POLITECNICO DI TORINO

Department of Electronics and Telecommunications

Master Thesis Course in

Communications and Computer Networks Engineering

Master thesis

State of the art of Cellular Vehicular Communication in 5G networks

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Abbreviation	Acronym
3GPP	3rd Generation Partnership Project
5G-NR	5th Generation New Radio
BSC	Base Station Controller
CAM	Cooperative Awareness Message
CDMA	Code Division Multiple Access
CoMP	Coordinated Multi Point operation
C-V2X	Cellular Vehicle-to-Everything
CSR	Candidate Sub-frame Resource
D2D	Device-to-Device
DENM	Decentralized Environmental Notification Message
DSRC	Dedicated Short Range Communications
EDGE	Enhanced Data Rates in GSM
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
eMBMS	evolved Multimedia Broadcast and Multicast Service
eNode-B	evolved Node-B
EPC	Evolved Packet Core
FCC	Federal Communications Commission
FDD	Frequency Division Duplex
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile communications
HLR	Home Location Register
HSPA	High Speed Packet Access
HSS	Home Subscriber Server
IEEE	Institute of Electrical and Electronic Engineers
IMS	IP Multimedia Subsystem
ITS	Intelligent Transport Systems
ITU	International Telecommunications Union
LTE	Long Term Evolution

Abbreviation	Acronym
LTE-A	LTE-Advanced
M2M	Machine-to-Machine
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
NFV	Network Function Virtualization
OFDM	Orthogonal Frequency Division Multiplexing
PCRF	Policy Control Resource Function
PDN-GW	Packet Data Network Gateway
ProSe	Proximity Services
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RSRP	Reference Signal Received Power
RSSI	Received Signal Strength Indicator
RSU	Road Side Unit
S-GW	Serving Gateway
SDN	Software Defined Networking
TDD	Time Division Duplex
TTI	Transmission Time Interval
UE	User Equipment
UMTS	Universal Mobile Terrestrial System
URLLC	Ultra Reliable Low Latency Communications
VANET	Vehicular Ad-hoc Network
VoLTE	Voice over LTE
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
WLAN	Wireless Local Area Network

1 INTRODUCTION

Today, being connected become the essential part in the modern society. Everyone can get information about almost anything at any time. The mode of communication, starting from the first wired networks over a hundred years ago, now evolved in the mobile cellular networks that we know and use every day. These cellular networks at first were used only for a communication between people, and now are finding much wider use in many other areas. One of them is the vehicular industry.

1.1 VEHICULAR NETWORKS

Over the last twenty years, with the increase of the number of vehicles, the amount of traffic accidents is in a rapid growth too. This is one of the main incentives for development of efficient intelligent transportation systems (ITSs), and eventually safer, greener and smarter roads. One of the solutions we have come up with is to create a Vehicular Ad-hoc Networks (VANET) that would enable exchange of information between vehicles. These networks are adapted to support the highly dynamic nature of the vehicles as network nodes, fulfill their mobility requirements, but with a limited effective network coverage.

Additionally, the vehicular OEMs came up with a new paradigm called "Autonomous Driving". These vehicles are intended to be able to operate the vehicle completely autonomously. To accomplish this, we must give them a certain awareness of the surrounding.

Fig.1 portrays the awareness that the vehicle can get.

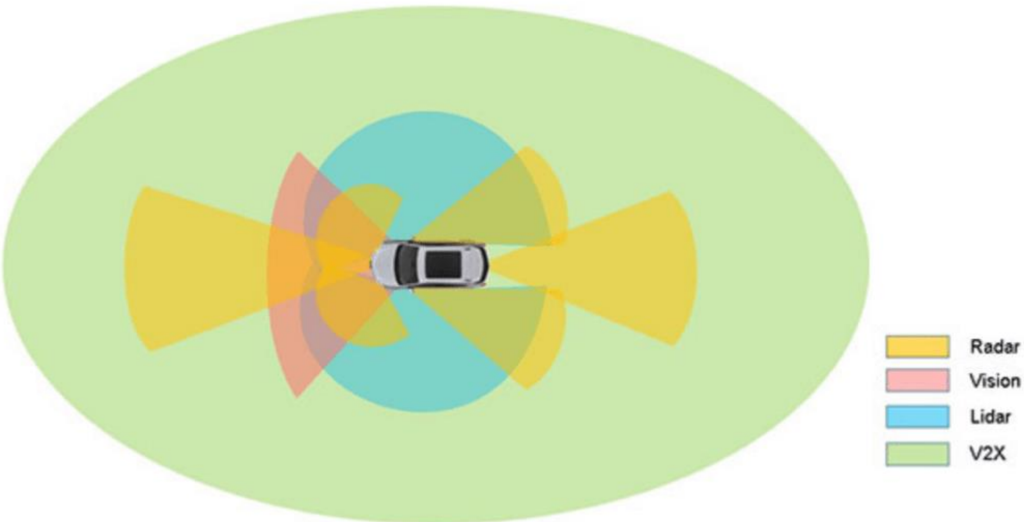

Figure 1 Vehicular Awareness using different technologies, Source: www.cbinsights.com

It can be split in two parts:

- Short range awareness: Onboard sensors in the vehicles
- Long range awareness: By enabling some mode of communication with the nearby vehicles and the nearby infrastructure.

In this thesis, we will be focusing on the second part, the long-range awareness technologies. Some of main use-cases for these technologies are:

- Forward collision warning
- Lane change warning/blind spot warning
- Emergency electric brake light warning
- Intersection movement assist
- Emergency vehicle approaching
- Roadworks warning
- Platooning

1.2 INTRODUCTION TO VEHICULAR COMMUNICATIONS

To help prevent vehicular accidents, facilitate eco-friendly driving and provide better and more accurate and real-time traffic information, the research community decided to start developing a new technology that would enable communication among vehicles or vehicles and road infrastructure while applying the principles used in Mobile Ad-hoc Networks.| This technology was named Vehicular Ad-hoc Networks (VANETs). VANETs rely on real-time communication among vehicles, pedestrians and roadside sensors located along transportation systems. Because of the nature of the messages they exchange, which are usually safety messages, they require low latency and high reliability. These requirements are very challenging to be met by the networks we have. However, with the technological advancement, we are moving towards the direction to satisfy and overcome these obstacles.

VANETs operate with little or no permanent infrastructure and are characterized by:

1. High mobility
2. Fixed road networks
3. Predictable speed and traffic patterns
4. Very few power constraints or storage limitations

The V2X paradigm in VANETs supports the following communication use cases:

- Vehicle-to-vehicle (V2V): the message exchange is between two neighboring vehicles. It can be unicast (one-to-one vehicle communication) or multicast/broadcast (one-to-many) which is usually used to send messages including their location, road warnings etc.
- Vehicle-to-infrastructure (V2I): the message exchange is between a vehicle and a road infrastructure (Road-Side Units (RSUs) in the DSRC standard).
- Vehicle-to-network (V2N): direct message exchange between the vehicle and the cellular network.
- Vehicle-to-pedestrian (V2P): enables direct communication between a vehicle and a pedestrian or multiple pedestrian within close proximity. The V2P is conducted directly or using network infrastructure.

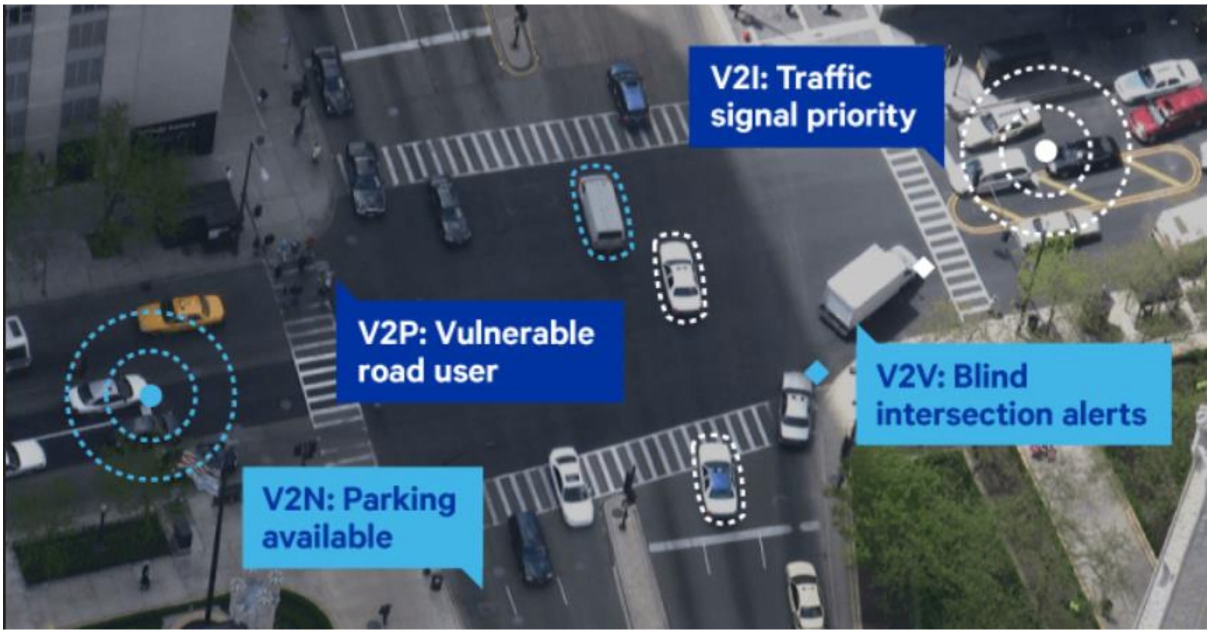

Figure 2 V2X use cases; Source: Qualcomm

These vehicular networks can help improve safety, the environment and mobility. The primary applications of VANETs are:

- **Safety**: When talking about automotive telematics, the vehicular safety is the most important factor. Message transmission can be either periodic or event driven. Periodic messages are used to keep drivers informed with details such as the speed of the speed of the vehicles surrounding them, optimal acceleration and deceleration settings etc. The event driven messages, in contrast, are triggered when there is a sudden change in the traffic, such as a sudden fast braking of a vehicle to warn the driver to start braking and/or decelerate, warnings when emergency vehicle is approaching, warning due to a possible collision with a vehicle coming to an intersection or from the rear side of the vehicle and many more use cases. These messages are not just useful for the nearby drivers, but also for the farther vehicles, allowing them to undertake early countermeasures to prevent even bigger accidents such as chain-reaction collisions.

- **Environmental**: to reduce fuel consumption and increase safety of both passenger cars and trucks, VANETs introduced the Platooning application. What this application does is it detects a group of vehicles and links them as a convoy, where the vehicles automatically maintain a set, close distance between each other. As a result, we get more optimized roads and increased capacity of roads. By suggesting a driving speed, the vehicles reduce their fuel consumption, and in turn, reduce their carbon footprint.
- **Convenience and commercial**: the non-safety applications are focused towards providing more information to the driver, such as travel time saving, route planning and in-car entertainment.

1.2.1 Dedicated Short Range Communications (DSRC)

The V2V (Vehicle-to-Vehicle) concept were first introduced back in the 1999, when the FCC (Federal Communications Commission) set the 5.9 GHz band for V2V communication. But the development of this technology did not start until 2002 where the 802.11p protocol (also known as Wireless Access in Vehicular Environment or WAVE in the USA and as ITS-G5 in Europe) was introduced. This protocol was the basis of the dedicated short-range communications (DSRC). It is used for direct communication between moving vehicles and is independent of any cloud or cellular infrastructure. In 2012, IEEE first published the specification of the WLAN-based V2X (802.11p). It was considered as an enhancement to the 802.11 standard (or more recognized as Wi-Fi).

The traffic infrastructure in DSRC is composed of so-called Road-Side Units (RSU) and their main applications are:

- Traffic monitoring
- Charging of congestions
- Access and parking system
- Enforcement systems

And some of the parameters it provides are:

- Road direction
- Start of RSU monitoring range location
- Road size
- Road name and descriptive direction
- End of congestion location

Although it has been introduced almost two decades ago, the mass production of DSRC-based V2X started in 2018 and it is still ongoing.

1.2.2 LTE-V or C-V2X

In 2016 a new V2X technology emerged, based on the preexisting cellular networks technology and it is called Cellular Vehicle-to-Everything (C-V2X). It was first introduced in the Release 14 of the 3GPP organization that is in charge for the cellular radio standards. In addition to the direct communication (V2V, V2I), C-V2X also supports wide area of communication over a cellular network (V2N). The additional mode of communication and the native migration path towards 5G are the two most important advantages over 802.11p based V2X systems. It also operates in the 5.9 GHz band as the DSRC.

Both technologies will be elaborated in further details in the following chapters.

1.3 Motivation

As one of the most emerging technologies today, before being deployed and put to real-world use, the V2X technology, as all others, needs to be properly tested and evaluated. The most feasible way to do this, besides the theoretical approach of performance evaluation, is to do a real-world simulation. Using simulators, we can mimic the real-world parameters to create an acceptable testbed to assess the performance of the technology. But, creating a perfect simulator is not trivial. It should be modular, customizable, to have a user-friendly experience, and many other important elements. The motivation for this thesis was to explore the V2X technology and introduce the state-of-the-art standardisation support for it as we move towards the 5G networks.

1.4 Goal of the thesis

To this date, the V2X technology is being extensively tested and prepared for deployment. The goal of the thesis is to provide a summary of the technology, including past, present and future implementations. Additionally, we provide a report of the existing simulation tools used to test

V2X, giving a description of how each of them is organized, what programing language they use, their internal structure etc.

This thesis work is meant to be a “handbook” for everyone who is interested to start working on this V2X technology, to provide them with a sufficient amount of information on how the network technologies are organized, to justify why we chose the Cellular-V2X technology, and finally, present a list of available simulators for testing this technology.

2 LTE OVERVIEW AND THE ROAD TOWARDS 5G

In our present-day society, the mobile communication has become not just a commodity, but a necessity. In the past, having a mobile phone was a luxury, but nowadays their number closes down to be almost a phone per person and the expectations are that in the next decade it will surpass it. In this chapter, we will give an overview of the evolution of the cellular networks through the generations, giving an accent to the current and upcoming technologies, LTE and 5G-NR.

2.1 EVOLUTION OF THE CELLULAR NETWORKS: FROM 1G TO 5G

The appearance of first commercial cellular communication systems was in the 1980s, and it is referred to as first generation (1G) cellular networks. They were founded on an analog-based technology able only to provide basic voice services. It was not massively used because of high prices for the services and was considered as a luxury.

Its successor was the 2nd generation cellular networks (2G), or more known as GSM (Global System for Mobile communications). It was introduced at the beginning of the 1990s and were considered as an improvement and future replacement of the 1G networks. It introduced the start of the digital era by using digital, circuit-switched network optimized for full duplex voice communication. Later on, it was expanded by the addition of the GPRS (Global Packet Radio Service) technology, that allowed packet data transport and was further enhanced by the, which enabled packet data exchange with significantly higher data rates. The 2G networks provided: expanded capacity, improved sound quality, better security, short messaging (SMS) and many other improvements over the 1G.

At the start of year 2000, the next cellular technology, i.e. 3G or UMTS (Universal Mobile Telecommunication Systems) started deploying. It was the first project that was developed and maintained by the 3GPP. It was the first cellular network technology whose aim was to provide the users with access to the Internet over mobile devices and laptops. The data rates were sufficient enough to support both voice and video calling, file transmission, web browsing, playing games and many more use cases. It is using CDMA (Code Division Multiple Access) technology. To satisfy the data rate requirements of the users, the 3G systems were enhanced with the HSPA (High Speed Packet Access) technology, allowing maximum theoretical data rates of up to 42 Mbps.

Long Term Evolution (LTE) or 4G, as all previous generations, was expected to and launched at the start of 2010, keeping the 10-year cycle for every generation of cellular advancement. The requirements it should satisfy were specified in 2008, from which, the main one was to support data rates up to 100 Mbps in high-mobility communication scenarios and up to 1Gbps for low-mobility communication scenarios. As a consequence of the high data rates it offered, it enabled support of many applications such as cloud computing, gaming services, VoLTE, video conferencing, HD television etc. As the 3rd Generation, it is developed and supported by the 3GPP. We will discuss the LTE technology in further details in chapter 3.3.

The hottest topic nowadays is the upcoming new, 5th Generation of cellular networks, or 5G-NR (New Radio). It represents a set of innovations in wireless communication technologies meant to support new services such as smart grids, e-health, autonomous driving, augmented reality, wireless industry automation (Industry 4.0) and many more that cannot be met by the older generations. Its deployment is expected to start in 2020. In order to be deployed, first it must meet all the pre-set requirements that will be discussed in one of the following chapters, where we will also give an overview and expectations of the 5G.

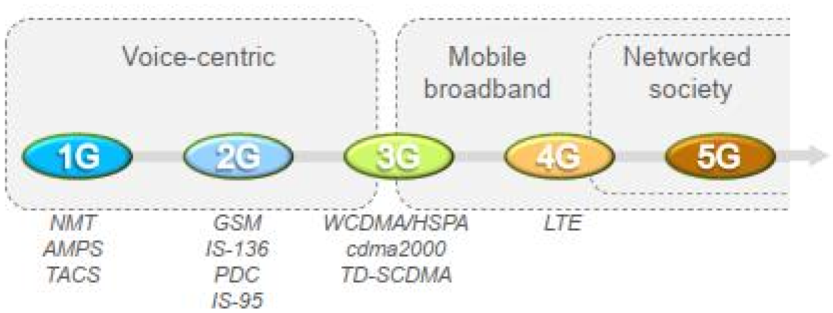

Figure 3 Cellular Networks Generations. (Dahlman, Parkvall and Skold, 2016)

2.2 3GPP (The Third-Generation Partnership project)

After the huge world-wide success of the 2nd Generation of mobile networks (GSM), the Third-Generation Partnership Project or 3GPP started with the purpose to ensure global reach for the 3rd Generation of Mobile networks and to be implemented on global basis. The 3GPP is composed of seven telecommunication standard development organizations (ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, TTC), known as "Organization Partners" and it provides its members with a stable environment to produce the Reports and Specifications that define 3GPP technologies. To facilitate this, the 3GPP was formed to develop the 3G WCDMA and TD-SCDMA technologies in the year of 1999 or known as Release 99. Continuing this trend, the 3GPP continued working on improving the 3G technology introducing new technologies with each release.

2.3 Long Term Evolution (LTE)

The 4G LTE technology first commercial launch was in late 2009 and was followed with a rapid deployment of LTE networks around the world. Since the beginning, it was developed to support packet data and did not support for the circuit-switched voice. Mobile broadband services were the focus, and the requirements on high data rates, low latency and high capacity had to be satisfied. It is important to mention that the LTE technology was the first mobile network technology with worldwide acceptance without any other competing technologies. The main improvements over the 3rd Generation mobile networks (UMTS) were in the following areas:

- A completely new air interface designed to overcome the effects of multipath fading. Instead of spreading the signal over the complete carrier bandwidth (5 MHz), LTE uses Orthogonal Frequency Division Multiplexing (OFDM) that transmits the data over many narrowband carriers of 180 kHz each. Instead of a single fast transmission, the data stream is split into many slower data streams that are transmitted simultaneously. Using these narrowband carriers makes LTE very adoptive to any available bandwidth, starting from 1.25 MHz up to 20 MHz. All LTE capable devices must support all bandwidths, and which one is used depends on the frequency band and the amount of spectrum available with a network operator. All LTE devices must support Multiple Input Multiple Output (MIMO) transmissions, which allow the base station to transmit several data streams over the same carrier simultaneously. Under very good signal conditions, the datarates that can be achieved this way are beyond those that can be achieved with a single-stream transmission. Both FDD and TDD are specified in a single standard. While FDD is the dominating air interface today, it is likely that TDD will find its use in the future.

