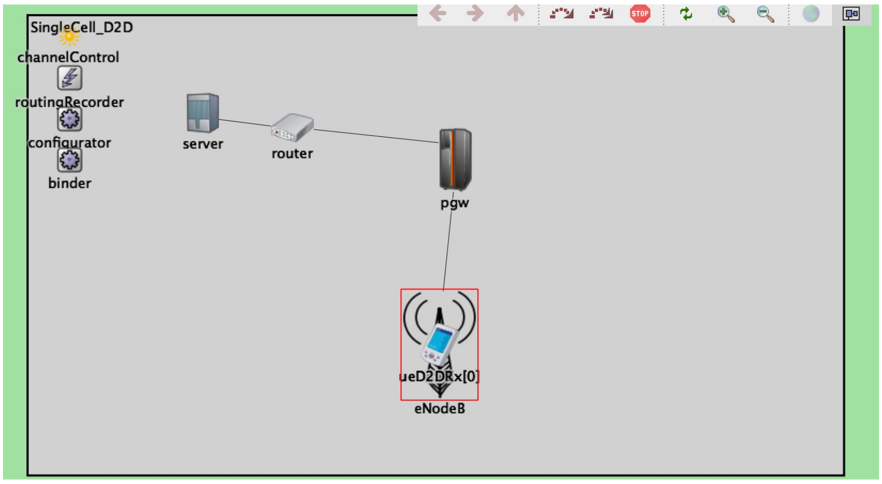

Figure 5.3: Network view in case of D2D mode switching in UDP. The position of eNodeB, UE1 and UE2 is the same.

of a value is a more complex process that implies hundred of simulations and much more studies on the real scenario we are interested into.

```
**.nic.phy.channelModel=xmldoc("config_channel_nofadshad.xml")
**.feedbackComputation = xmldoc("config_channel_nofadshad.xml")
```

The followings are the most important commands we have set to get position, speed and D2D capable UEs.
Position of the eNodeB:

```
*.eNodeB.mobility.initialX = 500m
*.eNodeB.mobility.initialY = 400m
```

Type of mobility of the UEs:

```
*.ue*[0].mobilityType = "LinearMobility"
*.ue*[0].mobility.speed = 10mps
```

Initial positions of the 2 UEs. In our configuration UE1 is transmitting packets of the same length, 1024 bytes, while UE2 is only receiving them.

```
#Initial position of UE1 (TX0)
*.ueD2DTx[0].mobility.initialX = 500m
*.ueD2DTx[0].mobility.initialY = 400m
*.ueD2DTx[0].mobility.constraintAreaMinX = 0m
*.ueD2DTx[0].mobility.constraintAreaMaxX = 1000m
*.ueD2DTx[0].mobility.angle = 180deg
```

```
#Initial position of UE2 (RX0)
*.ueD2DRx[0].mobility.initialX = 500m
*.ueD2DRx[0].mobility.initialY = 400m
*.ueD2DRx[0].mobility.constraintAreaMinX = 0m
*.ueD2DRx[0].mobility.constraintAreaMaxX = 1000m
*.ueD2DRx[0].mobility.angle = 0deg
```

To enable D2D for the eNodeB and the UEs involved in direct communications:

```
*.eNodeB.d2dCapable = true
*.ueD2D*[*].d2dCapable = true
**.amcMode = "D2D"
```

We have put the UEs in those position to easily keep track of the distance from each other. SimuLTE generates graphs with the simulation time on the x axis. If for example simulation time is 4 seconds, knowing that the speed is linear and constant at 10 m/s we can say that the distance between UE1 and UE2 in that particular instant of time is

$$distance_{UE1-UE2} = 2 \cdot time\,instant \cdot speed = 80\,meters. \quad (5.1)$$

The multiplication by 2 implied that we are not considering only the distance with the eNodeB but the total distance between the two devices.
Having done this we can observe the following results.

When our protocol is UDP we don't have the acknowledgement mechanism in the network so we can't talk about latency but about delay. Indeed the engineering definition of *latency* is *the time interval between the stimulation and response, or, from a more general point of view, the time delay between the cause and the effect of some physical change in the system being observed.* This means that in UDP we don't have any way to see the response at the transmitter, while we can see the packet delay at the receiver. It is then better to talk about delay.
Network latency in a packet-switched network is measured as either one-way (the time from the source sending a packet to the destination receiving it), or round-trip delay time (the one-way latency from source to destination plus the one-way latency from the destination back to the source). Round-trip latency is more often quoted, because it can be measured from a single point. This is why in case of TCP we will talk about latency or simply Round Trip Time.