- The second major change of LTE is the adoption of an all-Internet Protocol (IP) approach. While UMTS used a traditional circuit-switched packet core for voice services, for SMS and other services it inherited from GSM, LTE solely relies on an IP-based core network. The all-IP network infrastructure simplifies the design and implementation of the LTE air interface, the radio network and the core. But, since the GSM and UMTS networks are still used for voice transfer, the first LTE networks used a mechanism referred to as Circuit-Switched Fallback (CSFB) to UMTS and GSM voice call handling. Nowadays, because of the technological development and the huge success of LTE, with current coverage of over 60% and expecting to reach up to 90% global coverage by 2024 [1], the LTE networks and devices became Voice over LTE (VoLTE) capable thus no longer requiring the CSFB to other radio networks. The LTE standard leaves the choice of protocols to be used below the IP layer open, which means that the physical infrastructure becomes completely transparent and interchangeable.
- LTE introduces mobility support with very high speeds up to 350 km/h. This allows LTE to find its use in many applications such as, railways communication, vehicular communication etc.

With the 3GPP Release 10, new ideas to further push the limits are specified as part of the LTE-Advanced project.

2.3.1 LTE Network Architecture and its Interfaces

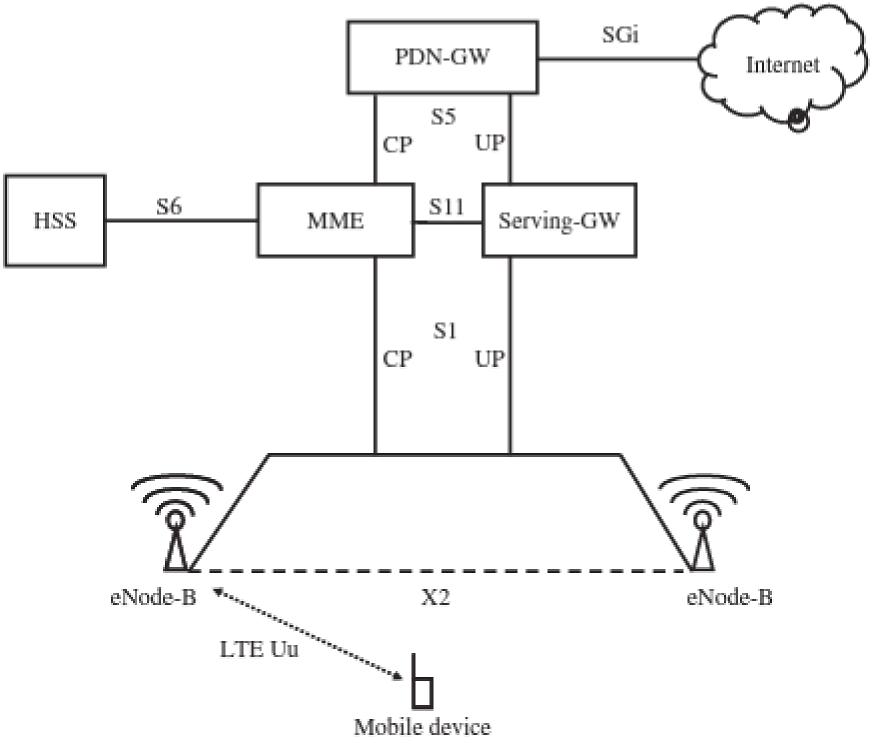

Figure 4 LTE Network Overview, (Sauter, 2011)

The general LTE network architecture is similar to that of GSM and UMTS. It is split into a radio network part and core network part. The number of logical network nodes has been reduced to reduce the cost and latency in the network. Figure 4 gives an overview of the LTE architecture and its components. The eNode-B and the User Equipment belong to the Evolved UMTS Terrestrial Radio Access Network E-UTRAN, while the MME, S-GW and PDN-GW belong in the Evolved Packet Core (EPC). In the following section, we will briefly discuss each of the network elements and their corresponding interfaces.

2.3.1.1 LTE User Equipment (UE) and the Uu Interface

In the LTE specifications, the mobile device is referred to as the User Equipment. In 3GPP Release 8, five different UE classes have been defined, the first one covering the worst case scenario with maximum downlink speed of 10 Mbps and the last class covering the best case scenario, reaching speeds up to 300 Mbps downlink, 75 Mbps uplink, up to 4x4 MIMO streams and it is the only class that supports 64-QAM modulation in the uplink direction. All 5 classes support the 64-QAM modulation in the downlink direction.

Most LTE networks and UEs use 2x2 MIMO, but nowadays the class 5 UEs can even use 4x4 MIMO if the network supports it and the conditions are ideal. Most of the LTE devices are backwards compatible with the GSM and UMTS technologies.

The interface between the eNodeB and the UE is known as the *Uu interface*. This is the only interface in the wireless networks that is always wireless. The theoretical peak datarates that can be achieved over the air depends on the amount of spectrum used by the cell. In a case of a 20 MHz band and a 2x2 MIMO configuration, that is the typical for the LTE networks and mobile devices, peak speeds up to 150 Mbps can be reached.

2.3.1.2 The eNode-B and the S1 and X2 Interfaces

The biggest change from the 3rd generation UMTS network architecture is in the base station, known as eNode-B in the LTE networks. The name has been derived from the UMTS base station, whose name was Node-B and an 'e' is added referring to 'evolved'. The eNode-B consists of three major elements:

- The antennas, which are the most visible parts of a mobile network;
- Radio modules that modulate and demodulate all signals transmitted or received on the air interface;
- Digital modules that process all signals transmitted and received on the air interface and act as an interface to the core network over a high-speed backhaul connection.

Unlike in UMTS where the base station at the beginning was little more than an intelligent modem, LTE base stations are autonomous units. It was decided that most of the functionality that was previously part of the Radio Network Controller (RNC) to be integrated into the base station itself. This gives the eNode-B much more responsibility than just the air interface such as:

- User management and scheduling air interface resources;
- Establishing the QoS, such as latency, minimum bandwidth, maximum throughput etc;
- Load balancing
- Mobility management
- Interference management

For example, the eNode-B decides on its own to hand over ongoing data transfers to a neighbouring eNode-B. It also executes the handover autonomously from higher layer nodes of the network, which are only informed of the procedure once it has taken place.

The interface between the eNode-B and the core network is referred to as the *S1 interface*. It is usually carried either over a high-speed copper or fibre cable, or alternatively over a high-speed microwave link. Transmission speeds from several hundred Mbps to couple of Gbps are required for most eNode-Bs as they usually consist of three or more sectors. The S1 interface is split into two logical parts, which are both transported over the same physical connection.

- User data is transported over the S1 User Plane (S1-UP) part of the interface.
- Control data is transported over the S1 Control Plane (S1-CP) part of the interface.

In the previous generations of networks, base stations were controlled by a central device, such as the Base Station Controller (BSC) in GSM and the Radio Network Controller (RNC) in UMTS. In LTE, this concept was abandoned to remove latency from the user path and to distribute these management tasks to reduce complexity. As a consequence of this autonomy, the LTE eNode-Bs are directly connected with each other over an interface referred as the *X2 interface.* This was done with two purposes:

1. Handovers are now controlled by the base stations themselves. If the target cell is reachable over the X2 interface, the cells communicate directly with each other. Otherwise, the S1 interface and a core network are employed to perform the handover.
2. The second use of the X2 interface is for the interference coordination. As in UMTS, neighbouring LTE base stations use the same carrier frequency so that there are areas in the network where mobile devices can receive the signals of several base stations. If the signals of two or more eNode-Bs have similar strength, they interfere with each other. The X2 interface is used so that the neighbouring eNode-Bs can communicate between themselves and agree on methods to mitigate or reduce the problem.

2.3.1.3 The Mobility Management Entity (MME)

The network node responsible for all the signalling exchanges between the base station and the core network and between users and the core network is the Mobility Management Entity (Figure 4). In large networks, there are usually many MMEs to cope with the amount of signalling and due to station redundancy. As the MMEs are not involved in the air interface matters, the signalling it exchanges with the radio network is referred as Non-access Stratum (NAS) signalling. In particular, the MME is responsible for the following tasks:

- Authentication
- Establishment of bearers

- NAS mobility management
- Handover support
- Interworking with other radio networks
- SMS and voice support

For all of these tasks, a number of different interfaces such as the S5, S6a, S11 and Sgs are used. Their connection is shown in Figure 4. When compared to GPRS and UMTS, the tasks of MMEs are the same as those of the SGSN. The difference between them is that the MME deals only with the signalling tasks described above and leaves the user data to the Serving Gateway (S-GW), described in the next section.

2.3.1.4 The Serving Gateway (S-GW)

The Serving Gateway (S-GW) is responsible for managing user data tunnels between the eNode-B in the radio network and the Packet Data Network Gateway (PDN-GW), which is the gateway router to the Internet. More about PDN-GW in the next section. On the radio network side, it terminates the S1-UP GTP tunnels, and on the core network side, it terminates the S5-UP GTP tunnels to the gateway to the Internet. Tunnel creation and modification are controlled by the MME, and commands to the S-GW are sent over the S11 interface.

In the standards, the MME and the S-GW are defined independently allowing them to be run on the same or different network nodes. This allows an independent evolution of signalling capacity and user data traffic.

2.3.1.5 The Packet Data Network Gateway (PDN-GW)

The Packet Data Network Gateway (PDN-GW) is the third core network node. This node is the gateway to the Internet it can also be used to interconnect to intranets of large companies over an encrypted tunnel to offer the employees of those companies a direct access to their private internal networks. The PDN-GW terminates the S5 interface. On the user plane, this means that the data packets for a user are encapsulated into an S5 GTP tunnel and forwarded to the S-GW which is currently responsible for that user. The S-GW then forwards the data packets over the S1 interface to the eNode-B that currently serves the user, from which it is then sent over the air interface to the user’s mobile device. The PDN-GW is also responsible for assigning IP addresses to mobile devices. Several IP addresses might be necessary in cases where the device uses services that are part of the network operator’s internal network such as the IP Multimedia Subsystem (IMS). The PDN-GW also plays an important role in international roaming scenarios.

In theory, the MME, S-GW and PDN-GW could all be implemented in a single device. In practice, the functionality is usually decoupled because of the different evolution of traffic and signalling load.

2.3.1.6 The Home Subscriber Server (HSS)

LTE shares its subscriber database with GSM and UMTS. In these systems, the database is referred to as the Home Location Register (HLR) and the Mobile Application Part (MAP) is used as the protocol between the Mobile Switching Center (MSC) and the SGSN on the one side and the HLR on the other side. In LTE, an IP-based protocol referred to as DIAMETER is used to exchange information with the database. Further, the name of the database has been changed to Home Subscriber Server (HSS). In practice, the HLR and the HSS are physically combined to enable seamless roaming between the different radio access networks. Each subscriber has a record in the HLR/HSS and most properties are applicable for communicating over all radio access networks. The most important user parameters in the HSS are:

- The user's International Mobile Subscriber Identity (IMSI), which uniquely identifies a subscriber;
- Authentication information that is used to authenticate the subscriber and to generate encryption keys on a session basis;
- Circuit-switched service properties such as the user's telephone number, referred to as the Mobile Subscriber Integrated Services Digital Network (MSISDN) number and the services the user is authorized to use.
- IMS-specific information
- The ID of the current serving MSC
- The ID of the SGSN or MME, which is used in case the user's HSS profile is updated to push the changes to those network elements.

2.3.1.7 Billing, Prepaid and Quality of Service

The network nodes described above are the main components of the LTE architecture that are required to offer network connectivity to the user. In addition, there are several other supporting network components and interfaces used to complement the network with additional services.

- To charge mobile subscribers for their use of the network, billing records are created, for example, on the MME. Then, they are collected and sent to a charging system, which once a month (or as the contract specifies) generates an invoice that is sent to the customer. This is more known as offline billing or postpaid billing.

- Another billing method is the online charging, which lets subscribers to buy vouchers for certain cervices or a certain amount of data. This service is referred to as prepaid billing.
- To provide data usage information to the user, a network function that monitors the data usage of each customer is used. This allows postpaid users to buy additional data volume which is then invoiced via their monthly bill.
- The Policy Control Resource Function (PCRF) is used to ensure the QoS that the customer has agreed upon. What it does is, it translates the user's application request and sends commands to the PDN-GW and the S-GW, which in turn, enforce the QoS request in the core and access network.

2.4 LTE-ADVANCED

In 2013, to further improve LTE, 3GPP introduced the new LTE Release 10, often referred as LTE-Advanced. It was meant to provide higher bitrates in a cost-efficient way and, at the same time, completely fulfil the requirements set by the ITU and IMT. It offered:

- Increased peak data rate, up to 3Gbps in Downlink and up to 1.5Gbps in Uplink
- Higher spectral efficiency, from a maximum of 16 bps/Hz in Release 8 to 30bps/Hz
- Increased number of simultaneously active subscribers
- Improved performance at cell edges

All of the improvements mentioned above were meant to be realised with new functionalities Release 10 introduced in LTE-Advanced and they are:

- **Carrier Aggregation**: a possibility to use different carriers simultaneously. The carriers are aggregated and jointly used for transmission to/from a single terminal. Each aggregated carrier is referred to as a component carrier (CC). The CC can have a bandwidth of 1.4, 3, 5, 10, 15 or 20 MHz and a maximum of five CCs can be aggregated. Hence the maximum bandwidth is 100MHz. The backward compatibility is catered for as each CC uses the Release 8 structure, meaning that each CC will appear as an LTE Release 8 carrier, while a carrier-aggregation capable terminal can exploit the total aggregated bandwidth

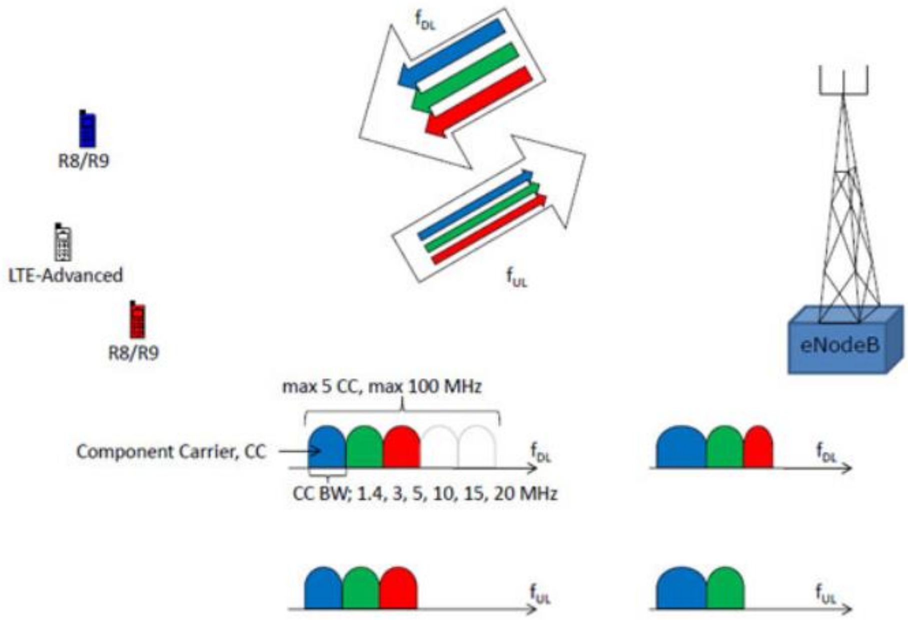

Figure 5 Carrier Aggregation in LTE-A [2]

The benefits from the Carrier Aggregation are:

- Higher speeds
- Capacity gain and improvement of network efficiency
- Optimum utilization of an operator's spectrum resources

The carrier aggregation can be: Intra-band contiguous, Intra-band non-contiguous and Inter-band non-contiguous.

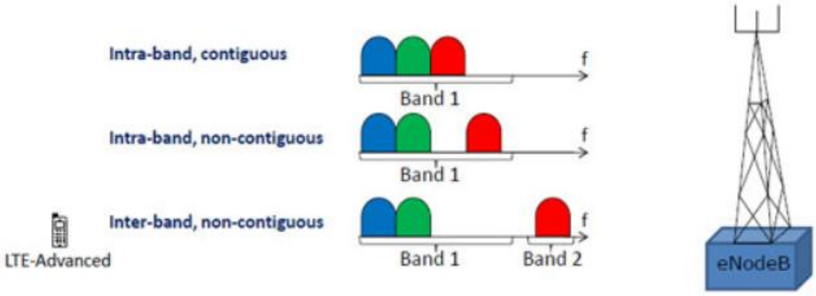

Figure 6 Types of Carrier Aggregation [2]

- **Higher order MIMO and Multi-user MIMO**: The major change in LTE-Advanced is the introduction of 8x8 MIMO in the Downlink and 4x4 MIMO in Uplink. MIMO can be used when the SNR (Signal to Noise Ratio) is high, i.e. high-quality radio channel. To be able to adjust the type of multi-antenna transmission scheme, a number of different Transmission Modes (TM) have been defined. In downlink, there are nine TMs, from which TM1 to TM7 are defined in Rel-8, TM8 is defined in Rel-9 and TM9 in Rel-10. In the uplink, there are only two Transmission Modes, TM1 and TM2, where TM1, the default, was introduced in Rel-8 and TM2 was introduced in R10. The different TMs differ in:

- Number of layers (streams, or rank)
- Antenna ports used
- Type of reference signal
- Precoding type

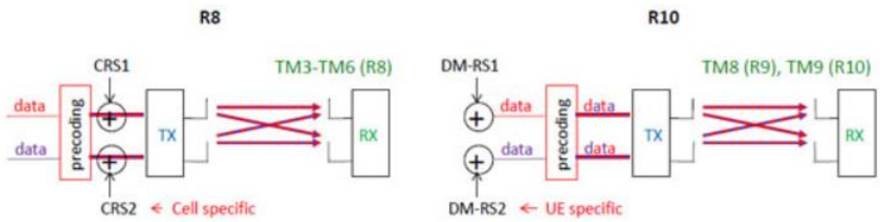

Figure 7 MIMO Transmission Modes in Rel-8 and Rel-10 [2]

The TM9 in DL is the 8x8 MIMO and TM2 in UL is the 4x4 MIMO, used only in ideal channel conditions, considering that both the network and the UE support them. Additionally, the data streams of different UEs are transmitted on the same time-frequency resources (Multi-user). To minimize the interference, the spatial streams of different UEs need to be well spatially separated (ideally orthogonal). The separation of the user signals is realized in the spatial domain at the eNodeB by means of precoding (i.e. beamforming) techniques that require the channel state at the transmitter, provided by the Channel State Information (CSI).

- **Relay Nodes:** In LTE-A, the possibility for efficient heterogeneous network planning, i.e. mix of a large and small cells – is increased by introduction of Relay Nodes (RNs). The Relay Nodes are low power base stations that provide enhanced coverage and capacity at cell edges, and hot-spot areas and it can also be used to connect to remote areas without fibre connection.
- **Coordinated Multi Point operation (CoMP):** the main reason to introduce CoMP is to improve network performance at cell edges. In CoMP, a number of Tx points provide coordinated transmission in the DL, and a number of Rx points provide coordinated

reception in the UL. A Tx/Rx point constitutes of a set of co-located Tx/Rx antennas providing coverage in the same sector. The set of Tx/Rx points used in CoMP can either be at different locations, or co-suited but providing coverage in different sectors. Also, they cen either belong to the same or different eNodeBs. There are multiple ways that CoMP can be done. When two, or more, Tx points transmit on the same frequency in the same subframe it is called *Joint Transmission*. When data is available for transmission at two or more Tx points but only scheduled from one Tx point in each subframe is called *Dynamic Point Selection.* When two or more Tx points share only the CSI for multiple UEs and data packet that is destined to a specific UE is available only at one Tx point, *Coordinated Scheduling/Beamforming* is used to realize it.

2.5 5G-NR (New Radio)

In the past few decades, the number of mobile users has dramatically increased. The telecommunications industry has become a key contributor in the economic and social development all around the world. The mobile communications have become part of the daily lives of billions of people and this is just the beginning. The predictions for the next decade say that the number of connected things (people, machines) is going to experience a drastic increase. As a consequence, there will be a demand of higher volumes of traffic and many different devices with different service requirements.

In order to meet these expanding needs for mobile communications, many organizations started discussing the key requirements, the use-cases and the vision of what the next generation mobile networks (5G) should be. Such a group already existed when the 3rd generation mobile networks and its requirements was being defined, and it was done by ITU (International Telecommunications Union) and all of the requirements were referred to as IMT-2000 (International Mobile Telecommunications for the year 2000). Following this example, the ITU issued new set of requirements for the 5th generation mobile networks in a recommendation called "IMT for 2020 and beyond" or IMT-2020. There are other organizations participating in this process, but we mention only the most significant one.

2.5.1 New and Upcoming Trends for Mobile Applications and Services

From the 1st generation mobile networks to today, the way of use of the mobile networks has greatly changed. What started as a voice-centric service provider now it is overwhelmed using services such as social networks, online gaming, online education etc. The amount of data an average person utilizes increases with each day and new solutions are being developed to sustain and improve user experience. With the technological development, new types of communications and devices, such as device-to-device, machine-to-machine, user-to-machine communications emerge. This imposes new trends of services and applications to be developed and shaped by the needs of the new generation of users and progress in technology and services.

In "Towards 5G" examples of such trends are given and in the next part we will present them.

2.5.1.1 New Types of Mobile Devices

In recent years, a wide range of new smart devices, such as smartphones, tablets, dongles, have emerged and have been the main consumers of the mobile broadband traffic. Today, devices like smartphones and tablets feature big screens and are able to stream videos in high resolution encouraging such data-consuming applications to be developed. This type of Internet use via mobile terminals is becoming more and more popular. The todays mobile terminals, or as we call them, smartphones are turning into hand-held computers equipped with powerful processors, big storage units, cameras, sensors etc. This permits creation of new types of applications such as movement and gesture recognition, 3D cameras and many more.

2.5.1.2 Video Streaming and Download Services

Video streaming and download are among the biggest traffic generators in mobile networks. Today, besides streaming uploaded videos, we can live stream videos of us in video calls, on social networks and many other ways. This adds even more on the increased data consumption in the mobile networks and it is expected that video traffic will be the biggest data traffic generator and consumer. According to the "Cisco Visual Networking Index" for global mobile data traffic forecast, it is predicted that by the year 2022 the video vs non-video mobile data traffic ratio will be 79% vs 21%. We can see the trend in the figure below.

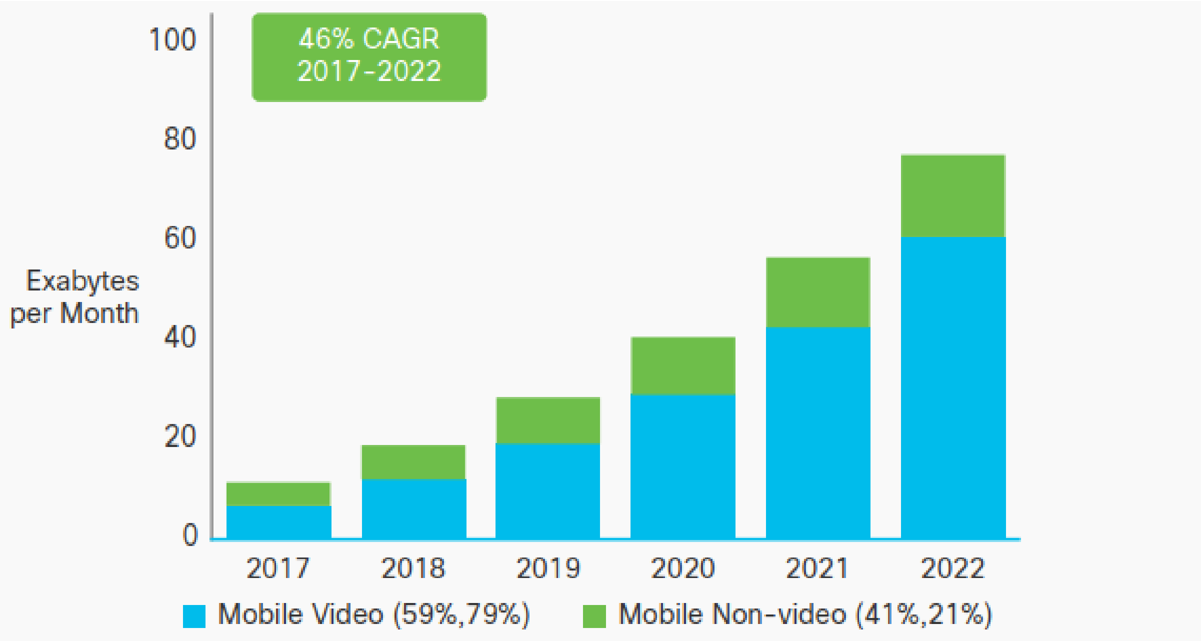

Figure 8 Mobile video traffic forecast in the period 2017-2022

2.5.1.3 Machine-to-Machine Services

The rapid development of automation technology and the introduction of Industry 4.0, enabling devices such as sensors or meters to directly communicate between each other, i.e. Machine-to-Machine communication, is expected to add a significant contribution to the increase in mobile data demand. M2M will cover many sectors such as fleet management, industrial asset management, security, healthcare etc and the number of M2M connections could be several orders of magnitude larger than the world population. Furthermore, the M2M market is expected to continuously grow creating more and more demand for mobile data. For example, smart sensors in homes consume hundreds of kilobytes per second while surveillance video monitoring consume tens of megabytes per second. Other significant contributors are the smart cities, smart agriculture, smart grids and many more up-and-coming technological concepts. Another set of applications for M2M is the topic we are discussing in this thesis, the communications in the transport sector or i.e. V2X:

- Vehicle to Vehicle (V2V)
- Vehicle to Infrastructure (V2I)
- Vehicle to Pedestrian (V2P)
- Vehicle to Network (V2N)

There are expected to improve traffic safety, both for drivers and pedestrians, provide entertainment services in the vehicles, add to the development of automated driving and use of augmented reality head up displays. Since this is the topic we are interested in, we will provide further details in the following chapters.

2.5.1.4 Cloud Services

Even though we do not notice it, we use cloud services with almost every interaction with our mobile phone or our personal computer. The rapid development of the ICT technologies will enable even more cloud services to be available on mobile devices and it is expected that they will account for more than 90% of the total mobile data traffic.

With the introduction of the Big data paradigm, many opportunities have arisen. Exploiting the huge amount of data stored in the cloud, we can improve the customer experience and provide a chance to generate new revenues from it. It is the most important driver of Machine Learning and Artificial Intelligence, which are one of the hottest topics in the present.

2.5.1.5 Broadcast Services

Internet TV over cable/fibre is an important emerging service. Users not only get real-time TV content, but also video on demand. Other example of broadcast services is to distribute or update software over the air for large number of devices. Of course, this comes with some special requirements like guaranteed service reliability, which would need new features to be added to broadcasts. In contrast, broadcasting by individual users and smaller communities is expected to become more popular in the future which, in turn, will increase the uplink traffic.

2.5.1.6 Virtual Reality (VR) and Augmented Reality (AR)

Virtual Reality creates a simulated artificial environment surrounding the user, while Augmented Reality is an overlay of technology on the real world. Both of these concepts are one of the most emerging trends in mobile technology and developing applications for their use has become widely popular.

While gaming is one of the key applications driving VR, AR is mostly been driven by industrial applications such as retail, medicine, education, tourism etc. Even though the popularity and mobile traffic demand of VR applications is bigger now, AR applications are expected to come close to, or even overcome, VR. According to “Cisco VNI Mobile forecast”, augmented and virtual reality traffic will grow nearly 12-fold from 22 petabytes per month in 2017, to 254 petabytes per month in 2022, as illustrated in the figure below.

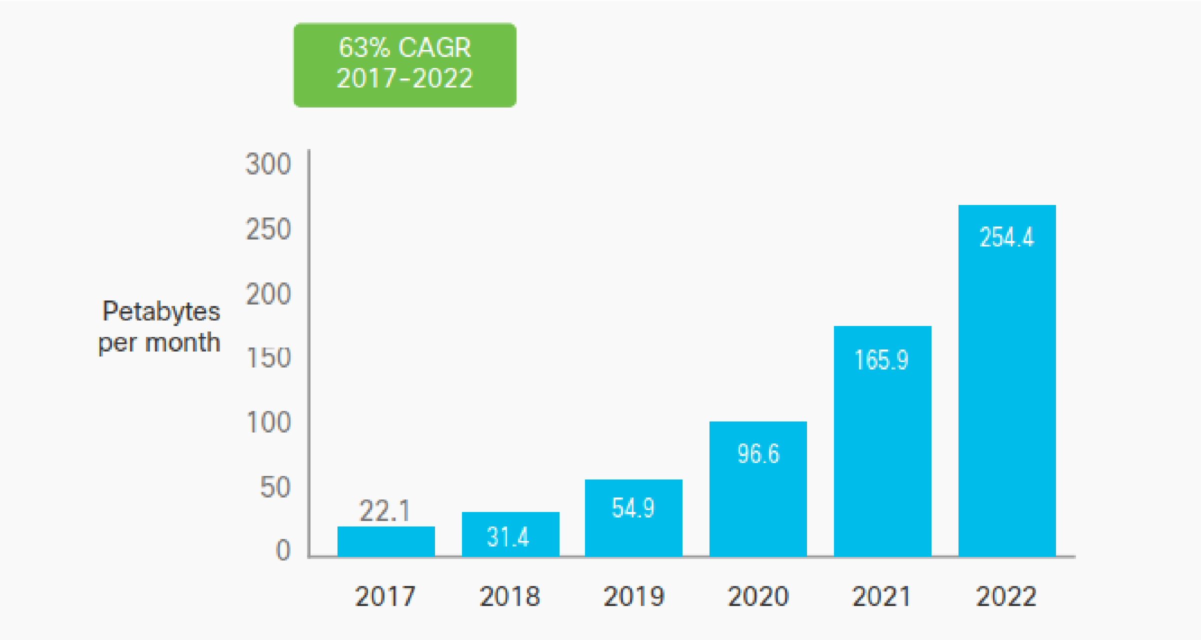

Figure 9 AR and VR Mobile Data Traffic

2.5.2 Technology trends

In the next section, we will describe the technology trends that should be met in order to satisfy the requirements of IMT 2020 services and applications.

2.5.2.1 Enhancement of the radio interface

Using advanced waveforms, modulation and coding, and multiple access schemes such as filtered OFDM (FOFDM), filter bank multi-carrier modulation (FBMC), pattern division multiple access (PDMA), sparse code multiple access (SCMA), interleave division multiple access (IDMA) and low density spreading (LDS) may improve the spectral efficiency of the future IMT systems (Source: IMT 2020).

Additionally, using advanced antenna technologies such as 3D-beamforming, active antenna system, massive MIMO can further improve the spectrum efficiency. In addition, TDD-FDD joint operation, dual connectivity and dynamic TDD can enhance the spectrum flexibility.

In small cells, higher-order modulation and modifications to the reference-signal structure with reduced overhead may provide performance enhancements due to lower mobility in small cell deployments.

Using some of the aforementioned radio interface improvements and providing flexible spectrum usage, joint management of multiple radio access technologies and flexible resource allocation, we expect to provide technical solutions to address the growing traffic demand in the future and further extend the efficiency of use of radio resources.

2.5.2.2 Network technologies

The future of networks is flexibility and configurability. One of the emerging paradigms, Software Defined Networking (SDN), can contribute exactly this, providing configurable network nodes and exploiting another trending technology, Network Function Virtualization (NFV) can administer for optimal processing of node functions and improve the operational efficiency of the network.

The cloud RAN (C-RAN), featuring centralized and collaborative system operation, can provide resources that can be managed and allocated on demand, while the radio units and antenna are deployed in a distributed fashion.

2.5.2.3 Enhancing mobile broadband scenarios

By exploiting a relay based multi-hop network, we can enhance the Quality of Service (QoS) of cell edge users. Additionally, using small cells e.g. femtocells, the QoS can be further improved by reducing the number of users per cell, also improving the Quality of Experience (QoE).

Bandwidth saving and transmission efficiency improvement is an evolving trend for Evolved Multimedia Broadcast and Multicast Service (eMBMS). Dynamic switching between unicast and multicast transmission can be beneficial.

Context aware applications may provide more personalized services that ensure high QoE for the end user and proactive adaptation to the changing context.

2.5.2.4 Enhancing massive machine type communications

As we already stated in the previous chapters, the future generation cellular networks are expected to connect a large number of M2M-capable devices and as the technology advances, they will have even lower costs and lower power consumptions while maintaining their complexity.

2.5.2.5 Ultra-reliable and low-latency communications (URLLC)

One of the main requirements of the 5G networks is to significantly reduce the latency. To achieve this, the data and control planes may both require significant enhancements and new technical solutions addressing both the radio interface and network architecture aspects. The services such as factory automation, autonomous driving and remote surgery will greatly benefit from such low latency networks. On top of the low latency, the next generation networks should also provide high reliability with packet error rates smaller than 1 packet loss in 10^5 packets.

2.5.2.6 Network energy efficiency technologies

The network energy efficiency can be improved by both reducing RF transmit power and saving circuit power. To enhance energy efficiency, the traffic variation characteristics of different users should be well exploited for adoptive resource management. Such examples are discontinuous transmission (DTX), base station and antenna muting and traffic balancing among multiple RATs.

2.5.2.7 Technologies enabling higher data rates

Multiple techniques can be used to help networks achieve higher data rates, such as:

- Spectrum based: utilization of large blocks of spectrum in higher frequency bands (millimetre waves) and carrier aggregation
- Physical layer: increased spectral efficiency by using advanced physical layer techniques (modulation, coding) and advances in spatial processing
- Network based: applying network densification, which can be densification over space (dense deployment of small cells) and frequency (utilizing larger portions of radio spectrum in different bands)

2.5.3 IMT for 2020 and beyond usage scenarios and capabilities

The usage scenarios for 5G networks can be grouped in three main categories:

- Enhanced Mobile Broadband: addressing the human-centric use cases for access to multi-media content, services and data
- Ultra-reliable low latency communications: This use case has the strictest requirements for capabilities such as throughput, latency and availability. We mentioned some of the practical use cases in chapter 2.5.2.5.
- Massive machine type communications: As we already said, this use case is characterized by a very large number of connected devices typically transmitting a relatively low volume of non-delay-sensitive data. Devices are required to have a low cost and a very long battery live.

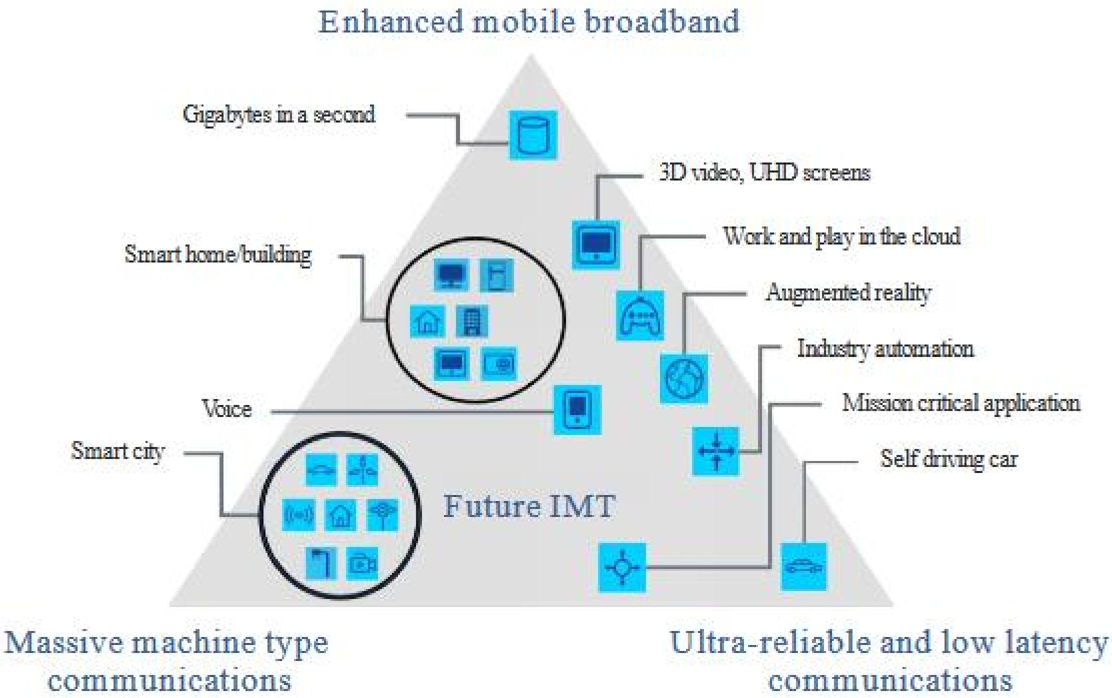

Figure 10 Usage scenarios of IMT for 2020 and beyond; Source IMT for 2020 and beyond

When considering the future mobile networks, the research community presented their expectations in IMT for 2020. In the following figure, we will present them in contrast to the expectations in IMT-Advanced, which were expectations and requirements for LTE/LTE-A.

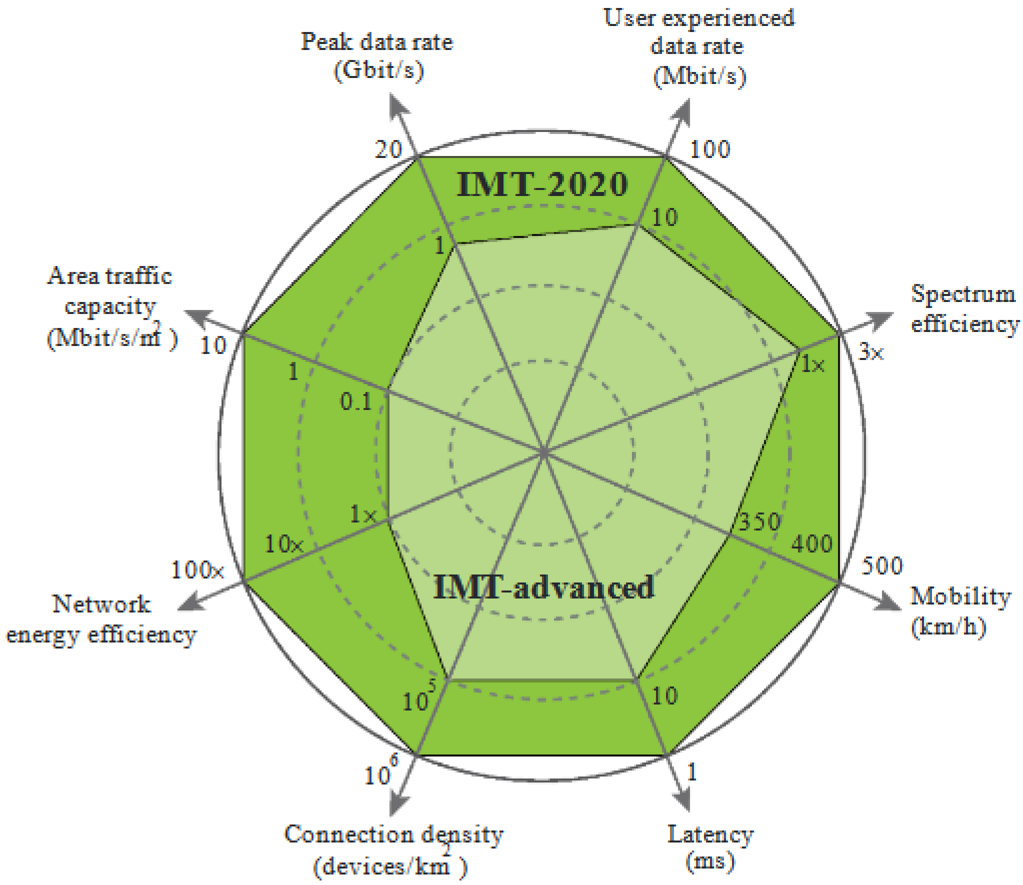

Figure 11 Expectations and requirements from IMT-Advanced to IMT-2020; Source: IMT -2020 and beyond

In the next part, we will discuss the targets for IMT-2020.