As we can see from figure 5.4 and figure 5.5 the graphs represent the frame delay and the frame loss. In the frame loss graph we can see clearly that the only loss is during the switching mode from D2D to eNodeB, this is due to the absence of fading and shadowing that are normally the disturbances at the origin of losses. In

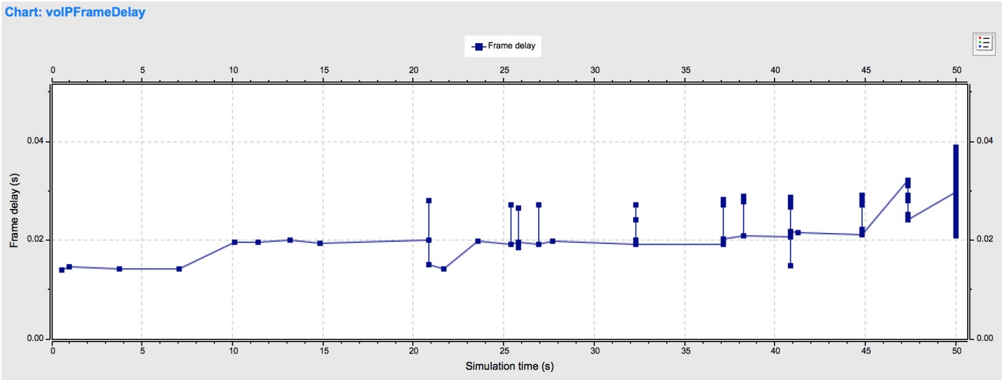

Figure 5.4: Frame delay using UDP as protocol and switching mode. The switching mode is at the second 21 of the simulation in the x axis.

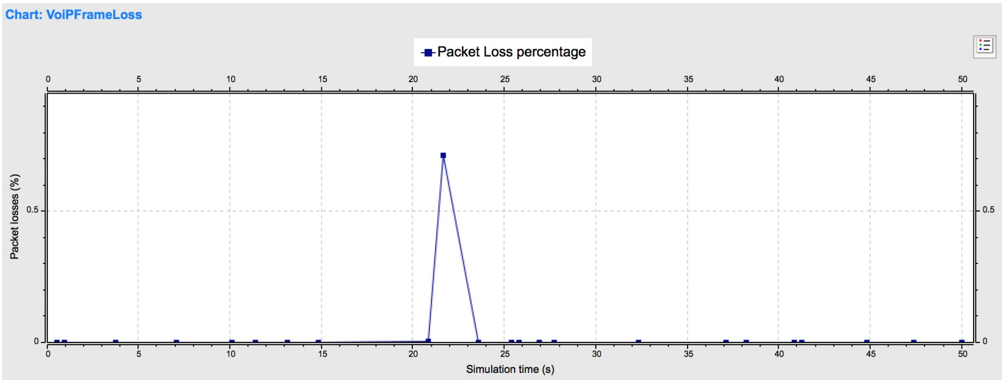

Figure 5.5: Packet loss in UDP case.

this case we have lost 70% of the packets so it's a cost operation in terms of packet losses.
The delay is increasing until 21 seconds. This is normal because the 2 UEs are getting far from each other and the D2D performances are strictly connected to the distance (the less distance the better it is the Sidelink between them). After the switching mode the delay in average will remain the same even though we have the presence of some peaks (figure 5.4). The fact that the delay is similar to the D2D mode is because the eNodeB is in the middle of the distance between the 2 UEs so the link is now represented by 2 smaller links (EU-eNodeB). The peaks are due the variance of the jitter error. In every network we have the presence of the jitter error that essentialy takes into account the fact that the packets travel trough the eNodeB that does several operations and of a very complex index. The delay variance is then represented by this random variable that changes in a very unpredictable ways, we can measure it in some instances but never estimate it in a deterministic way. As we can see in figure 5.6 the jitter error variance is calculated

in some instants of time.

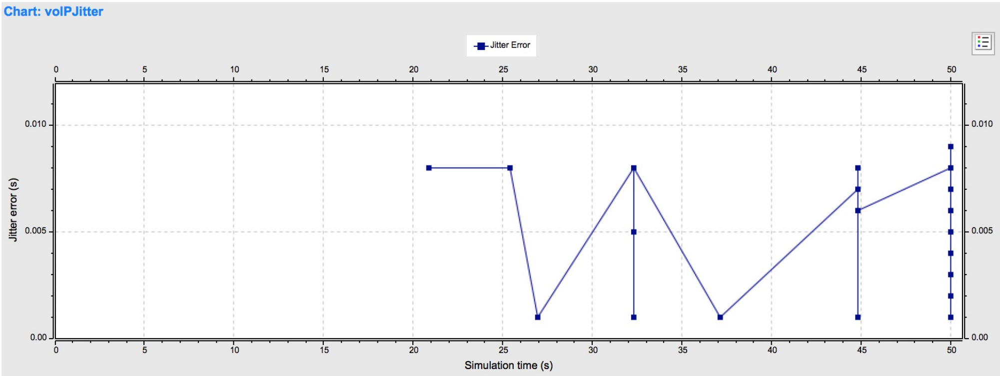

Figure 5.6: Jitter error in UDP. The graph starts from second 21 that is the instant in which we switch to the eNodeB. In D2D mode there is no presence of jitter because it is a direct link between devices, in fact it does not relay on any other infrastructure that can bring delay or non deterministic errors like jitter.