- Peak data rate: for Mobile Broadband it is expected to reach up to 10 Gbit/s, and under certain conditions and scenarios even up to 20 Gbit/s in enhanced Mobile Broadband. For wide area coverage cases, e.g. in urban and sub-urban areas, a user is expected to experience a data rate of 100 Mbit/s.
- Spectrum efficiency: it is expected to be up to 3 times higher compared to IMT-Advanced for enhanced Mobile Broadband.
- Mobility: from the next generation networks it is expected to support high mobility up to 500 km/h while maintaining acceptable QoS.
- Area traffic capacity: In hotspots, IMT 2020 is expected to support up to 10 Mbit/s/m^2 area traffic capacity.
- Latency: IMT 2020 requires networks to be able to provide 1 ms over-the-air latency, capable of supporting services with very low latency requirements.

- Connection density: when discussing massive M2M communication, this is the most important parameter, and IMT 2020 expects support of up to $10^6/km^2$ connection density.

3 LTE-V AND THE TRANSITION TO 5G-V2X

Support for direct device-to-device (D2D) connectivity was first introduced in 3GPP Release 12, providing a direct radio link between devices. For obvious reasons, the D2D connectivity is only possible between devices in relatively close proximity of each other. Hence, the services based on D2D connectivity, in Rel-12, are referred to as *proximity services* or "*ProSe"*. The support of D2D opens the gates towards countless applications that the LTE now, and 5G in near future, can support.

LTE distinguishes between two types of D2D connectivity:

- D2D communication: exchange of user data directly between devices.
- D2D discovery: the possibility for a device to transmit signals that enable its presence to be directly detected by other devices in its neighbourhood. In contrast to D2D communication, D2D discovery already has a wide range of use cases, including commercial services.

Since we talk about a direct communication between two or more devices, the downlink and uplink transmission directions are not applicable. Instead, the 3GPP introduced the term *sidelink* to characterize the direct D2D link. It is important to stress that the sidelink connectivity is fundamentally unidirectional in the sense that all current LTE sidelink transmissions are, essentially, broadcast transmissions.

3.1 CELLULAR V2X

As part of the expansion of the LTE platform to new services, and to keep track with the increasing need of the automotive industry, the 3GPP decided to develop functionality specialized for vehicular communications, both in terms of direct communication (vehicle-to-vehicle, vehicle-to-pedestrian or vehicle-to-infrastructure) and for cellular communications with networks.

The first Cellular Vehicle-to-Everything (C-V2X) standard was published in the Release 14 of the 3GPP. The Vehicle-to-Vehicle (V2V) communications are based on D2D communications defined as part of the ProSe services in Release 12 and 13 of the specification. As part of the ProSe services, a new D2D interface (named PC5 but often referred as to "sidelink") was introduced and in Release 14 is further enhanced to support vehicular cases, addressing high speed (up to 250 km/h) and high density (thousands of nodes).

In Release 14, two new communication modes were presented, the mode 3, which is an extension of mode 1 for vehicle-to-vehicle communication, supporting higher mobility, and mode 4, which enables autonomous communication without the eNode-B as a mediator.

There are two types of PC5 communication:

1. **Network assisted configuration (mode 3)**

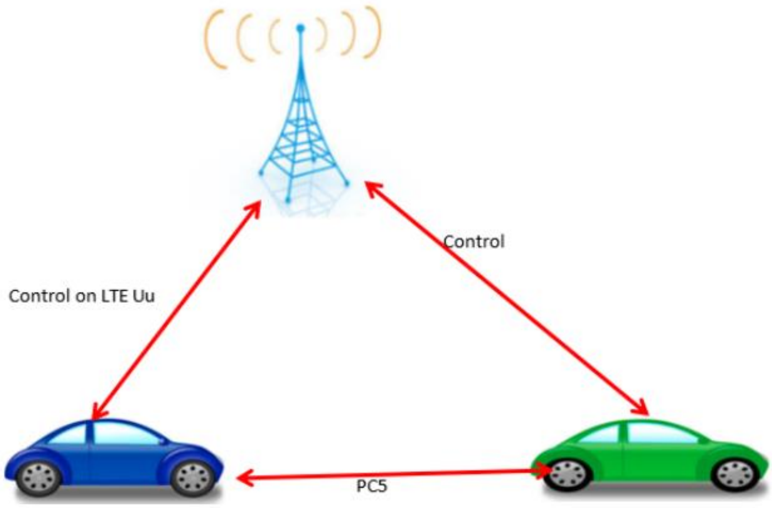

Figure 12 Network assisted direct communication [3]

In this scenario, the scheduling and interference management of the V2V traffic is handled by the eNodeBs via control signalling over the Uu interface. To achieve better and more optimized use of the network resources, the resource allocation is also done in the eNodeB. When a vehicle wants to transmit a CAM, it sends a sidelink resource-assignment request to the nearest eNode-B. The eNode-B then informs the vehicle which sidelink/PC5 resource it can use for the CAM transmission by sending a resource grant message. The resource can be granted for a single CAM transmission or, in case of periodic traffic, for a number of consecutive CAMs. The eNode-B may utilize the knowledge of previously issued resource grants, request patterns, V2V pathloss estimates, vehicle position reports, packet HOL (head-of-line) delay, per-packet priority, etc. to select the best resource and achieve the lowest transmission latency. Since the transmissions are centrally scheduled, collisions can be avoided under Mode 3, at least among vehicles associated with the same eNode-B. If cross-eNode-B coordination is performed, all transmissions can be collision-free.

2. **Autonomous configuration (mode 4)**

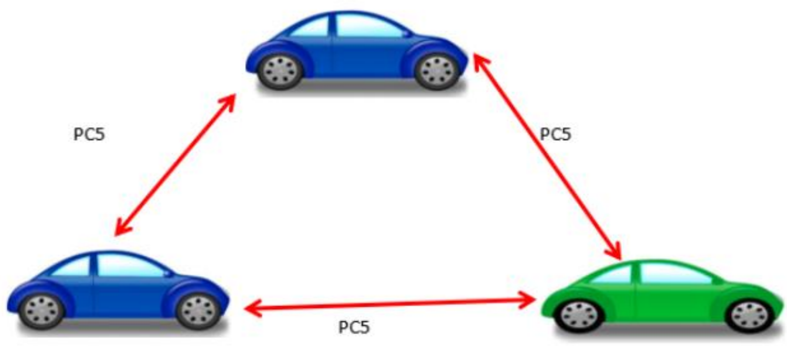

Figure 13 Autonomous direct communication [3]

The C-V2X Mode 4 does not require cellular coverage, and vehicles autonomously select their radio resources using a distributed scheduling scheme supported by congestion control mechanisms. As presented in the C-V2X mode 4 specification, radio resources are selected from a resource selection window, which can be between 200 and 100 TTIs (Transmission Time Interval with duration of 1ms) long and composed of k sub-channels. (k=2 in Fig.14).

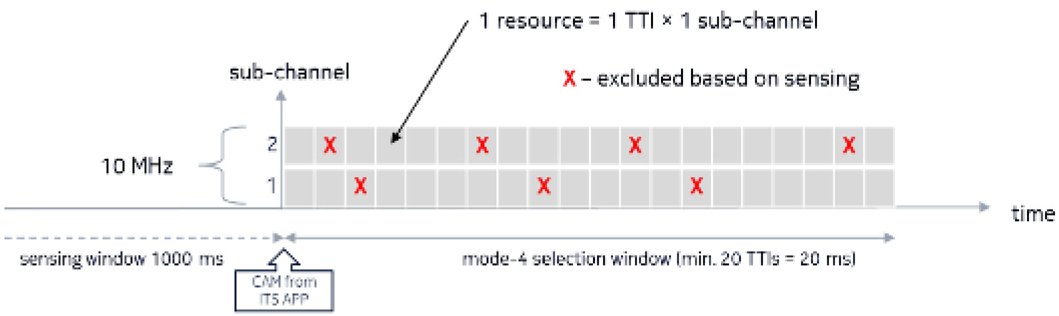

Figure 14 Resource Selection in C-V2X Mode 4

The length of the selection window is a parameter that can be set. The maximum transmission latency is limited by the length of the selection window. A shorter window provides a shorter transmission latency, but it increases the collision probability under high traffic loads. The selection window can be either 20, 50 or 100 TTIs long. Choosing the lowest one minimizes the CAM transmission latency. Every vehicle senses the radio channel to learn about the periodic transmission patterns of the neighbouring vehicles and see which resources are occupied. An important note is that while the vehicle is transmitting a message, it cannot sense the channel or vice versa, which is a constraint due to the half-duplex communication. When a vehicle needs to send a CAM, it has to sense the channel for 1000ms (the sensing window) and determine which resources inside the resource selection window are likely to be used by other vehicles. The first step is to exclude all of those resources and are no longer Candidate Sub-frame Resources (CSRs). The second step is filtering based on the Reference signal Received Power (RSRP). At the beginning of the sensing, a RSRP threshold is set, and after the sensing period, every CSR having lower RSRP than the threshold is excluded, and a list of potential CSRs is created. This list must include at least 20% of all CSRs in the selection window. If this is not satisfied, the first and second step are repeated iteratively until the 20% condition is met, and with each iteration, the RSRP threshold is increased by 3dB. The final list of CSRs includes the CSRs that experienced the lowest average Received Signal Strength Indicator (RSSI) over all its Resource Blocks. This RSSI value is averaged over all the previous subframes. Finally, the vehicle randomly chooses on of the CSRs and reserves it. Once a resource is selected, it is used semi-persistently, meaning that a certain number of consecutive CAM transmissions will use that same resource. The resource is released after a number of consecutive CAM transmission using a mechanism called resource re-selection counter: When a vehicle selects a resource, it also randomly picks a re-selection counter value (usually between 5 and 15). With every CAM transmission, the re-selection counter is decremented. When it becomes zero, resource re-selection is triggered, and new resources are reserved with probability (1-P) and the same resources are kept with probability P.

3.1.1 Enhancements for sidelink/PC-5

- **Efficient radio resource allocation**: one of the biggest challenges of vehicular communication is radio resource management in areas with high vehicle densities. The Semi-Persistent Transmission (SPT) mechanism and Semi-Persistent Scheduling (SPS) mechanism exploit the fact that many V2X messages, such as CAMs, are generated periodically. SPT and SPS allow a vehicle to make a recurrent use of the same radio resource for a number of subsequent CAM transmissions. This avoids the need for frequent resource re-selection and allows a vehicle to predict the resource usage of surrounding vehicles based on the history of channel sensing.
- **Mitigation of the near-far effect**: in C-V2X, sidelink communication is broadcast-based with open-loop power control, which is inherently subject to the near far problem and consequently unbalanced receive power at different vehicles. A key mechanism introduced in Rel.14 to mitigate this effect is a geographical zone-based resource usage concept (also known as Geo-zoning). Geo-zoning allows a group of vehicles located in one geo-zone and other vehicle groups in neighbouring zones to use radio resources in

a time-multiplexed manner, based on their GPS coordinates. Geo-zones as well as the mapping between the geo-zones and sidelink radio resource pools can be either configured by the eNode-B or pre-configured for vehicles that are out of network coverage. A vehicle determines the geo-zone identity based on the abovementioned configuration and its current location. The vehicle will then use the resource pools that are mapped to that particular zone.

- **Support for high-velocity and seamless mobility:** high speeds of vehicles make the channel estimation and mobility management more challenging. C-V2X increases the amount of demodulation reference symbols on the sidelink from 2 symbols to 3 or 4 symbols per subframe to deal with large Doppler shifts. In addition, the demodulation reference symbols sequence randomization is also enhanced for better interference suppression in high vehicle density scenarios. Support for seamless mobility is also improved: When geo-zoning is used, a communication interruption may happen when a vehicle moves from one to another geo-zone because different geo-zones are associated with different radio resource pools. To prevent such interruptions, so-called exceptional resource pools are pre-defined and used by the vehicles that are crossing the boundaries of geo-zones.

Even though the main goal of the D2D and C-V2X technologies is to be used in safety applications, such as road safety, the C-V2X is expected to find use in a wide range of use-cases such as:

- Forward collision warning: each vehicle broadcasts its position, speed and direction. An on-board computer in the vehicle processes the data and builds a “real-time” map of the immediate surroundings and alerts the driver for any potential collisions.
- Control loss warning: this application allows the vehicle to broadcast a warning of loss of control over it. The nearby vehicles receiving this message determine the relevance of this message for them and provide a warning to the driver.
- Emergency vehicle warning: each vehicle on the road acquires the location, speed and direction information of a surrounding emergency vehicle to assist by making the emergency vehicle’s path free.
- Left turn assist: Alerts are given to the driver as they attempt an unprotected left turn across traffic to help them avoid crashes with opposite direction traffic

- Emergency electric brake light warning: driver is alerted to hard braking in the traffic stream ahead. It provides the driver with additional time to assess the situations developing ahead.
- Intersection movement assist: Informs the driver when it is not safe to enter an intersection- for example, when something is blocking the driver's view of the opposing or crossing traffic
- Vulnerable road user discovery: provides ability to identify potential safety condition due to the presence of vulnerable road users such as pedestrians or cyclists.
- Queue warning: the infrastructure sends warning messages to the vehicles (V2I) to warn vehicles of queues and potential rear-end or other collisions.
- Platooning: forming a convoy in which the vehicles are much closer together than in human-controlled vehicles, increasing the road utilization and saving fuel.
- Automated parking system: APS (Automatic Parking System) contains a database which provides real-time information to vehicles in a specific area on availability of parking spots, both on the street or in public parking garages.

3.1.2 Architecture model of C-V2X

There are two modes of operation for V2X communication, namely over the PC5 and over LTE-Uu. LTE-Uu can be unicast and/or MBMS (Multimedia Broadcast Multicast Services). MBMS is a point-to-multipoint interface specification for existing and upcoming 3GPP cellular networks, designed to provide efficient delivery of broadcast and multicast services, both within a cell as well as within the core network. These two operation modes may be used by a UE independently for transmission and reception e.g. a UE can use MBMS for reception without using LTE-Uu for transmission. A UE can also receive V2X message via LTE-Uu unicast downlink.

As a reference architecture, we will consider the Non-roaming architecture for PC5 and LTE-Uu based V2X communication, since it is the most used one. Besides the standard entities from the LTE architecture, additional functional entities are added:

- V2X Control Function: the logical function that is used for network related actions required for V2X. It is used to provision the UE with necessary parameters in order to use V2X communication. Furthermore, it is also used to provision the UE with parameters that are needed when the UE is not served by E-UTRAN.
- The User Equipment (UE)

- V2X Application Server: a part of the capabilities it provides are: receiving uplink data from the UE over unicast, delivering data to the UE(s) in a target area using Unicast or MBMS delivery, mapping from geographical location information to appropriate target MBMS SAI and ECGI for the broadcast, etc.
- MME: 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.
- BM-SC: in addition to the functions defined in the TS 23.246 it also receives L. MBMS information from V2X Application server, sends L. MBMS information to the MBMS-GW.
- MBMS-GW: in addition to the functions defined in TS 23.246, in case of V2X if receiving L. MBMS information from the BM-SC, skipping the allocation procedure for IP multicast distribution, e.g. allocation an IP multicast address.

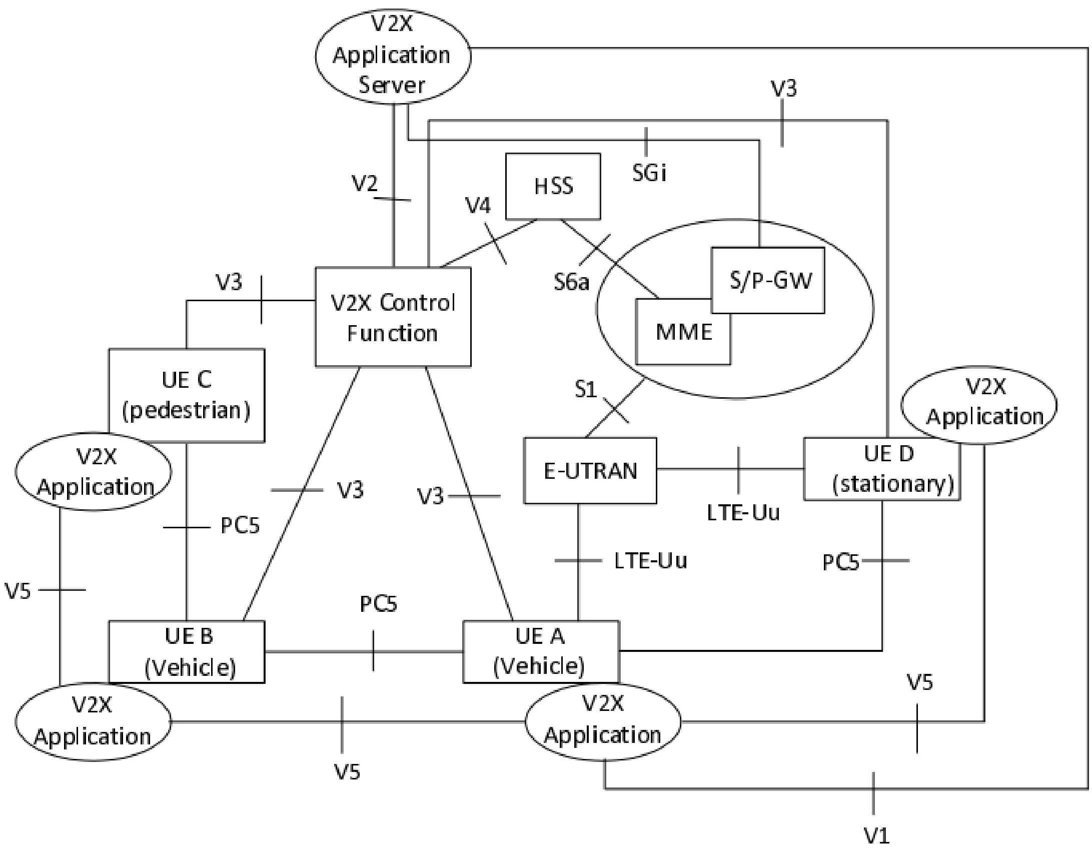

Figure 15 Non-roaming reference architecture for PC5 and LTE-Uu based V2X communication [5]

3.2 802.11P (DSRC) VS C-V2X

In this part, we will present a quick summary of the 802.11p – based V2X technologies and do a comparison with the C-V2X to try and justify why we think C-V2X will overcome DSRC.

3.2.1 802.11p – based technologies overview

The IEEE 802.11 community adopted the 802.11a standard to support the 802.11p standard, which is commonly referred to as Dedicated Short-Range Communication (DSRC) in the US and as ITS-G5 in Europe and it is a standard to address dynamic vehicular environments. The final specification for 802.11p was finished in 2012. The changes on the MAC layer enable very efficient communication group setup without the need to establish a basic service set (BSS) as in the IEE 802.11 MAC. Therefore, 802.11p MAC operates in so-called OCB (Outside the Context of a BSS) mode. The physical layer of 802.11p is OFDM based and similar to 802.11a, with minimal changes introduced to enable communication among fast moving vehicles. This involves the introduction of 10 MHz channels instead of the 20 MHz used in 802.11a to address the increased root-mean-squared delay spread in the vehicle environment. This result in doubling of all OFDM timing parameters and halving of the maximum supported data from 54 Mbps to 27 Mbps. It operates in the 5.9 GHz ISM band. Additionally, more strict receiver performance requirements in adjacent channel rejections and new spectrum masks are introduced to deal with cross-channel interference.