5.7.2 Channel Quality Indicator (CQI)

CQI stands for Channel Quality Indicator. As the name implies, it is an indicator carrying the information on how good/bad the communication channel quality is. This index has been used for LTE networks.
To properly understand how this indicator works we have to observe different CQI graphs and compare them. In our experiment we have set the speed of the UEs as constant to 10 m/s and in this situation the uplink and downlink CQI are the followings (figure 5.7 and 5.8). Figure 5.7 represents the average uplink CQI measured from the eNodeB. It is totally normal to see that the quality starts from the index 15 (maximum CQI index), because the channel has no disturbances, and decreases up to index 2 due to the distance of the UEs has from the eNodeB. The distance does not effect the link in downlink, because the eNodeB has a more powerful antenna than the device so it can handle bigger distance. This why in downlink the CQI is constant at 15, the maximum index.

This is going to change if we consider a higher speed of the 2 UEs, because the link will get worst in less time and also the eNodeB will not manage to maintain the CQI constant.

5.8 Switching mode D2D-eNodeB in TCP

Without touching at all the previous scenario we have simply changed the protocol from UDP to TCP and observed the differences in our results.

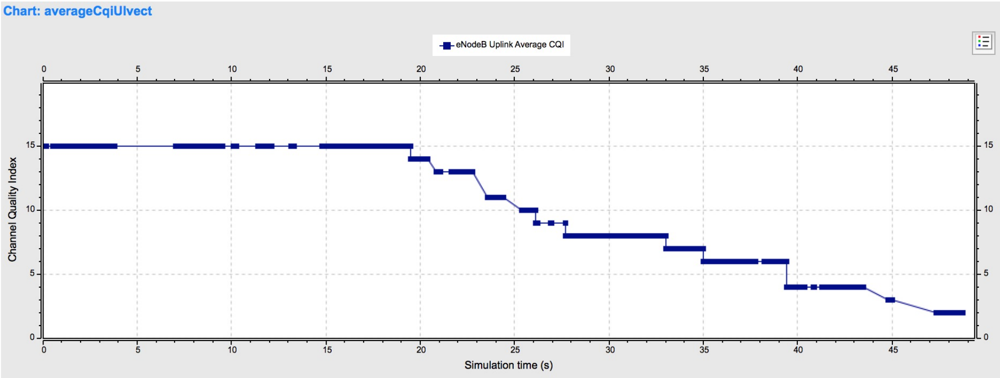

Figure 5.7: Average Uplink CQI measured from the eNodeB using UDP. Constant speed of the 2 UEs 10 m/s.

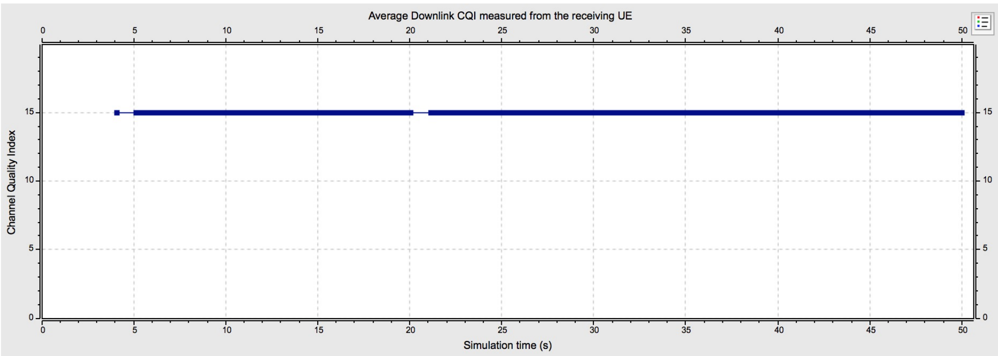

Figure 5.8: Average Downlink CQI measured from the receiving UE. Constant speed of the 2 UEs 10 m/s.

5.8.1 Latency and packet loss

In the case of TCP, it is literally correct to talk about latency with the definition of round trip time. In fact the round trip time is the time for a packet to be transmitted from one node to the other plus the time for the receiver to transmit another dummy packet to acknowledge the reception of it.

Figure 5.10 and figure 5.11 represent the measured and smoothed round trip time. The smoothed is an average graph of the measured one, useful to see the evolution of the latency for our experiments.

Until the second 21 (the instant of switching mode) with the D2D we keep more or less a constant RTT. The lowest RTT happens only when the 2 UEs are very close to each other. From the switching mode the RTT will increase because the distance between UEs and eNodeB will increase and because of the jitter error presence. We have the RTT behaviour curve of figure 5.11.

Also these results would be different in presence of shadowing and fading that here were not activated to highlight the switching mode behavior.

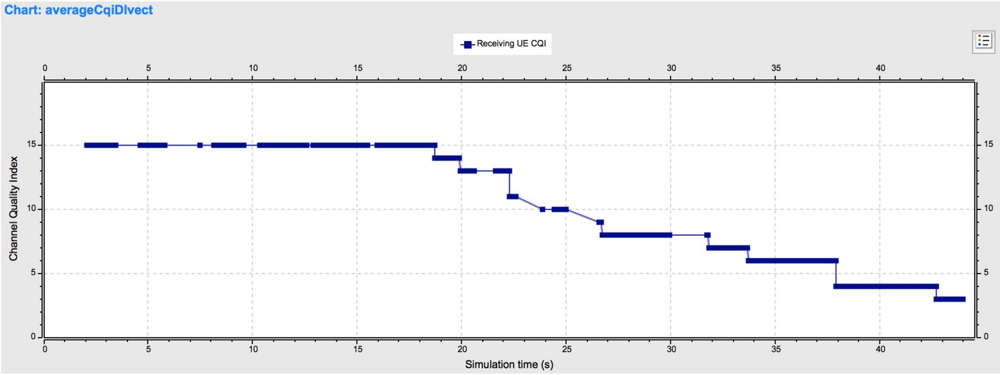

Figure 5.9: Average Downlink CQI measured from the receiving UE. Constant speed of the 2 UEs 30 m/s.

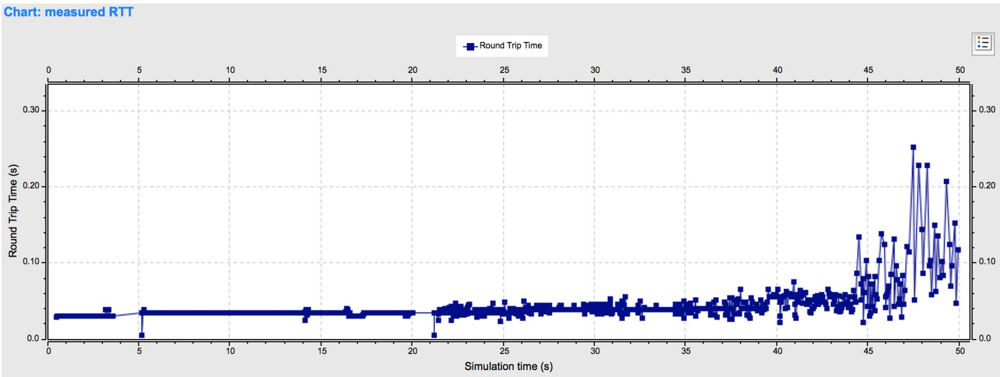

Figure 5.10: Measured RTT.

We didn't talk about packet losses because we don't have any losses in TCP that is a reliable protocol and uses the retransmission mechanism. This assures us the there are no losses but we can have several retransmissions that can enlarge the round trip time. This explains the difference in seconds between the RTT and the delay for the UDP case. Indeed the delay is normally very lower than the RTT.
Even in case of TCP the CQI keeps looking like a decreasing scale in uplink (figure 5.12) and constant (at maximum index) in downlink (figure 5.13).

5.9 Real scenario with eNodeB mode communication in TCP and UDP

This case concerns the absence of D2D as communication technology. The only way for the 2 UEs to communicate is through the network with the connection with the eNodeB.
In this configuration, UEs run a VoIP application (using UDP as transport layer

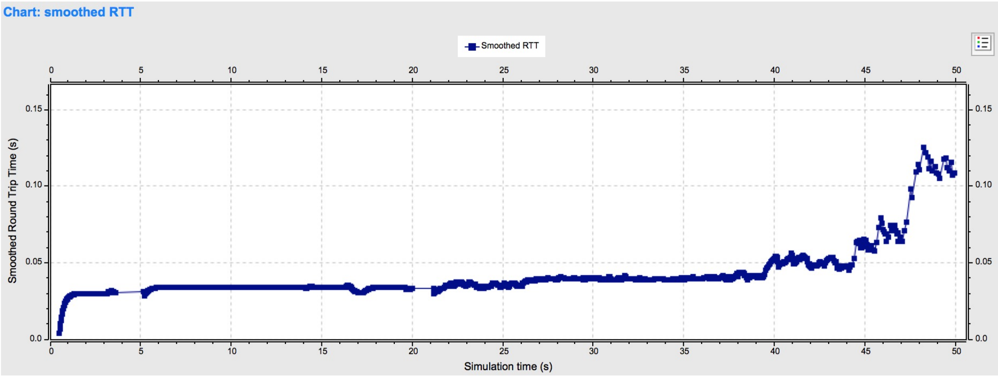

Figure 5.11: Smoothed RTT.

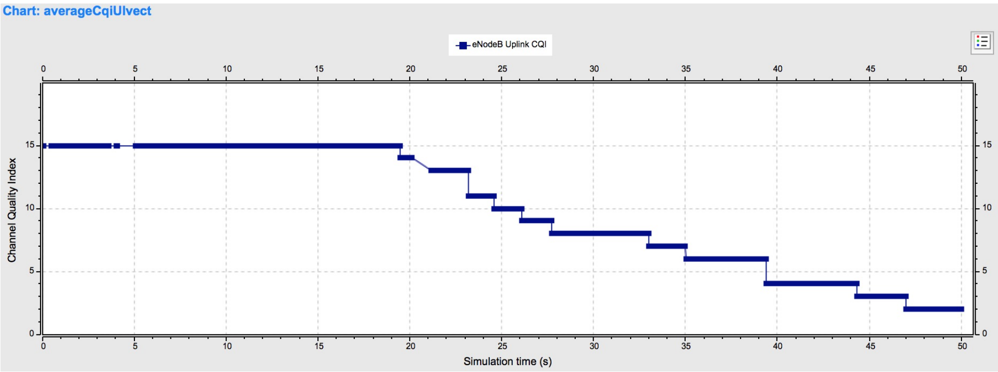

Figure 5.12: Average Uplink CQI measured from the eNodeB using TCP.