IEEE 802.11p has been designed to address road safety and traffic efficiency applications:

- It works in a fully distributed fashion, so it does not require a central controller
- It achieves low message latency through direct ad-hoc communication among neighbouring vehicles.
- Its signalling overhead is reduced to a minimum compared to 802.11a.

However, it also keeps some features that are not well-suited for vehicular communication. The synchronization and channel estimation approach is sub-optimal for highly time-variant radio channels. Moreover, IEEE 802.11p relies on an uncoordinated channel access strategy based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). It is well known that CSMA/CA does not perform well in congested scenarios and hence it is not scalable to high number of vehicles on the road. With an increasing number of transmitters, in fact, the channel access latency and the probability of data packet collision increases. A method called Decentralized Congestion Control (DCC) only partially solves the problem by reducing the transmission rate of CAMs. This however may affect the performance of some road safety and traffic efficiency applications.

3.2.2 Comparison between C-V2X and 802.11p

The 802.11p technologies are in the V2X game for almost two decades now. They have been tested extensively under many different scenarios. On the other hand, the C-V2X, a very young technology, being standardized only in 2016, nowadays is getting a lot of attention. Many vehicle manufacturers are split to choose which technology they should go with. This led to many comparisons of the results from tests designed to objectively assess and compare the DSRC and the C-V2X. In (5GAA, 2019), such tests are performed to assess the two technologies for their suitability to deliver broadcast V2V safety messages. The key takeaways from these tests are:

3.2.2.1 Reliability

Test results confirm that in ideal conditions, i.e. line of sight RF propagation with no interference and strong RSSI level, both V2X technologies reliably deliver BSM payload sizes of 193 bytes respecting the low end-to-end latency requirements for vehicular safety applications. The results revealed a significant reliability performance advantage of C-V2X over DSRC. This performance advantage was observed also in non-ideal conditions (Non-line-of-sight) involving fixed and moving obstructions, adjacent and near adjacent channel interference and congestion. These non-ideal scenarios represent real-world vehicular traffic scenarios that must be included in the analysis to facilitate informed decision making. To summarize, the test results indicate that in the presence of signal attenuation from real-world obstructions such as buildings, other vehicles or foliage, C-V2X is more reliable than DSRC in terms of V2V communication.

3.2.2.2 End-to-End Latency

Both C-V2X and DSRC exhibited similar end-to-end application layer latencies under non-congested conditions and both technologies met the latency requirements for the V2V safety applications defined in SAE J2945/1. Inter-packet gap performance was within 10 ms for both V2X technologies, typically increasing very quickly when the devices went out of range. Only C-V2X was tested for a highly congested scenario in a laboratory setting and even in this scenario, the latency remained bounded by the 100ms latency budget configured for that scenario.

3.2.2.3 Channel Congestion

To be able to remain operative in dense deployments is a key requirement for any V2X technology. The test results showed that the PER (Packet Error Rate) performance of high-priority BSM is noticeably better than lower-priority messages when high attenuations are used, or the received signals are weak. The reason is that high-priority safety messages can be protected more efficiently for channel-congested and collision scenarios by the C-V2X resource selection algorithm. For actual highly congested deployment scenarios, it is expected that this packet reception improvement of high-priority BSM to translate to noticeable and meaningful reliability improvement of critical safety messages.

3.2.2.4 Resilience to Interference

Another major problem for the V2X communications is the Interference. It increases as other devices in the surrounding emit RG energy into the V2X channel. These devices can be Wi-Fi devices operating in the UNII-3 band. They can also be V2X devices in the neighbouring channels. The final result is elevated channel noise level at the V2X receiver. With the interference in close proximity, the improvement in range for C-V2X over DSRC with UNII-3 interferer resulted in 1.7x while the improvement for C-V2X over DSRC with the adjacent DSRC interferer was 2.9x.

3.2.2.5 Shadowing Scenarios

A same comparison test for the shadowing scenarios was done for both C-V2X and DSRC. Although the same test was conducted in 2011 for DSRC, it was reproduced for both radios to ensure the results are compared under similar parameters, environmental conditions and physical setup. The test results under similar conditions showed a significant advantage of C-V2X over DSRC.

3.2.2.6 Near-Far Effect

One of the key features of C-V2X is frequency division multiplexing (FDM). However, because of the potential for transmissions on adjacent subchannels, FDM can lead to near-far effect. This impact of the near-far effect though is limited by the minimum in-band emissions requirements defined in 3GPP specifications. The data from the near-far test showed that the average leakage of the device under test of around -35dB meets the minimum requirements.

To summarize, the testing results confirmed that the C-V2X technology is able to deliver broadcast V2X safety messages in a variety of environments, both ideal and adversarial.

Additionally, the testing showed that C-V2X outperforms DSRC in range and reliability, while satisfying the requirements for latency and IGP.

3.3 C-V2X Roadmap and Evolution towards 5G

The 3GPP Release 14 first introduced the V2X support, nowadays referred as C-V2X or LTE-V2X. That is the key step towards the next generation of cellular technology, the 5G NR (New Radio), where in Release 15 and 16, the V2X technology is referred to as 5G NR-V2X. C-V2X was developed with evolution in mind, with improvements and enhancements coming in new releases, where the implementations of the specifications will support backwards compatibility. This means that vehicles deployed now based on Release 14 will continue to operate with future vehicles that will leverage emerging 3GPP specifications including Release 16. The 5GAA (5G Automotive Association), an organization created to connect the telecom industry and the vehicle manufacturers to develop end-to-end solutions for future mobility and transportation services, are working to ensure that the C-V2X technology is tested, validated, and commercially available in vehicles starting in 2020.

Between 2018 and 2020 it is expected that more than 125 million connected vehicles that will use V2N to ship globally. Because of the C-V2X direct communication functionality is being included as part of the new cellular chipsets that will be embedded into vehicles for V2N communications, newer vehicles will be able to benefit from the higher level of traffic safety enabled by supporting the direct communication.

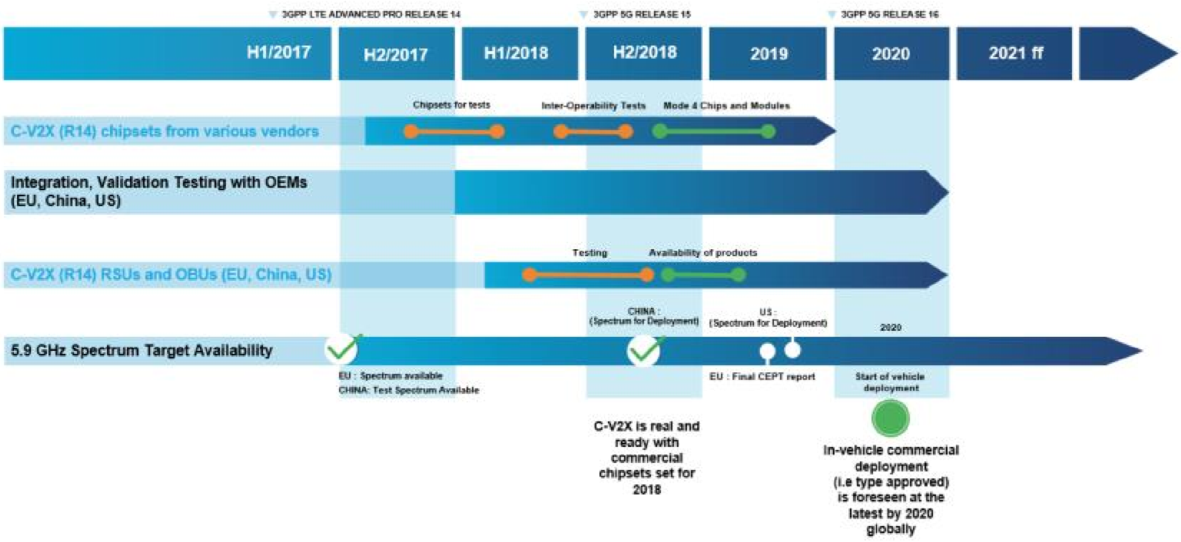

Figure 16 Timeline for deployment of C-V2X (5GAA, 2019)

3.3.1 Evolution to 5G-V2X

3GPP Release 14 including C-V2X direct communication is a significant milestone as it is the result of automotive and telecom collaboration for an optimized solution for a specific industry segment, and its ongoing evolution is also a key step to the next generation of cellular networks, 5G.

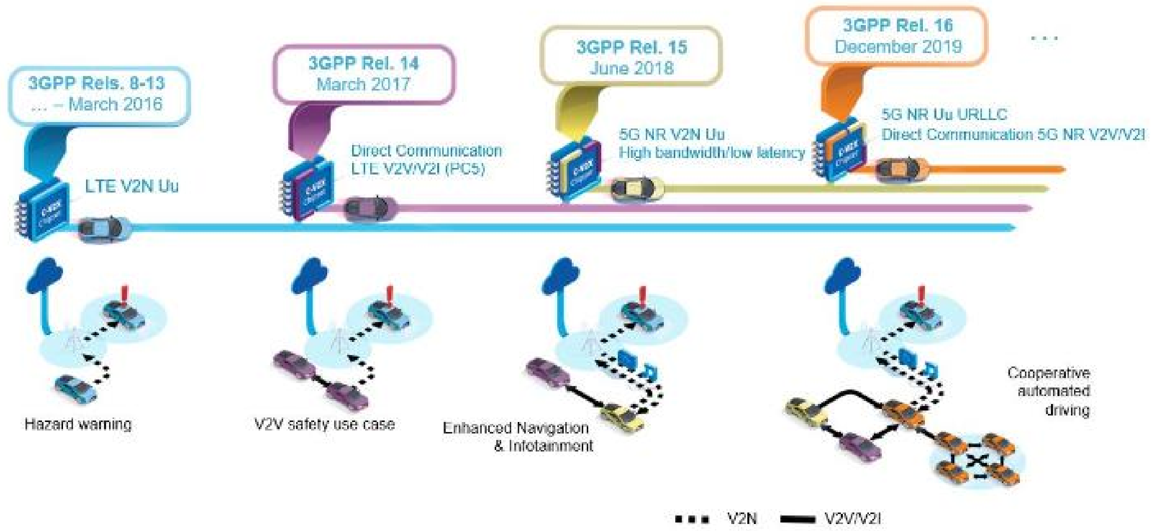

Figure 17 C-V2X: Evolution to 5G (5GAA, 2019)

The figure above illustrates the C-V2X technology in the past specifications and in the upcoming one, Release 16, in December 2019. It gives an insight on when vehicles based on such releases may start to commercially ship on the road.

3GPP Release 15 introduces New Radio (5G NR) capabilities as a follow-on next generation to 4G LTE with regards to network communication at the Uu interface. In Release 15, higher data rates and lower latencies for V2N network communication are provided. The first chips are expected to be available this year and, consequently, first deployments of the vehicles that use those chips are expected to start as early as 2021. Release 15 also includes some minor enhancements to the direct communications (PC5) radio including transmit diversity and high-order modulation (64-QAM).

3GPP Release 16 is expected to introduce additional capability to 5G NR, specifically in terms of short range direct communication, increasing bandwidth and reducing latency further, sometimes referred to as Ultra Reliable Low Latency Communication (URLLC). 5G-V2X offers the features which are predominant to highly and fully automated and cooperative driving. Release 16 is still in specification phase and the first deployments using it may be expected at the earliest in 2023.

Backward compatibility of 3GPP releases guarantees that all vehicles with at least Release 14 chipsets will be able to communicate using direct communication.

3.3.2 5G-V2X Biggest Challenges

In this section, we will discus the main challenges, presented in (5GCAR, 2018), that cannot be met by deploying existing technologies or technologies that are currently or will be under standardization, but need innovative solutions, that can partially be based on existing standards and research results. Providing reliable and low latency radio links for fast moving vehicles usually requires high quality channel estimation, adaptive and robust beam management and efficient adjacent channel interference mitigation.

3.3.2.1 Meeting Low Latency and High Reliability Requirements in V2X Communication Scenarios

The targeted latency and reliability for future V2X services are:

- Reliability = $1*10^{-5}$
- User plane latency = 3 to 10 ms

Meeting these requirements simultaneously in highly mobile vehicular scenarios is a major challenge and are considered as few of the key requirements for future 5G V2X services. To deal with this problem, we need to figure out how to deal with the high Doppler and delay spread in highly dynamic wireless environments caused by moving transmitters, receivers and scatters. This highly dynamic environment has large impacts on the direct device-to-device (sidelink-based) V2X communication where the transmitting and receiving antennas are placed at lower elevation than that of the Base Stations in cellular networks.

Moreover, the high frequency bands that are considered for 5G V2X can worsen the detrimental impact caused by Doppler spread, frequency error, and phase noise. Some of these sources of errors were not that big of an issue in the LTE-based V2X systems because since they are using a band under 6 GHz.

3.3.2.2 Mitigating Interference between V2X and Mobile Broadband Communications

Dynamic resource sharing between eMBB and URLLC services can be beneficial for some V2X use case classes, e.g. automated driving (that requires URLLC) and mobile entertainment (requiring high data rate). A well-known way of multiplexing eMBB and URLLC traffic is to use orthogonal frequency and/or time resources, but, this is inefficient in terms of resource usage for sporadic URLLC transmissions, such as event-triggered traffic. Therefore, we need a dynamic way of sharing resources for eMBB and URLLC in V2X communications.

One way to multiplex eMBB and URLLC services is by using a pre-emption-based mechanism where the URLLC transmission is ensured virtually zero latency and interference-free scheduling using the resource of an ongoing eMBB transmission. However, pre-emption corrupts the eMBB transmission since the eMBB decoder receives its scheduled information punctured.

Furthermore, there are many V2X services that require exchange of large amount of data among vehicles. For the unlicensed spectrum at 5.9 GHz, only 30 MHz of ITS spectrum are currently available for V2X safety use cases. Also, there is a high possibility of sharing the bandwidth with the DSRC technology, which will further increase the maximum amount of data that can be exchanged. Therefore, to enable additional increased aggregated sidelink bandwidth, licenced bands can be considered.

Another big challenge is to satisfy the strict requirements of V2X in scenarios when both conventional UEs and vehicular UEs are served in the same time and resources are allocated in a centralized manner. However, to efficiently mitigate the intra-cell interference resulting from resource reuse and satisfy the V2X requirements is very challenging.

3.3.2.3 Adaptive and Robust Beam Management in mmWave Spectrum Bands

Several V2X application impose a requirement to deliver a common message to a set of vehicles over the V2I communication link. Such use cases are “Network Assisted Vulnerable Pedestrian Protection” and “High Definition Local Map Acquisition” falling under the use case classes of Cooperative Safety and Autonomous Navigation respectively. In such scenarios, the downlink transport mode based on multicast/broadcast improves the resource efficiency of the V2I/N links significantly compared to that of unicast.

On the other hand, utilization of mmWave bands holds a great potential in realizing the high data rates required by these advanced V2X applications, due to the large spectral channels available. Using beamforming techniques in these mmWave bands imposes a challenge in highly dynamic environments typical for V2X communication.

Beam-domain broadcasting is targeting scenarios where vehicles communicate at mmWave with infrastructure nodes such as next generation Node-B (gNode-B) or Road Side Unit (RSU) that are equipped with a large antenna array, and investigates adaptive and robust beam management techniques for V2I broadcasting/multicasting.

3.3.2.4 Providing High-quality Uplink for V2N and V2I Communications

V2X applications beyond road safety services, including platooning, automated driving and broadband infotainment services impose strict latency, rigorous reliability, high data rate and large communication range requirements. Such advanced applications benefit from maintaining communication links with advanced infrastructure nodes, such as cellular Base Stations and Road Side Units equipped with a massive number of antennas and associated advanced transceiver and spatial multiplexing capabilities. Satisfying all of the aforementioned requirements is a big challenge for the future networks.

In multicell MU-MIMO networks, state of the art research has shown that controlling the power of the pilot as well as the data channels has a large impact on the system performance. Efficient, scalable and fast converging power control algorithms, especially those that can account for the trade-off between the power used for pilot and data signals are not available in the literature. This problem represents a significant challenge in presence of fast fading channels with short coherence time and narrow coherence bandwidth, such as in high frequency bands.

3.3.2.5 Mitigating Adjacent Channel Interference for V2V Communications (mode 4)

Traffic safety applications typically use broadcast communication to convey safety related messages. However, these applications require low latency and high reliability, therefore, setting stringent conditions upon V2V broadcast communication. One big limiting factor in V2V and V2I communication is the Adjacent Channel Interference (ACI) when these communication links use a dedicated spectrum and all vehicle-transmitters are scheduled in non-overlapping RBs. One way is finding proper scheduling and power control algorithms, which are crucial for V2V and V2I broadcast communication.

3.3.2.6 Facilitating Highly Reliable and Timely Peer Device Discovery for V2V Communications

V2X discovery comprises a necessary condition for the establishment of the direct communication path between vehicles located in close proximity with each other as well as for the realization of the sidelink message exchange. RSUs may also be involved in the discovery process to provide an additional assistance for the establishment of the communication among the different vehicles. traditional localization-based vehicle discovery methods introduce high signalling overhead in high-mobility scenarios, since vehicles have to frequently report their current location to the eNode-B to maintain connectivity. Moreover, they have to remain always connected of frequently alternate between idle and connected mode which leads to high power consumption. In contrast, vehicle discovery schemes relying on beacon transmissions often lead to underutilization of the scarce radio resources. Thus, besides the need for an adaptive resource allocation to optimize the utilization of resources, the strict requirements in terms of latency and reliability for a successful link establishment must be addressed too. The V2X discovery problem becomes especially challenging in highly dense scenarios, where the presence of many communicating nodes may lead to severe scalability problems.

3.3.2.7 Accurate and Ubiquitous Real-time Positioning

The majority of V2X use cases require knowledge of the current position of a road user on a certain level of accuracy ranging from a few centimetres (such as remote driving) to several meters (see-through application).

As presented in (5GCAR, 2018), we can consider the need to accurate positioning from two different perspectives. First, by improving the accuracy of the positioning, we help improve some of the other aforementioned challenges, such as enabling a robust and adaptive beam management in mmWave bands and interference mitigation and proximity detection.

Second, the positioning procedure itself is a challenge for the radio interface design. We have to have a sufficiently large set of Positioning Reference Signals (PRS) in the downlink, uplink and sidelink. These PRS should be configurable with respect to the occupied bandwidth, time periodicity, power setting as well as correlation properties for reliable Time of Arrival (TOA) measurements.

The need for centimetre-level accuracy and the possibility for precise angular estimation places more strict requirements on synchronization and antenna calibration than for communication purposes. Furthermore, it is important that we understand the synergies between positioning and communications, as channel estimation during communication can support positioning methods, just as position information can support beam management and handover prediction.

3.3.3 State of Art for V2X Communications

The V2X services have been developing for almost two decades. The first use they found was in services with low-rate communication, such as toll collection, where the communication was between a vehicle and infrastructure node. Initially, the supported data rate was limited to 0.5 Mbps and was later on, enhanced up to 54 Mbps.

Realizing that the vehicular communications' demand is increasing, 3GPP started developing their V2X technology support and was first introduced in Release 14. These 3GPP V2X communications, with the technical support provided by 3GPP Release 14, can be used both for safety and non-safety purposes, thus satisfying the requirements of ETSI for delivering messages such as CAMs and DENMs.

To expand the LTE platform to meet the evolving requirements of the automotive industry, 3GPP published Release 15 to enhance the technical components of Release 14, and they are expected to further enhance and develop the technology to adapt it for the 5G NR. These enhancements are driven by the 25 use cases identified for advanced V2X services by the 3GPP Services and Architecture (SA1) working group, that are categorized as vehicle platooning, extended sensors, advanced autonomous driving and remote driving (S. Chen, 2017).

Main technical challenges for providing the aforementioned services and corresponding requirements by the Rel-15 and Rel-16 NR relate to the design of the new V2V broadcast, multicast and unicast sidelink. Coexistence of multiple unicast (multicast) and broadcast sidelink transmissions with the ongoing cellular DL and UL creates new challenges for synchronization and time alignment between multiple transmissions and users. Moreover, network-assisted resource allocation needs to assign physical resources to users for the V2V sidelink, while at the same time avoiding high overhead for reference signals, as well as signalling overhead and information exchange between mobile users and cellular network.

At the same time, the research community has been exploring the possibility of using mmWave frequency bands for V2X communications, as a natural evolution towards the 5G cellular networks. Both DSRC and C-V2X operate in the same frequency, 5.9 GHz, and with the increase of the amount of data from onboard vehicle sensors, cameras and LiDARs, there is a high probability that they will not be able to satisfy the exchange of that much data.

Although using mmWave for vehicular communications is part of the 5G connected vehicle solutions, communicating in mmWave presents some challenges due to unfavourable propagation characteristics including large path los and LOS blockage probability and to the potentially large Doppler shift and spread. One possible solution for mitigation of Doppler spread is using directional beams that allow the Doppler shift effects to be handled more easily. On the other hand, using directional transmission and reception introduces some channel state information (CSI) acquisition and beam alignment overhead. Obtaining accurate CSI at transmitting and receiving vehicles, as well as infrastructure nodes, in high mobility vehicular environments adds another challenging task that needs to be solved. There are proposals of the use of implementations combining analogue and digital components for mmWave transceivers, also known as hybrid precoding techniques.

Today, localization relies mostly on the Global Navigation Satellite Systems (GNSS) such as the Global Positioning System (GPS), which can be complemented by onboard equipment of vehicles such as cameras, radars and other sensors. GPS works well in open areas with unobstructed LOS links to a sufficient number of satellites. However, when a vehicle enters in tunnels, under bridges, parking garages, the accurate GPS localization presents a challenge. One possible solution is to use the network information to obtain better localization.

4 C-V2X SIMULATORS

The complex large scale and highly dynamic nature of ITS systems introduces significant challenges before efficient and reliable solutions and applications can be deployed. Field Operational Tests (FOTs) can test the effectiveness and potential of ITS systems under small scale scenarios in localized areas and with a reduced number of vehicles. However, the possibility to test large scale traffic scenarios is crucial for the evaluation of traffic management solutions, network performance and other services. In this context, simulation tools represent the most adequate and viable alternative.

In this thesis, we are interested in Cellular-based Vehicular Networks and their testing and analysis. To create a simulation for this technology, we need two types of simulators:

- Network communication simulators, that will simulate the network behaviour and the required protocol layers compliant with the standard we are testing
- Mobility and traffic simulators, that will simulate the movement patterns and the parameters of the vehicles, such as speed, acceleration, deceleration etc.

This chapter will be organized in the following order: first, we will describe the most popular network simulators used by the research community, then, we will briefly discuss two mobility and traffic simulators, and finally, we will present the most popular simulation frameworks for C-V2X simulation, that in some case, are built upon the previously mentioned network and mobility and traffic simulators, and in some cases, they are just system-level simulators.

4.1 NETWORK SIMULATORS

4.1.1 OMNeT++

OMNeT++ is a C++-based discrete event simulator for modelling communication networks, multiprocessors and other distributed or parallel systems. The motivation for developing this software was to provide the academic world with a powerful open-source discrete event simulation tool for the simulation of computer networks and distributed parallel systems. OMNeT++ tries to fill the gap between open-source, research-oriented simulation software like NS-2 and NS-3 and the expensive alternatives like OPNET. It can be used on most of the platforms such as: Linux, Mac OS and Windows, using the GCC tool chain or the Microsoft Visual C++ compiler.

4.1.1.1 OMNeT++ Design

OMNeT++ is built in such a way that it provides us with the basic tools to write a simulation instead of just providing pre-made components, giving it more of a framework-like approach. It was designed to support network simulations on a large scale, to provide user-friendly debugging and execution of the simulation models, to be modular and customizable, to be able to generate and process input and output files with commonly available software tools and to provide an IDE that facilitates model development and analysing results.

Modules

The main building blocks of the OMNeT++ model are *modules* that communicate among themselves with message exchange. The basic modules are referred to as *Simple Modules*. Their behaviour is written in C++, using the simulation class library.

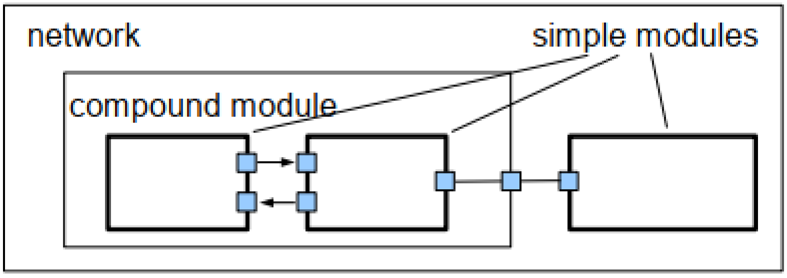

Figure 18 Model Structure in OMNeT++ [8]

Simple modules can further be grouped into *Compound Modules.* The number of hierarchy levels is not limited. Messages can be sent either via connections that span between modules or directly to their destination modules. Both simple and compound modules are instances of module types and can serve as components for more complex module types. At last, we can create the system module as a *Network Module* which is a special type of compound module without any gates going in or out of it.

As we mentioned before, the modules communicate through message exchange. These messages can contain some usual information such as timestamps, but also any other data. They can be defined by specifying their content in a .msg file. Simple modules usually send messages via gates, but they can also be sent directly to their destination modules. The gates emulate the input and output interfaces of modules – the messages are sent via output gates and received via input gates. An input and an output gate can be linked with a *connection*. Connections are created within a single level of module hierarchy. Connections spanning across hierarchy levels are not allowed. In an OMNeT++ simulation, the messages typically travel through a chain of connections, to start and arrive in simple modules. Compound modules act as ‘cardboard boxes’ in the model, transparently relaying messages between their inside and the outside world. To emulate real world scenarios, the connections can get some properties such as propagation delay, data rate, bit error rate, etc. We can also create a connection type with specific properties and reuse them in several places.

Like the connections, the modules can also have parameters, usually used to pass configuration data to simple modules, and to help define model topology. Compound modules may pass parameters or expressions of parameters to their submodules.

The NEtwork Description (NED) Language

We define the structure of the model (the modules and their interconnections) in the NED language, which is a proprietary language for the OMNeT++ IDE. It is used for simple modules declarations, compound module definitions and network definitions. Simple module declarations describe the interface of the module, such as gates and parameters. Compound module declarations consist of the declaration of the module’s external interface and the definition of submodules and their interconnection. Network definitions are compound modules that qualify as self-contained simulation models. The main features of the NED language are:

- **Inheritance**: Modules and channels can be sub-classed. Derived modules and channels may add new parameters, gates, and new submodules and connections. They may set existing parameters to a specific value, and also set the gate size of a gate vector.
- **Interfaces**: Module and channel interfaces can be used as a placeholder where normally a module or channel type would be used, and the specific module or channel type is determined at network setup time by a parameter. Concrete module types have to ‘implement’ the interface they can substitute.
- **Packages**: To address name clashes between different models and to simplify specifying which NED files are needed by a specific
- **Hierarchical:** The traditional way to deal with complexity is by introducing hierarchies. Any module which would be too complex as a single entity can be broken down into smaller modules and used as a compound module.
- **Component-based:** Simple modules and compound modules are inherently reusable, which not only reduces code copying, but more importantly, allows component libraries (like the INET Framework, etc) to exist.

- **Inner types:** Channel types and module types used locally by a compound module can be defined within the compound module, in order to reduce namespace pollution.
- **Metadata annotations:** It is possible to annotate module or channel types, parameters, gates and submodules by adding properties. Metadata are not sued by the simulation kernel directly, but they can carry extra information for various tools, the runtime environment, or even for other modules in the model.

The NED language has an equivalent tree representation which can be serialized to XML, that is, NED files can be converted to XML and back without loss of data. This lowers the barrier for programmatic manipulation of NED files, for example extracting information, refactoring and transforming NED, generating NED from information stored in other systems like SQL database, etc.

Model Behaviour and Topology

The description of the model in OMNeT++ is separated in:

- Model behaviour: using C++ code to describe what each module behaves like
- Model topology: using the NED language in .ned files.

This approach allows us to keep the different aspects of the model in different places, allowing to have a cleaner model. In a generic simulation scenario, we usually want to know how the simulation behaves with different inputs. These variables neither belong to the behaviour (C++) nor with the topology (NED) as they can change from run to run. In this case, .INI files are used to store these values. INI files provide a great way to specify how these parameters change and enable us to run our simulation for each parameter combination we are interested in.

Results Analysis

To make the result analysis results analysis easier, OMNeT++ makes the result analysis rule based. Simulations and series of simulations produce various result files. We then, select the input of the analysis by specifying file names or file name patterns. Data of interest can be selected into datasets by further pattern rules. We can complete the datasets by adding various processing, filtering and charting steps in a very easy way, using the provided GUI. Whenever the underlying files or their contents change, the dataset contents and charts are recalculated. OMNeT++ supports several chart and graph types which are rendered directly from datasets.

In the next part, we will present C-V2X simulators based on the OMNET++ network simulation environment.

4.1.2 ns-3

The ns-3 simulator is a discrete-event network simulator aimed to be primarily used by the education and research community. It is open-source and open for researchers to contribute and share their proprietary ns-3-based software. It is completely written in the C++ programming language and it is an evolution of the from the ns-2 simulator, though it should be noted that it is not backwards-compatible with it.

Ns-3 is developed to provide an open, extensible network simulation platform for networking research and education. It provides models of how packet data networks work and perform and provides a simulation engine for users to conduct simulation experiments. As most simulators are used for, ns-3 provides an excellent environment to test and evaluate scenarios that are difficult or not possible to be performed using real systems, to study their behaviour and present how networks work in a comprehensive way.

Ns-3 is built as a system of software libraries that work together. User programs are written in either the C++ or Python programming languages. It is distributed as a source code, meaning that the target system needs to have a software development environment to build the libraries first, then build the user program.

One important distinction that we have to account for is the ns-3 models and modules.

- Ns-3 software is organized into separate modules that are each built as a separate software library. Individual ns-3 programs can link the modules (libraries) they need to conduct their simulation.
- Ns-3 models, on the other hand, are abstract representation of real-world objects, protocols, devices, etc.

An ns-3 module my consist of more than one model (the internet module contains models of both TCP and UDP). Our focus is on a specific ns-3 module, the ns-3 LTE module. The LTE module is composed of the LTE model and the EPC (Evolved Packet Core) model.

The LTE model has been designed to support the evaluation of the following aspects of LTE systems:

- Radio Resource Management

- QoS-aware Packet Scheduling
- Inter-cell Interference Coordination
- Dynamic Spectrum Access

The main objective of the EPC model is to provide means for the simulation of end-to-end IP connectivity over the LTE model. To this aim, it supports interconnection of multiple UEs to the Internet, via a radio access network or multiple eNode-Bs connected to the core network.

The architecture of the LTE radio protocol stack model for the UE is depicted in the following figure.

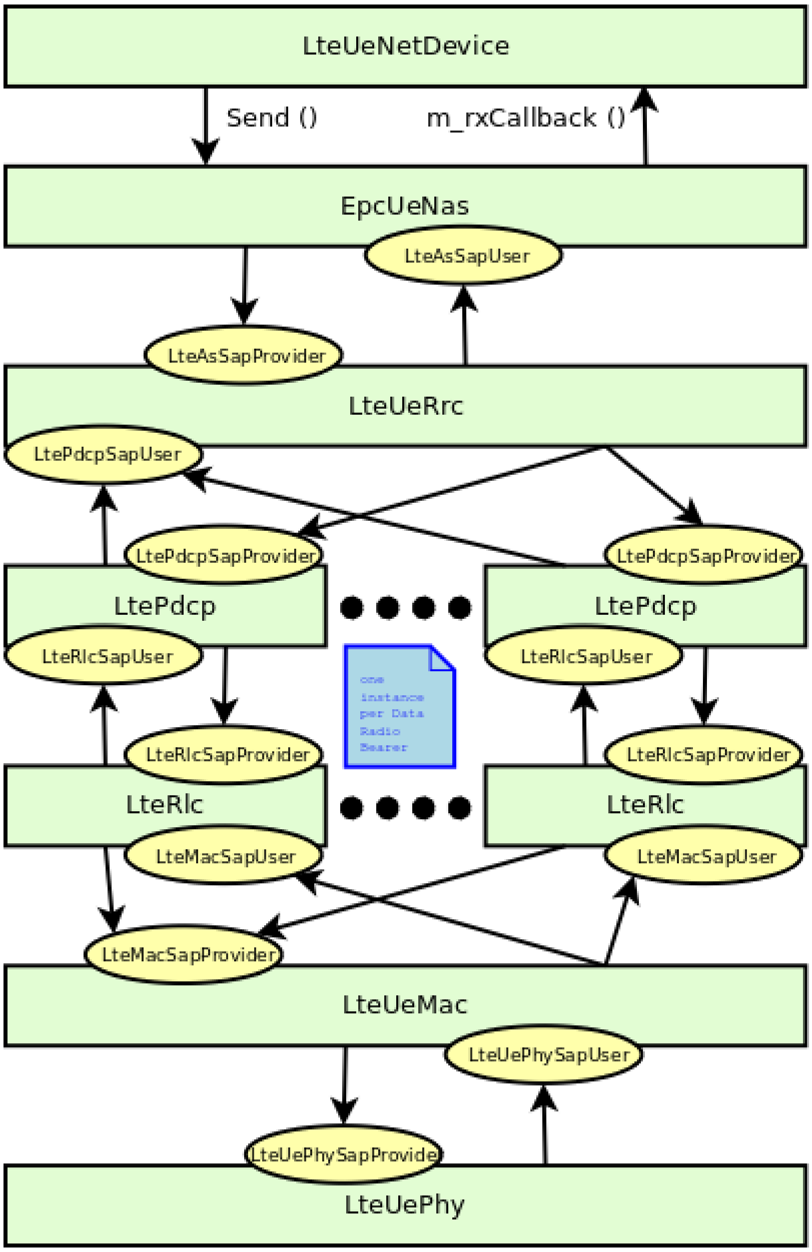

Figure 19 Architecture of LTE radio protocol stack model for the UE; Source: nsnam.org

While, the architecture of the LTE radio protocol stack model of the eNode-B is portrayed in Fig.19

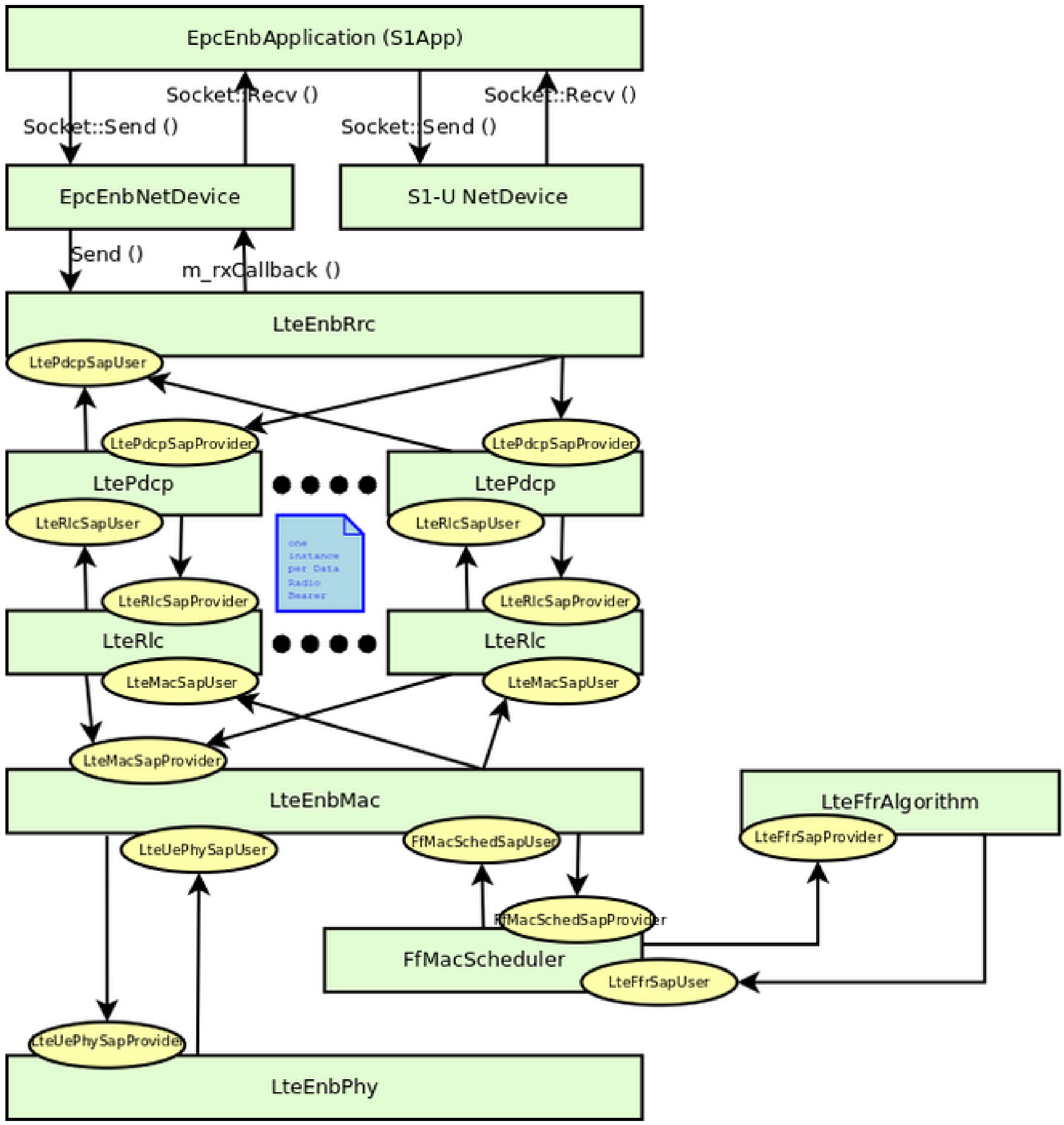

Figure 20 Architecture of LTE radio protocol stack model for the eNode-B; Source: nsnam.org

The fundamental unit being used for Resource Allocation is the Resource Block (RB). The packet scheduling is done on a per-RB basis, and eNode-B might transmit on a subset only of all the available RBs, hence interfering with other eNode-Bs only on those RBs where it is transmitting.

The preferred propagation model in the LTE module is the Buildings model provided by the Buildings module, which is designed specifically with LTE. The buildings model does not know the actual type of the transmitting node, it only cares about its position: whether it is indoor and outdoor, and what is its z-axis with respect to the rooftop level.

4.2 TRAFFIC SIMULATORS

4.2.1 SUMO

Simulation of Urban Mobility or "SUMO" for short, is an open source, microscopic, multi-modal traffic simulator. The main incentive for its development was to support the traffic research community with a tool with the ability to implement and evaluate own algorithms. It lets us simulate how a given traffic demand consisting of single vehicles moving through a given road network. Since SUMO works on a microscopic scale, each vehicle is modelled explicitly, has an own route and moves individually through the network. Simulations are deterministic by default but there are ways for introducing randomness in them. SUMOs' main features are:

- Space-continuous and time-discrete vehicle movement
- Different vehicle types
- Multi-lane streets with lane changing
- Different right-of-way rules, traffic lights
- An openGL graphical user interface
- Ability to manage large networks (up to more than 10.000 edges)
- Fast execution speed
- Interoperability with other applications at run-time
- Network-wide, edge-based, vehicle-based, and detector-based outputs
- Support of person-based inter-modal trips

Since its creation, SUMO has been used in many national and international research projects for:

- Traffic lights evaluation
- Route choice and rerouting
- Evaluation of traffic surveillance methods
- Simulation of vehicular communications
- Traffic forecast

To create road networks, the graphical network editor NETEDIT is used. NETEDIT is a visual network editor. It can be used to create networks from scratch and to modify all aspects of existing networks. NETEDIT is built on top of NETCONVERT, which is a command line application used to convert a real map into a SUMO-friendly XML file.