protocol). They communicate using the traditional infrastructure mode (two-hop path through the eNodeB).
Disturbances are also active (fading and shadowing model implemented in the channel during the simulation) to recreate a real environment in which operate. Still we have only 2 User Equipments so our network will be underpopulated.
We have collected a series of results respectively for a packet of 8, 128 and 1024 bytes that has been sent using first UDP and then TCP. The position of the 2 UEs (specified by the code below, part of the ini file) is varying from 500 meters of distance from the eNodeB to 100 meters. While the x axis is moving closing to the eNodeB, the y axis of the 2 UEs are fixed and they are at a distance of 5 meters between each others. Our main goal is to observe the changing of the CQI respect to the distance and the delay/latency behavior in time evolution. The same operation was repeated 3 times (one for each packet size).

```
#eNodeB position
*.eNodeB.mobility.initialX = 500m
```

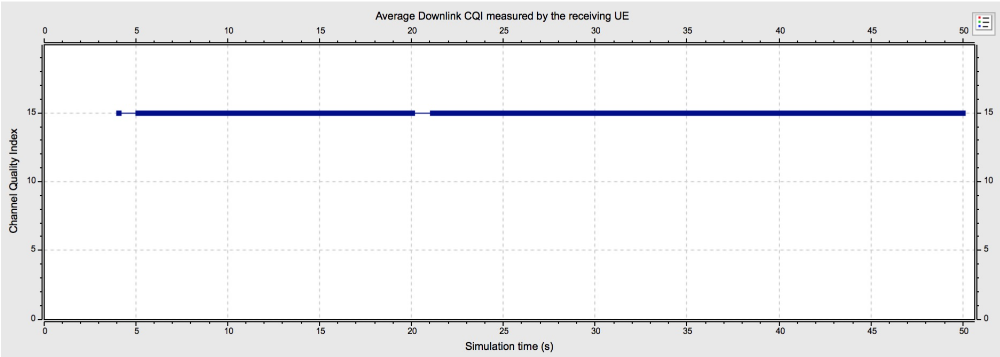

Figure 5.13: Average Downlink CQI measured from the receiving UE using TCP.

```
*.eNodeB.mobility.initialY = 400m

#position of the UE1 (TX0)
*.ueD2DTx[0].mobility.initialX = 1000m
*.ueD2DTx[0].mobility.initialY = 405m

#position of the UE2 (RX0)
*.ueD2DRx[0].mobility.initialX = 1000m
*.ueD2DRx[0].mobility.initialY = 400m
```

Setting the x coordinates of both UEs at 1000 meters means collocating them at a distance of $1000 - 500 = 500 meters$ from the actual eNodeB position (500 meters) that remain fixed, as we have done in the previous line of codes in the ini file.
To set the size of the UDP packet we have added this line of code in the ini file:

```
*.ueD2DTx[0].udpApp[*].PacketSize = 1024
```

And for the TCP protocol:

```
*.ueD2DTx[0].tcpApp[*].sendBytes = 1024B
```

5.9.1 Delay/latency and CQI

The 2 main values we are interested into are the delay (or latency in case of TCP) to understand exactly how the distance from the eNodeB influences our communication and the CQI. The channel quality index in our case is useful because it makes clear the fact that for certain distance the communication can happen but with very low quality.
The following table represents our results for the 3 different size of packet (8, 128

and 1024 bytes).

Starting from table 5.2 we can observe that trasmitting a packet with a quite big payload like 1024 bytes means expecting a bigger delay the further the UE is from the eNodeB. We reduce the delay from 1.44 seconds to 27.5 ms only moving closer the device. If we observe the graphs of the delay in different positions we can also highlight the fact that the jitter error is very present at 500 meters distance (figure 5.14), while at 100 meters is almost zero (5.15) and does not affect too much the communication.
The yellow cells of table 5.2 represent the best situation, for the delay and CQI point of view, using UDP and TCP as transport protocols. It makes sense to have a higher TCP value because in TCP we measure the round trip time and in some case also the retransmission time.
All the values in the table are obtained averaging 3 different values obtained from 3 SimuLTE simulations with different seeds. This assures us that every simulation is randomly different from the other and it can give results or in certain cases it does not give any results. The 100 meters distance simulation gives always results because the quality of the channel is normally good enough to make the communication works for every simulations. Altought, this is not true for every distance. For example at 500 meters distance from the eNodeB only one simulation over 3 gives a result.

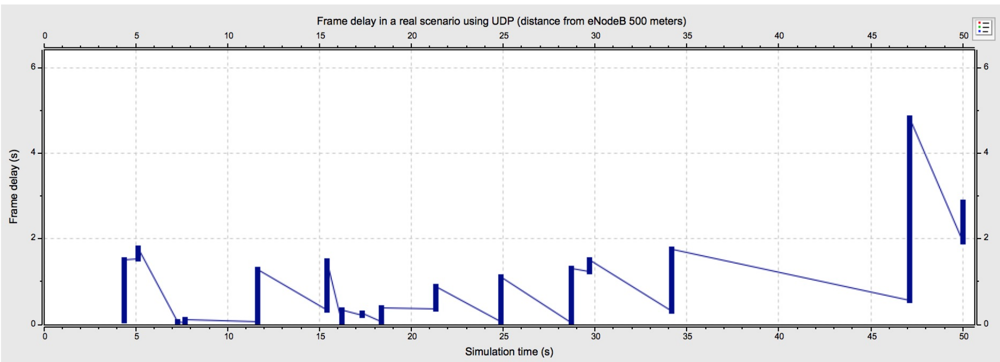

Figure 5.14: Frame delay using UDP with the UEs at 500 meters distance from the eNodeB.