When defining a vehicle in SUMO, it is important to know that it consists of three parts:

- A vehicle type which describes the vehicle's physical properties
- A route the vehicle shall take
- The vehicle itself

Both routes and vehicle types can be shared by several vehicles. It is not mandatory to define a vehicle type and if not defined, a default type is used. The driver of a vehicle does not have to be modelled explicitly. When building our own routes, there are few important things to be mentioned:

- Routes must be connected.
- Routes must contain at least one edge
- The route file must be sorted by starting times.

Other than defining the vehicles and routes, we can also define some parameters such as the speed the vehicle moves, its acceleration and deceleration, the vehicle length etc.

Other important thing that need to be mentioned about SUMO is the traffic demand modelling. It covers the part of describing how the vehicles move in the network. The main two movements are:

- Trip: a vehicle movement from one place to another defined with a starting edge, destination edge and the departure time.
- Route: an expanded trip, meaning that it contains not just the first and the last edge, but all edges the vehicle will pass.

These trips and routes can be generated in several ways such as flow definitions, using randomization (the quick way to generate traffic), using OD-matrices (origin-destination), using flow definitions and turning ratios, using detector data, generating them by hand, using population statistics and using data from other sources. The SUMO networks are always encoded in Cartesian coordinates (meters) and may contain geo-referencing information to allow conversion to longitude, latitude.

4.2.1.1 VEINS

The VEINS or (Vehicles in Network Simulation) simulator was developed as a result of the increasing need to do research in VANET (Vehicular Ad-hoc NETworks) domain. VEINS is a simulation framework that provides coupled network and road traffic simulation. This is done using OMNeT++, which we described in the previous section, used to model realistic communication patterns between VANET nodes. While, for traffic generation and simulation it uses the SUMO (Simulation of Urban MObility) simulator. The availability of both simulators' C++ source code makes it possible to integrate all needed extensions into the respective simulation cores.

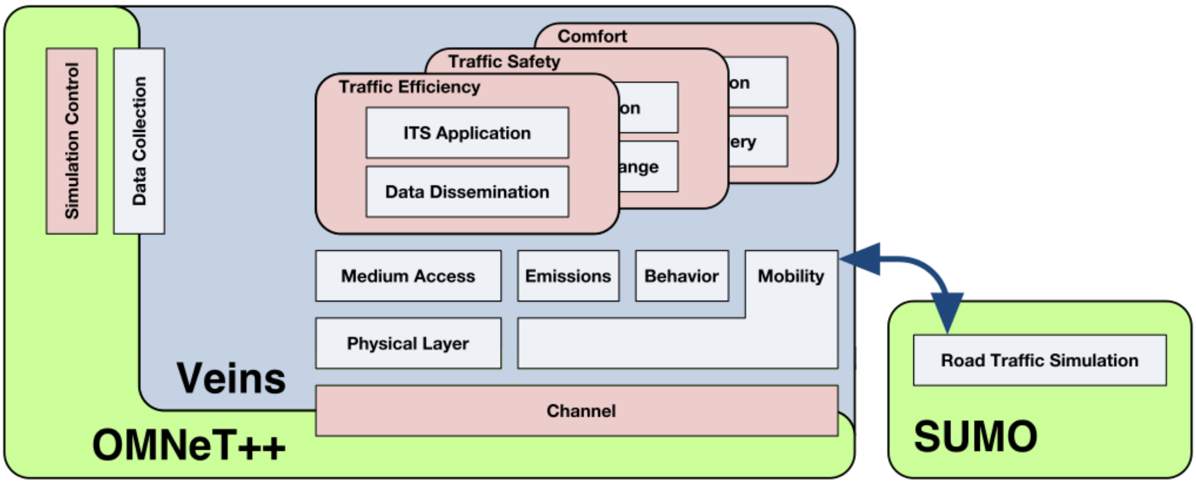

Figure 21 Integration of OMNeT++ with VEINS and SUMO; Source: SUMO wiki

As we can see from the image above, OMNeT++ is in charge of the network nodes and the IVC (Inter Vehicle Communication) protocol events, while the mobility is managed by SUMO using accurate street maps as a basis, or it also allows us to create our own map. To better understand how VEINS works, in the following part, we will explain the network simulation, road traffic microsimulation and the bidirectionally coupled simulation.

Network simulation

Network simulation is a widely used field in the research community, used to evaluate the behaviour of newly developed network protocols. There are many simulation frameworks in this domain such as the ns-2 network simulator, OMNeT++, J-SIM and JiST/SWANS, which are open source frameworks, and commercial tools such as OPNET. In VEINS, as we said before, the OMNeT++ framework together with its INET framework are used for simulation VANET protocols. The way OMNeT++ works, we explained it in chapter 3.1.

Road Traffic Microsimulation

To model realistic simulation of moving nodes, the mobility would need to be modelled according tot race files obtained in real-world measurements. However, using such traces limits us to testing only those specific scenarios we have the movement traces for. A possible solution to this problem is to generate these traces using simulation tools. This opens up the possibility to generate movement traces on the fly.

Traditionally, road traffic simulation models are classified into Macroscopic, Mesoscopic and Microscopic models, according to the granularity with which traffic flows are examined. Macroscopic models design the traffic at a large scale, treating traffic like a liquid and often applying hydrodynamics flow theory to vehicle behaviour. Mesoscopic models, on the other hand, are focused to the movement of whole platoons, using e.g. aggregated speed-density functions to model their behaviour. But when we model VANET scenarios, we want to do the modelling as accurate as possible, therefore we require exact position of simulated nodes.

The traffic simulation in VEINS is performed by the microscopic road traffic simulation package SUMO, which uses the car-following mobility model by Stefan Krauss (SK). It can perform simulations both running with and without a GUI, and imports city maps from a variety of file formats. SUMO allows high-performance simulations of huge networks with roads consisting of multiple lanes, as well as of intrajunction traffic on these roads, either using simple right-of-way rules or traffic lights. Vehicle types are freely configurable with each vehicle following statically assigned routes, dynamically generated routes, or driving according to a configured timetable. More on SUMO in chapter 3.3.

Bidirectionally Coupled Simulation

VEINS successfully achieved to bidirectionally couple both frameworks, OMNeT++ and SUMO, by extending each with a dedicated communication module. During simulation runs, these communication modules exchange commands, as well as mobility traces, via TCP connections. OMNeT++ handles the mobility by scheduling node movements at regular intervals. This fits well with the approach of SUMO, which also advances simulation time in discrete steps.

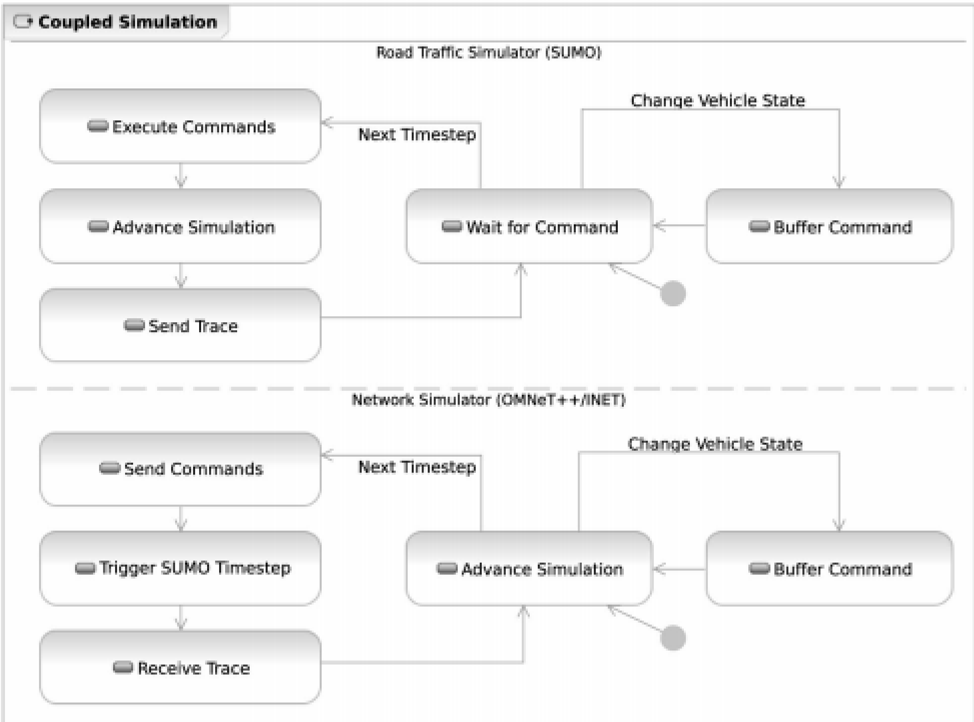

Figure 22 Overview of the coupled simulation between OMNeT++ and SUMO (Cristoph Sommer, 2011)

As we can see from Fig.22, the control modules integrated with OMNeT++ and SUMO are able to buffer any commands arriving in-between timesteps to guarantee synchronous execution at defined intervals. Furthermore, vehicles can be stopped to create artificial traffic jams, they can be resumed to resolve those jams, and each simulated vehicle can be individually rerouted around arbitrary road segments. This way, VEINS can accurately reflect how drivers that know about a traffic obstruction will try to avoid it. This is an excellent feature that can be extended for simulating vehicles slowing down because of hazards in front, allowing simulations for autonomous vehicles to be performed and analysed.

The common interface

In order to foster comparability of research results and to allow realistic simulations of VANET protocols with any of a whole range of network simulators, a common interface between road traffic and network traffic is highly desired. TraCI (Traffic Control Interface) is the generalized traffic control interface used to couple OMNeT++ and SUMO. It uses command-response approach and a TCP connection. It connects to a TraCI server (SUMO or sumo-launchd) and subscribes to events like vehicle creation and movement. For each vehicle created in SUMO, it instantiates one OMNeT++ compound module in the OMNeT++ simulation. This module is assumed to contain a mobility submodule of type TraCIMobility. At regular intervals it will use this module to advance the simulation in SUMO and update the node's mobility information based on the behaviour of the vehicle.

4.2.2 VanetMobiSim

VanetMobiSim is an extension to CanuMobiSim, a generic user mobility simulator. CanuMobiSim is a platform and simulator-independent software coded in SUN Java and produces mobility traces for network simulators such as: ns-2, GloMoSim, and QualNet. VanetMobiSim therefore aims at extending the vehicular mobility support of CanuMobiSim to a higher degree of realism.

4.2.2.1 Software Architecture

VanetMobiSim is a modular discrete event simulator based on SUN Java. The software architecture is articulated around two extension objects: The Universe and the Node. The former is modelling static objects, while the latter models moveable objects. The software architecture of VanetMobiSim is shown in Fig.23.

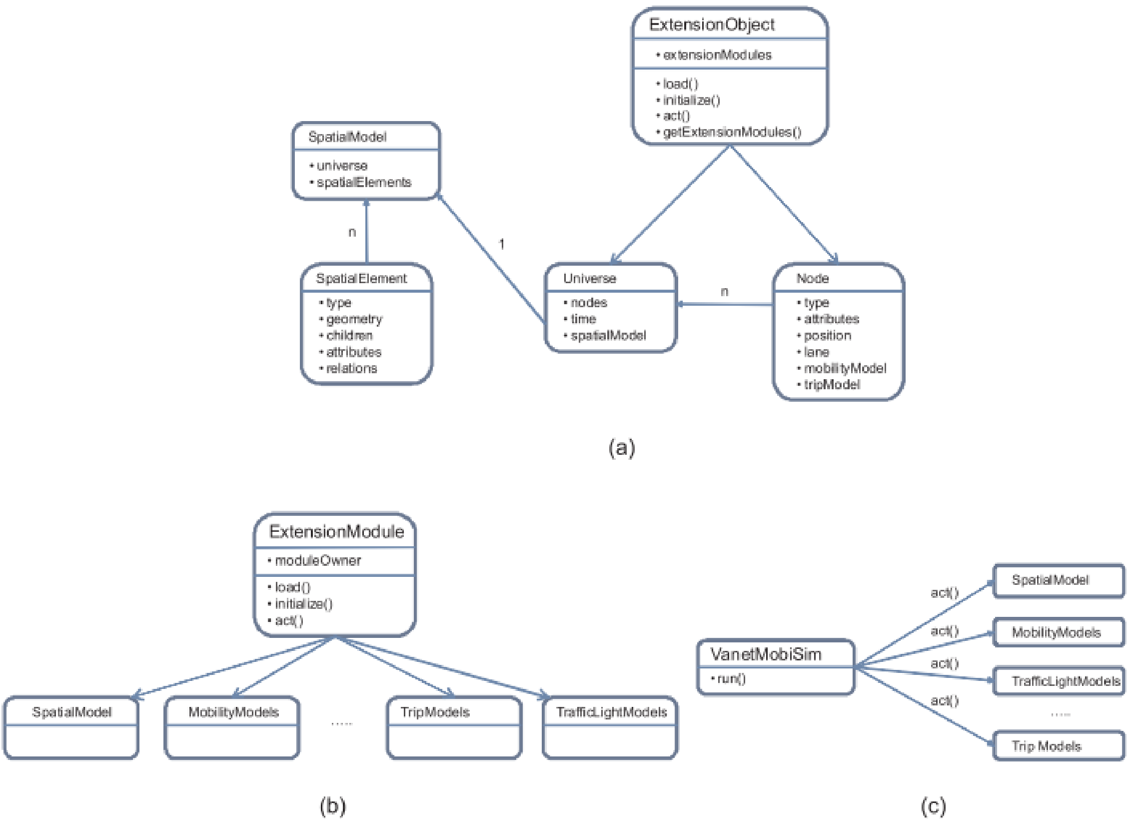

Figure 23 VanetMobiSim Software Architecture: a) extension object and spatial model concept; b) extension module concept; c) discrete event calls; (Jerome Harri, 2009)

Extension objects contain extension modules which roles is to model the motion constraints and the traffic generator blocks. Conceptually speaking, extension objects represent actors of a simulation, while extension modules represent the actors' details and behaviour. The Universe module contains references to all nodes and to the full spatial environment. For the simulation, all modules are attached to the central coordinator and are activated when an event requires actions. Each feature contained in VanetMobiSim is implemented as a module and is loaded at start-up from an XML scenario file.

4.2.2.2 Data structure

The data structure of VanetMobiSim is based on three levels of detail in the geographic objects.

- Features: a feature is the description of a real-world element such as a street, building, car or intersection.
- Relationship: in order to describe the interactions between features, a relationship description is employed. They are critical as they inter-link the different features such as road elements and junction and therefore crucial to path and trip planning, and notably to intersection management.
- Attributes: the properties of real-world objects are represented as attributes, for example, Speed Limit is an attribute of a Road Element.

4.2.2.3 Motion Constraints

The motion constraints do not only take into account the road topology, but also the road structure, the road characteristics and the presence of traffic signs. All motion constraints are loaded in the VanetMobiSim Spatial Model and can be used irrespectively of the traffic generator.

4.2.2.4 Traffic Generator

The VanetMobiSim traffic generator includes all aspects related to an individual car's behaviour, from the selection of target movement destination and routes to reach them, to spped and acceleration modelling. The traffic generator description plays the main role in the realism of car movements, as it is responsible for effects such as smooth speed variation, cars queues, traffic jams and overtaking.

4.3 SIMULTE

SimuLTE is born as a result of the lack of open-source simulation frameworks in the LTE/LTE-Advanced research community, that could serve as a reference simulator for comparing results.

SimuLTE is based on the OMNeT++ simulation framework, which can be used to model many things, not only networks. It simulates the data plane of the LTE/LTE-A Radio Access Network and Evolved Packet Core. The general structure of the three main nodes in SimuLTE is shown in Fig.24.

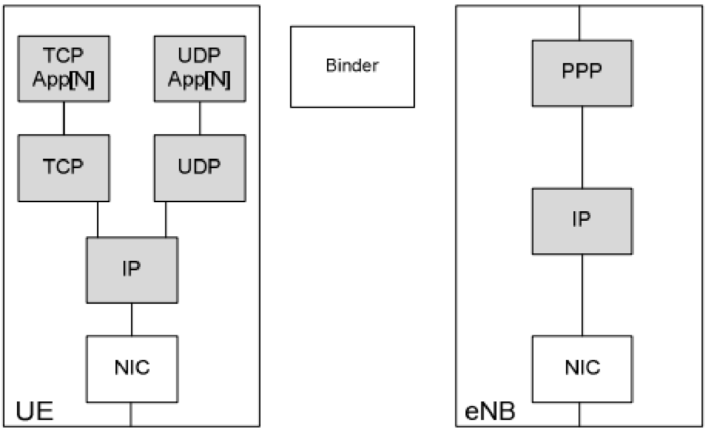

Figure 24 The three main nodes SimuLTE is composed of, UE, eNode-B and Binder (Antonio Virdis, 2016)

SimuLTE implements the UE (User Equipment) and eNode-B (evolved-Node-B) as compound modules. They can be connected with each other and with other nodes 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. Every module has an associated Network 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. Also, the IP module is taken from the INET package. In the UE it connects the Network Interface Card (NIC) to applications that use TCP/UDP, while in the eNode-B it connects the eNode-B itself to other IP peers via PPP (Point-to-Point Protocol). The NIC module 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 us to build hybrid connectivity scenarios, e.g. with nodes equipped with both Wi-Fi and LTE interfaces. The communication between modules takes place only via message exchange, thus each action starts from a message handler.

The NIC module structure is the presented in Fig.25.

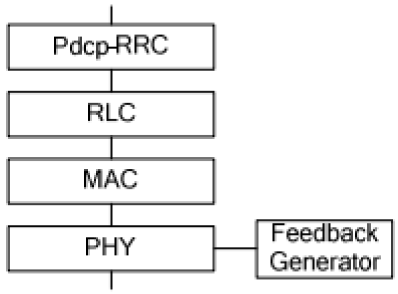

Figure 25 NIC module architecture on the UE; (Antonio Virdis, 2016)

The only module that has no counterpart in the eNode-B module is the Feedback Generator, which creates channel feedbacks that are managed by the PHY module. Each network layer of the stack is represented by a separate module in OMNeT++. Every module structure is described using the .ned files and their functionalities are implemented by using class definitions. Each layer has a main class called LtePhyBase, LteMacBase, LteRlcBase and LtePdcpRrcBase respectively. The UE and eNode-B modules are created by extending the Base class of the layer they represent, and each add their own functionalities. This makes it easier if any user wants to modify or create a new PHY, MAC or other layer themselves.

Communication between different layers occurs via message exchange, same as data transmission between UEs and eNode-Bs. On the other hand, resource accounting is decoupled from data transmission. The Binder module monitors which resources, i.e. Resource Blocks (RBs) are used by both the eNode-Bs (for downlink transmission) and the UEs (for uplink transmission). Air transmissions between LTE NICs are modelled by the ChannelModel class, that is a part of the PHY layer of the LTE NIC itself. On reception of a new message, ChannelModel computes the Signal-to-Interference-and-Noise-Ratio (SINR) perceived by the node. To do this, it obtains information from the Binder about the usage of the RBs for all the nodes in the network and decides whether the message can be successfully decoded or not. ChannelModel is also responsible for computing and reporting the Channel Quality Indicator (CQI) of the UEs, which is used for scheduling operations at the eNode-B. The ChannelModel also takes into account realistic path loss and fading effects which can be configured by the user. When the packet reaches the PHY layer, a message is sent to the receiving UE using a sendDirect() call. As for the multicast (broadcast) case, the sendBroadcast() function sends a copy of the message to all UEs within the transmission range of the sender, exploiting the implementation of wireless broadcast transmissions of INET. At the receiving end, if the UE is not subscribed to the relevant multicast group, it discards the message.