Table 5.3 and table 5.4 shows the obtained results for a packet of 8 and 128 bytes.
As expected the delay and the TCP latency have decreased reasonably. Indeed the packet is smaller so we need less time to transmit it. The difference between 8 bytes and 128 bytes does not influenciate the TCP that can trasnmit successfully with a latency of 37.7 ms at a distance of 100 meters. In general the TCP communication is

		Distance from eNodeB (meters)				
		500	400	300	200	100
Used protocol	UDP	1.44 s	1.02 s	49.4 ms	29.5 ms	27,5 ms
	TCP	no packets	no packets	56 ms	45 ms	45.3 ms

Table 5.2: Delay/latency values collected transmitting a 1024 bytes packet using UDP and TCP.

		Distance from eNodeB (meters)				
		500	400	300	200	100
Used protocol	UDP	34 ms	30.8 ms	24.5 ms	20.7 ms	21.4 ms
	TCP	no packets	no packets	56.1 ms	48.2 ms	37.7 ms

Table 5.3: Delay/latency values collected transmitting a 128 bytes packet using UDP and TCP.

		Distance from eNodeB (meters)				
		500	400	300	200	100
Used protocol	UDP	29.1 ms	21.2 ms	19.7 ms	19.4 ms	17.1 ms
	TCP	no packets	no packets	63.2 ms	39.2 ms	37.7 ms

Table 5.4: Delay/latency values collected transmitting a 8 bytes packet using UDP and TCP.

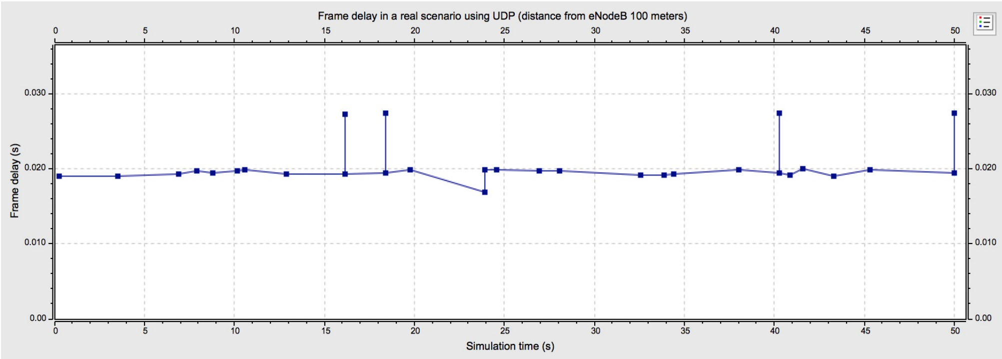

Figure 5.15: Frame delay using UDP with the UEs at 100 meters distance from the eNodeB.

more complex to deploy because it is a reliable protocol that uses acknowledgements and retransmissions mechanism that can slow down the transmission and increase the latency calculation. A better evaluation of the quality of the communication in the cell can be done looking at the CQI in the following tables.

As we can observe from the data, up to 300 meters of distance in case of UDP the CQI is stable at 2 both in Uplink and Downlink. This means that the communication can happen but it lacks of quality and if we have to build a cellular cell we should not overpass 300 meters of radius even if the UDP can transmitt also at more than 300 meters.
For the TCP there are more constrains because the simulation does not give us any results at 400 and 500 meters. This means to have a decent CQI we should stay closer to the eNodeB (up to 250/300 meters) to guarantee a communication.

5.10 Multiple pairs of UEs

Up to now we have studied the network in the condition in which we have no other active users besides the 2 UEs communicating with each other. SimuLTE lets us simulate also the case in which there are other couples of UEs communicating with D2D technology or without it.
In case we don't have D2D technology the UEs run a File Transfer application (using TCP as transport layer protocol) and they communicate using the traditional infrastructure mode (two-hop path through the eNodeB). We have then kept the same network specifications and users but added other 4 couples. There a total of 10 active users now in the network.

In this case we have also reported the smoothed RTT that can depict the curve behaviour in a better way. Respect to the scenario in which we don't have other users (depicted in figure 5.16) we can see that we start more or less with the same latency values (around 40 ms) then we drastically increase the further the UE is

		Distance from eNodeB (meters)				
		500	400	300	200	100
Used protocol	UDP	2/2	2/2	2/2	4/2	14/7
	TCP	no packets	no packets	8/2	15/2	15/6

Table 5.5: Channel quality index (CQI) values collected transmitting a 1024 bytes packet using UDP and TCP.

		Distance from eNodeB (meters)				
		500	400	300	200	100
Used protocol	UDP	2/2	2/2	2/2	6/2	14/7
	TCP	no packets	no packets	8/2	15/2	15/6

Table 5.6: Channel quality index (CQI) values collected transmitting a 128 bytes packet using UDP and TCP.

		Distance from eNodeB (meters)				
		500	400	300	200	100
Used protocol	UDP	2/2	2/2	2/2	2/6	14/8
	TCP	no packets	no packets	8/2	15/2	15/6

Table 5.7: Channel quality index (CQI) values collected transmitting a 8 bytes packet using UDP and TCP.

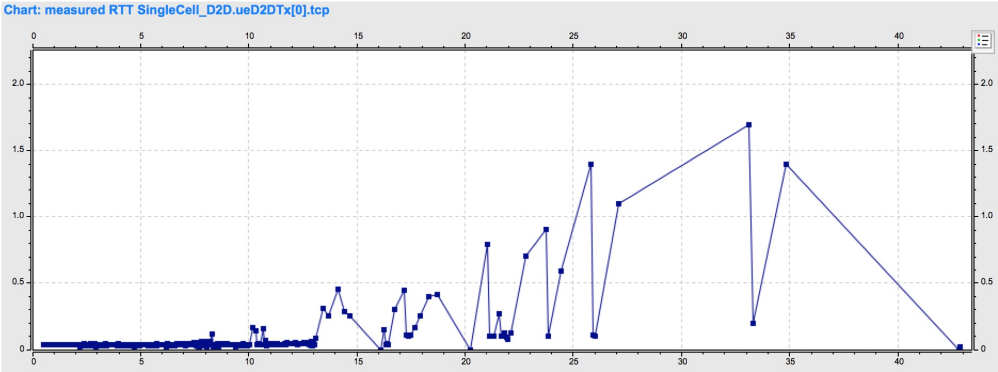

Figure 5.16: Measured RTT for TCP case in presence of multiple users communicating in pairs.

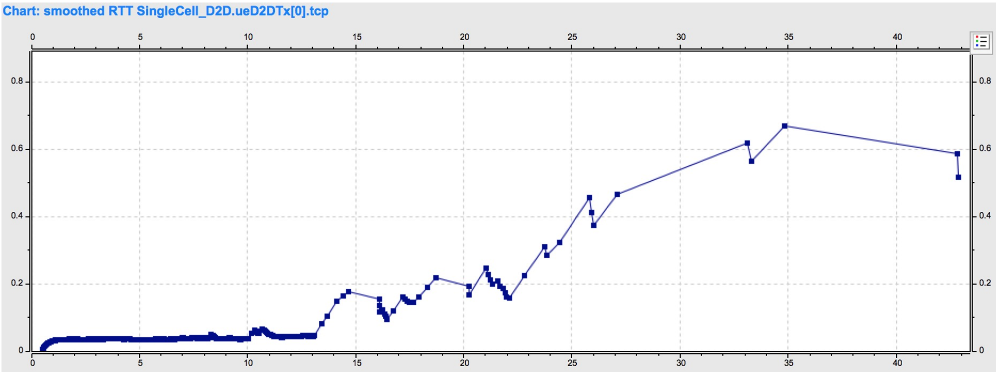

Figure 5.17: Smoothed RTT for TCP case in presence of multiple users communicating in pairs.

from the other UE so to the eNodeB. If we compare the previous smoothed RTT with the current one we can see that now the behaviour is faster to increase so it means that presence of more devices can create interference and disturb the other ones. From 250 meters our latency is in average greater than 0.4 seconds that are very high values.

I have done the same experiment using also the D2D technology. In this case we have measured values until 8 seconds that means 80 meters of distance between UEs. After 80 meters we have probably the switch to eNodeB communication type so the simulator doesn't record the RTT anymore. Here the RTT stays in the limit of 50 ms up to the distance of 25 meters between UEs, then it strongly increases up to 150 ms. This means that if we are considering a scenario with disturbances (fading and shadowing), multiple vehicles around the 2 communicating vehicles the consequences would be an increasing of the latency with big distances. Therefore the 2 UEs need to be close to each other of maximum 30 meters to give good performances.

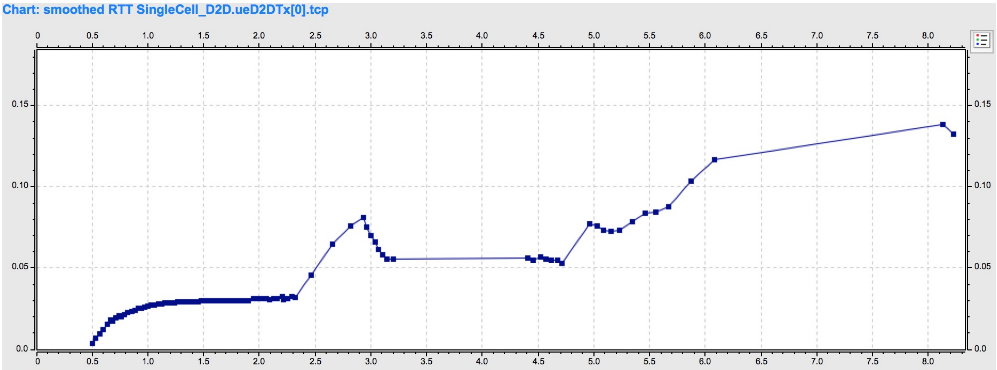

Figure 5.18: Smoothed RTT for TCP case in presence of multiple users communicating in pairs and for the duration of the D2D communication.

5.11 Conclusions

The goal of the second group of simulations (the real scenario) was to identify the main parameter factor that influences a mobile communication in a single cell, considering a standard communication with the eNodeB and without the D2D capabilities of UEs. Inside the cell was also present noise, path loss model and interference to simulate a real scenario. As we tested only the single cell environment we can say that all this results stand if the UEs are within the same cell. We don't have a cell range or limitation with SimuLTE but from the collecting data we can estimate an ideal cell range to have the best communication in mobility.
The idea at the base of the standard mobile communication is that the main factor is represented by the distance from the eNodeB. The further the UEs are from the eNodeB, the weaker will be the signal received and therefore the signal will suffer of high path loss and more interference. At high distances it is harder to send packets with bigger payload. Indeed, as we can see from the tables 5.2, 5.3 and 5.4, sending a packet of 8 bytes will take around 17 ms at a distance of 100 meters from the eNodeB, while at 500 meters the delay is 29 ms. This two numbers are highly different and they underline the distance dependence for a good communication. This data are obtained using UDP as a transport protocol.
Another important factor is the protocol used for the transport. Returning to the case of the 8 bytes packet, the data changed radically using TCP to 37.7 ms for a 100 meters distance. Of course we are considering a latency and not only a delay, but the TCP is not the best protocol in case of big distances. In fact simulations could not detect any received packets at distances of 500 and 400 meters.
Increasing the size of the packet I obtained bigger latency and delay values as represented in table 5.2, 5.3 and 5.4. This was expected, because we need more time

to send bigger sized packet.
To clearly understand the condition of the channel during this experiment we can refer to tables 5.5, 5.6 and 5.7 that represent the Channel Quality Indicator. The CQI is normally high at short distances and if it is smaller than 9, it usually represents a situation in which channel quality is not enough to handle the communication.
The last factor to consider is surely the presence of multiple pairs of UEs. The last tests were performed with 5 pairs of UEs to observe how the communication will change if the cell is filled with users transmitting packets at the same time. This test was performed in TCP and from figure 5.16 we can clearly see that at short distances our couple of UEs can transmit at decent latency, while at high distance the RTT is more and more unstable. The presence of too many devices, in fact, increases the interference inside the cell.

Bibliography

[1] J. S. Stefan Parkvall, Erik Dahlman, *4G, LTE-Advanced Pro and The Road to 5G, Third Edition*. Elsevier Ltd, 2016.

[2] ETSI, *TS 123 285 V14.4.0*, 10 2017.

[3] M. O. Magri Hicham, Noreddine Abghour, "Device-to-device (d2d) communication under lte-advanced networks," *RITM Research Lab, ESTC, Hassan II University, Casablanca, Morocco*, 2016.

[4] G. Dimitrakopoulos, *Current Technologies in Vehicular Communication*. Springer International Publishing, 2017.

[5] W. Chen, *Vehicular Communications and Networks. Architectures, Protocols, Operation and Deployment*. Elsevier Ltd, 2015.

[6] ETSI, *EN 302 665 V1.1.1*, 09 2010.

[7] ETSI, *TS 122 185 V14.3.0*, 03 2017.

[8] Wikipedia, `https://en.wikipedia.org/wiki/Autonomous_car#Classification`.

[9] Tutorialspoint, `https://www.tutorialspoint.com/lte`.

[10] Techtarget, `https://searchnetworking.techtarget.com/definition/5G`.

[11] Techtarget, `https://www.techtarget.com`.

[12] GSMA, *Cellular Vehicle-to-everything (C-V2X), enabling intelligent transport*.

[13] V. S. Inc, *LTE Multimedia Broadcast Multicast Services (MBMS)*, 2015.

[14] T. Toukabri, *CVS : a framework architecture for D2D-based cellular vehicular services in 4G networks and beyond*. Networking and Internet Architecture [cs.NI]. Institut National des Télécommunications, 2016.

[15] A. R. J. Schlienz, *Device to Device Communication in LTE Whitepaper*, 2016.

[16] ETSI, *TS 123 303 V15.1.0*, 07 2018.

[17] D. Q. Xi Zhang, *Quality, Reliability,Security and Robustness in Heterogeneous Networks*. Springer International Publishing, 2010.

[18] S. Singh, "D2d and v2x communications," *Industrial Technology Research Institute Taiwan*, 2017.

[19] ETSI, *EN 302 636-1 V1.2.1*, 04 2014.

[20] G. Araniti, "Lte for vehicular networking: A survey," *IIEEE Communications Magazine, vol.51, no. 5, pp. 148-157*, May 2013.

[21] V. N. Stea, "Simulating lte/lte-advanced networks with simulte," *Dipartimento di Ingegneria dell'Informazione, University of Pisa, Italy*, 2016.

[22] V. N. Stea, “Modeling unicast device-to-device communications with simulte,” *Dipartimento di Ingegneria dell’Informazione, University of Pisa, Italy*, 2016.

[23] OMNeT++, *https://www.omnetpp.org*.

[24] Inet, *https://inet.omnetpp.org*.

[25] SimuLTE, *http://simulte.com*.