To start a C-V2X simulation, we first need to create a configuration file, usually called omnetpp.ini, in the simulation folder. The .ini file is grouped into sections named [General] and [Config]. In the [General] section, we define some general parameters such as the network, which is the model to be set up and run, the simulation length, etc.

```
[General]
cmdenv-express-mode = true
cmdenv-autoflush = true

network = lte.simulations.cars.Highway

###########################################################
#              Simulation parameters                      #
###########################################################
debug-on-errors = false
print-undisposed = false

sim-time-limit = 70s

**.sctp.**.scalar-recording = false
**.sctp.**.vector-recording = false

**.coreDebug = false
**.routingRecorder.enabled = false

*.playgroundSizeX = 20000m
*.playgroundSizeY = 20000m
*.playgroundSizeZ = 50m

###########################################################
#              VeinsManager parameters                    #
###########################################################
*.veinsManager.moduleType = "lte.corenetwork.nodes.cars.Car"
*.veinsManager.moduleName = "car"
*.veinsManager.moduleDisplayString = ""
*.veinsManager.launchConfig = xmldoc("heterogeneous.launchd.xml")
*.veinsManager.updateInterval = 0.1s

###########################################################
#                        Mobility                         #
###########################################################
*.car[*].mobilityType = "VeinsInetMobility"

**.deployer.positionUpdateInterval = 0.001s

###########################################################
#       IP configuration for dynamic-created UEs          #
###########################################################
# enrolled multicast groups must be set in the HostAutoConfigurator (instead of demo.xml), seperated by a single space character
*.car[*].configurator.mcastGroups = "224.0.0.10"

###########################################################
#                   channel parameters                    #
###########################################################
**.channelControl.pMax = 10W
**.channelControl.alpha = 1.0
**.channelControl.carrierFrequency = 2100e+6Hz

# PhyLayer & Feedback parameters
**.lteNic.phy.channelModel=xmldoc("config channel.xml")
**.feedbackComputation = xmldoc("config channel.xml")
```

Figure 26 Example of the [General] section in the simulation .ini file

In the section [Config <configname>], we define different configuration parameters we want to test in the simulation. When the simulation is run, we select one of the configurations to be activated.

```
102
103 # ------------------------------------------------------------------------------ #
104 # Config "VoIP-Uplink"
105 #
106 [Config VoIP-UL]
107
108 ###########################################################
109 #                     App Layer                           #
110 ###########################################################
111 *.server.numUdpApps = 10
112 *.server.udpApp[*].typename = "VoIPReceiver"
113 *.server.udpApp[*].localPort = 3000 + ancestorIndex(0)
114
115 *.car[*].numUdpApps = 1
116 *.car[*].udpApp[0].typename = "VoIPSender"
117 *.car[*].udpApp[0].destAddress = "server"
118 *.car[*].udpApp[0].destPort = 3000 + ancestorIndex(1)
119
120
121 # ------------------------------------------------------------------------------ #
122 # Config "VoIP-Downlink"
123 #
124 [Config VoIP-DL]
125
126 ###########################################################
127 #                     App Layer                           #
128 ###########################################################
129 *.server.numUdpApps = 10
130 *.server.udpApp[*].typename = "VoIPSender"
131 *.server.udpApp[*].localPort = 3000 + ancestorIndex(0)
132 *.server.udpApp[*].destAddress = "car[" + string(ancestorIndex(0)) + "]"
133 *.server.udpApp[*].startingTime = 0.05s
134
135
136 *.car[*].numUdpApps = 1
137 *.car[*].udpApp[0].typename = "VoIPReceiver"
138
139
```

Figure 27 Screenshot of the [Config] section in the simulation .ini file

In the figure above, we can see that there are two different configuration sections, the first one called [Config VoIP-UL] and the second one [Config VoIP-DL]. We can see that in the [Config] section we can set up parameters used by different modules in the simulation. For example, in line 115, we say that in the module with name car, we set the variable with name numUdpApps to 1, meaning that the car module can only have one UDP application running.

To introduce vehicular mobility, SimuLTE uses the Veins framework that simulates vehicular networks and is based on the road traffic simulator SUMO. By integrating Veins into the SimuLTE project, it allows us to simulate cellular communications in vehicular networks. As shown in Fig. 26, we can define which module is going to be used by the VeinsManager, which network configuration will be used, the update interval, etc.

4.4 LTEV2VSIM

LTEV2Vsim is a simulator developed and written in MATLAB. Its main focus is the LTE-V2V resource allocation for the cooperative awareness service. It allows parameter tuning to realize the wanted environment we want to analyse, including propagation settings, the modulation and coding scheme (MCS) and the vehicular traffic. As for the traffic generation, the user can either create simple mobility models or to use traffic traces, which are input files describing the realistic position of vehicles in time.

As aforementioned, LTEV2Vsim mainly focuses on the resource allocation for the cooperative awareness service and to realise this, the following assumptions are made. The vehicles periodically broadcast beacon messages addressing all the neighbours that are within a certain distance, referred to as awareness range. As for the resource scheduling, the semi-persistent scheduling of resources is considered. The way it works is once a group of RBs is obtained and selected for the transmission of CAMs from a vehicle, the same RBs are periodically reserved for the same transmission until a new decision is taken for some reason. In LTEV2Vsim, in addition to the normal half duplex radios, also full duplex is considered. With half duplex, vehicles rely on the different transmission and reception phases on a subframe basis, whereas by using full duplex, vehicles can transmit their CAMs while decoding the same subframe and thus receiving CAMs sent by their neighbours.

In terms of structure, LTEV2Vsim is a discrete-event simulator, developed in MATLAB, which reproduces the cooperative awareness service and faces the issue of resource allocation in vehicular networks. The minimum time step is the beaconing interval. The simulation flow is portrayed in Fig.28.

- Initialization: reads configuration parameters from the config files or the command line. Calculates the number of available beacon resources (BRs) per beacon period, where a BR is a group of RBs able to carry one beacon. It initializes the traffic trace for the vehicles.
- First radio resources assignment: in order to reduce the duration of the initial transient period, a first resource assignment is carried out for all the vehicles in the scenario at the beginning of the simulation, just as they have all been under cellular coverage.
- Cycle start: once the initial configuration is finished, the main simulation cycle starts and it is performed in three steps: position update, error evaluation and radio resource reassignment.
- Position update: sets the current position of all vehicles and their position estimated by the network.
- Quality assessment (error evaluation): the main part of the cycle is to evaluate whether beacon transmission succeeded or not while using resources allocated before the cycle begins. The beacon reception errors are evaluated through calculation of the SINR.

- Radio resource reassignment and blocking events: after the evaluation of packet errors, BRs are reassigned for all vehicles that have observed collisions within their awareness range. In this phase we can implement our resource allocation algorithms for testing. In the network-controlled case, the reassignment is performed by the base station, which knows the position of the vehicles. In the autonomous case, each vehicle performs the reassignment autonomously, using a sensing procedure that recognizes if a BR is busy or free within a configurable sensing range.
- Cycle end and output evaluation: the simulation cycle blocks are cyclically repeated at each beacon period T_{bc}, until the end of the simulation time. At this point, the key performance indicators (KPIs) are computed and collected into the output files.

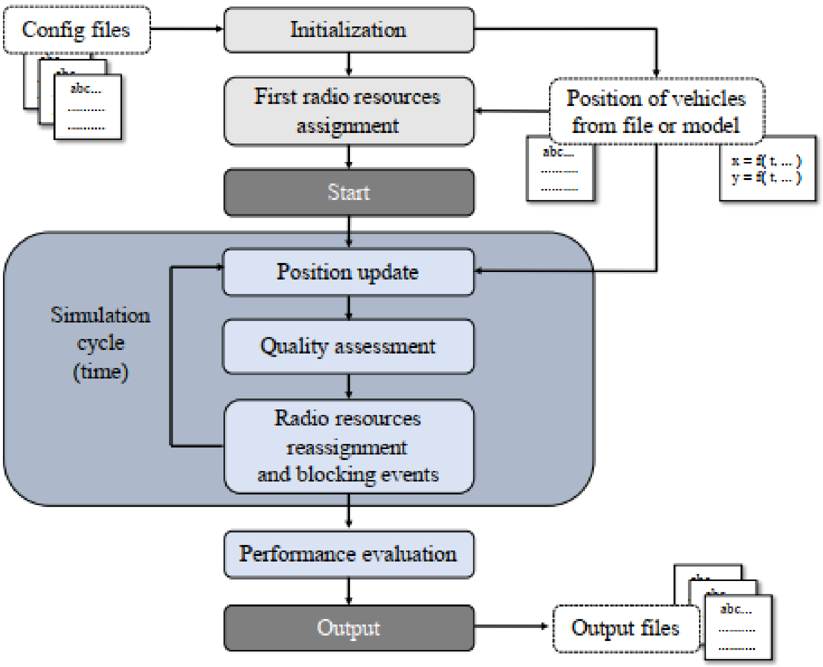

Figure 28 LTEV2Vsim block diagram (Giammarco Cecchini, 2017)

4.5 VSIMRTI (V2X SIMULATION RUNTIME INFRASTRUCTURE)

The V2X Simulation Runtime Infrastructure (VSimRTI) is a comprehensive framework for assessment of new solutions for Cooperative Intelligent Transportation Systems (ITS). It couples different simulators to allow the simulation of the various aspects of future ITSs.

The concept of VSimRTI, in contrast to the other simulators, is that it allows easy integration and exchange of simulators. With that, it comes with very high flexibility and enables the coupling of the most appropriate simulators for a realistic presentation of vehicular traffic, emissions, wireless communication (cellular and ad-hoc), user behaviour and modelling of mobility applications.

VSimRTI uses an ambassador concept inspired by some fundamental concepts of the High-Level Architecture (HLA). Thus, it is possible to couple arbitrary simulation systems with a remote control interface. Attaching an additional simulator only requires that the ambassador interface is implemented and, then, the specified commands are executed. There are some simulators already coupled with VSimRTI, such as:

- Traffic simulators: SUMO and PHABMACS
- Communication and network simulators: ns-3, OMNET++, SNS and VSimRTI_Cell
- Application simulator: VSimRTI_AppNT
- Several visualization and analysis tools

4.5.1 The VSimRTI Application Simulator

This simulator is optimized for the simulation of Smart Mobility applications. They run in a sandbox which offers vehicle-like interfaces. Data provided by traffic, communication network and further connected simulators are transformed in a format used by components of real vehicles. To run an application, its logic is implemented in Java and its settings and behaviour are configurable.

The structure of the Application Simulator is based on the ETSI ITS Standard. In the next part, we will briefly describe its individual aspects:

- Station Positioning: the realistic movement information from the traffic simulator is provided for application of the EGO-vehicle. This information is already formatted in GPS coordinates to simulate real navigation system. Map and own route information are available.

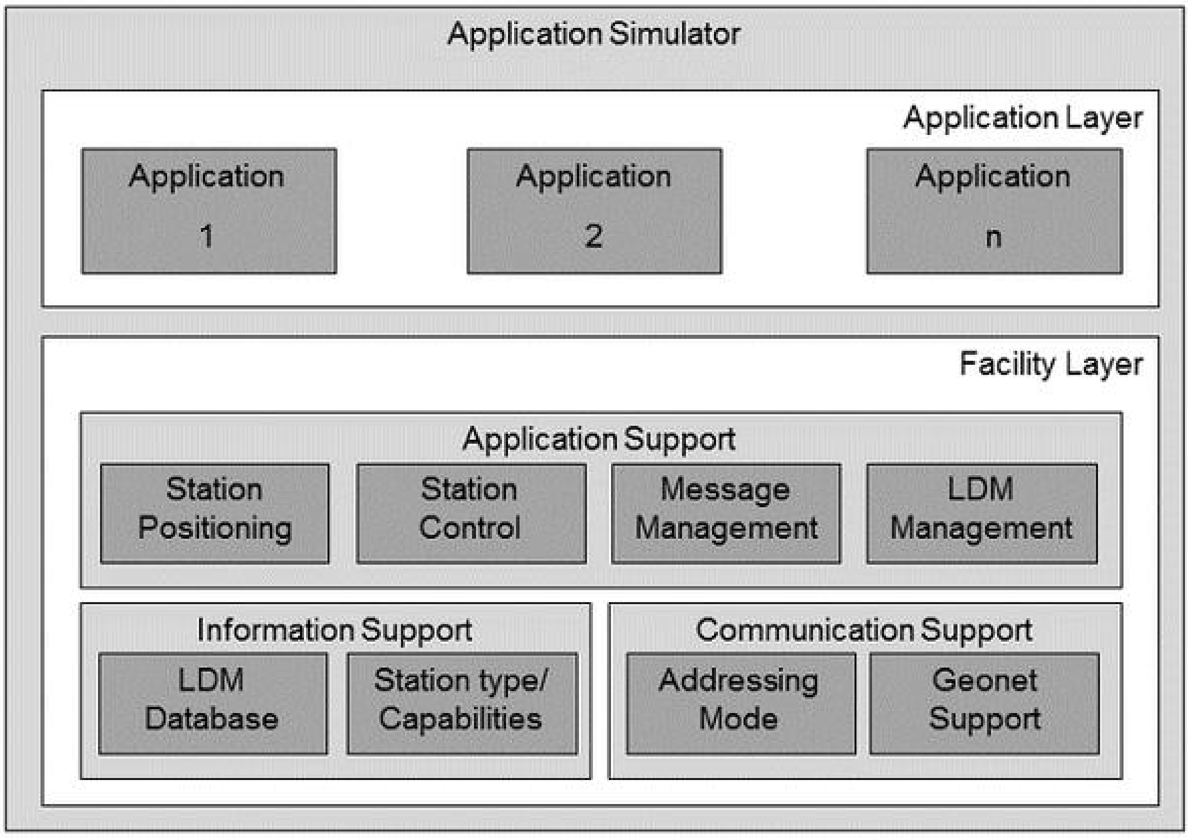

Figure 29 Features of the VSimRTI Application Simulator

- Station Control: the vehicle is able to sensor events, which can be simulated by the Environment Simulator. The vehicle can additionally influence its driving manoeuvres, such as slowing down, accelerating, decelerating, on its own.
- Message Management: both periodical CAM and event based DENM messages are supported.
- LDM Management and LDM Database: The features of a dynamic knowledge base, or local dynamic map are implemented following the concepts of the LDM++.
- Station type/Capabilities: Simulated stations can be specified with different capabilities. The configuration is part of the VSimRTI Mapping Component, which supports different kind of vehicles and also Roadside Units as well as intelligent Traffic Lights.
- Addressing and GeoNetworking: The actual routing in VSimRTI is implemented in the Communication Simulator, but the Application Simulator supports different addressing schemes for ad-hoc communication (Unicast, Broadcast, Geocast) as well as for communication over the infrastructure-based cellular networks.

4.5.2 The VSimRTI Cellular Simulator

The VSimRTI cellular simulator enables the simulation of wireless transmissions via cellular networks. This simulator consists of two main components: the GEO Server and the Cellular Network Simulation (CNS). In contrast to ad-hoc communication, cellular systems always require a deployed network infrastructure. The addressing between the nodes needs to be realized by IP. The GEO Server is a central server which is connected to the Gateway GPRS Support Node (GGSN). It has the task to maintain a table with all vehicles in the region. In this way, Geo addressing similar to geographic ad-hoc routing can be realized.

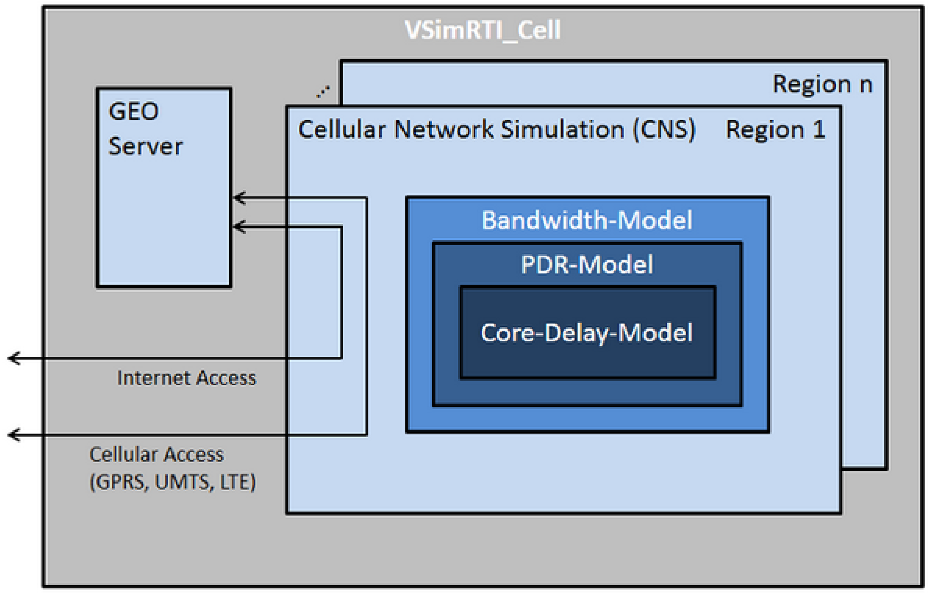

Figure 30 Architecture of VSimRTI Cellular Simulator (Schuenemann, 2011)

The second component is the CNS, which is the most important component for the simulation of the Radio Access Network (RAN) and its connection to the IP-based core network. The CNS subdivides the simulation area into various regions to modulate a network with different coverage properties. For each region, three nested models are used to simulate the packet transmission: The Core Network Delay Model, the PDR Model and the Bandwidth Model.

- The Core Delay model supports different basic delay types to simulate the transmission time for every packet statistically.
- The PDR model is named after the Packet Delivery Ratio and models the effect of individual packet losses between the node and the base station due to inappropriate signal coverage.
- The Bandwidth model considers the channel load of a region and calculates the final delay for the individual packets.

4.6 ITETRIS SIMULATOR

The simulation platform iTETRIS (an Integrated Wireless and Traffic Platform for Real-Time Road Traffic Management Solutions) is an open source platform developed under the European FP7 Program. The purpose was to create a framework built on existing open source simulators and avoid their tight integration. As a result, commercial wireless and traffic simulation platforms were not considered, and an in-depth analysis of the available open source platforms was realized.

4.6.1 Wireless Simulation

To simulate the wireless environment and communications, the simulators ns-2, ns-3 and OMNeT++ were analysed. These platforms include a high number of communications libraries, and are widely used by the wireless communications and networking communities. A lower physical layer modelling accuracy provides OMNeT++ more scalability compared to ns-2 and ns-3. However, when the modelling of the physical layer in OMNeT++ is improved, its computation time and required memory resources considerably increase. After testing and evaluation of the three simulators under different scenarios, ns-3 was chosen to be adopted as the wireless reference simulator for iTETRIS.

4.6.2 Traffic Simulation

As open source traffic simulators, as potential candidates for iTETRIS, VanetMobiSim and SUMO platforms were analysed. VanetMobiSim is developed as a tool to retrieve vehicular mobility patterns (featuring microscopic mobility modelling and real-world road topologies) to study cooperative vehicular communications at the expanse of its traffic modelling accuracy. On the other hand, SUMO is developed as a tool for evaluation of pure traffic engineering solutions at large scale, and therefore offers a more complete and accurate solution than VanetMobiSim. Hence, SUMO is chosen as a reference traffic simulator for iTETRIS. An important feature of SUMO is that it allows external applications to connect to the simulator through the use of the API TraCI that relies on a socket connection. TraCI allows external applications to retrieve or modify values characterizing SUMO objects (e.g. vehicles' speed).

4.6.3 iTETRIS Architecture

As we explained before, the network nodes, whether they are vehicles or infrastructure units (i.e. Road Side Unit) exchange information with other nodes, and therefore need to be represented in ns-3. Vehicles are also represented in SUMO to simulate their mobility. To handle the representation of a node over different platforms, iTETRIS implements a new central block referred to as iCS (iTETRIS Control System). The iCS handles SUMO and ns-3 interaction, in addition to preparing, triggering, coordinating and controlling the execution of iTETRIS simulations.

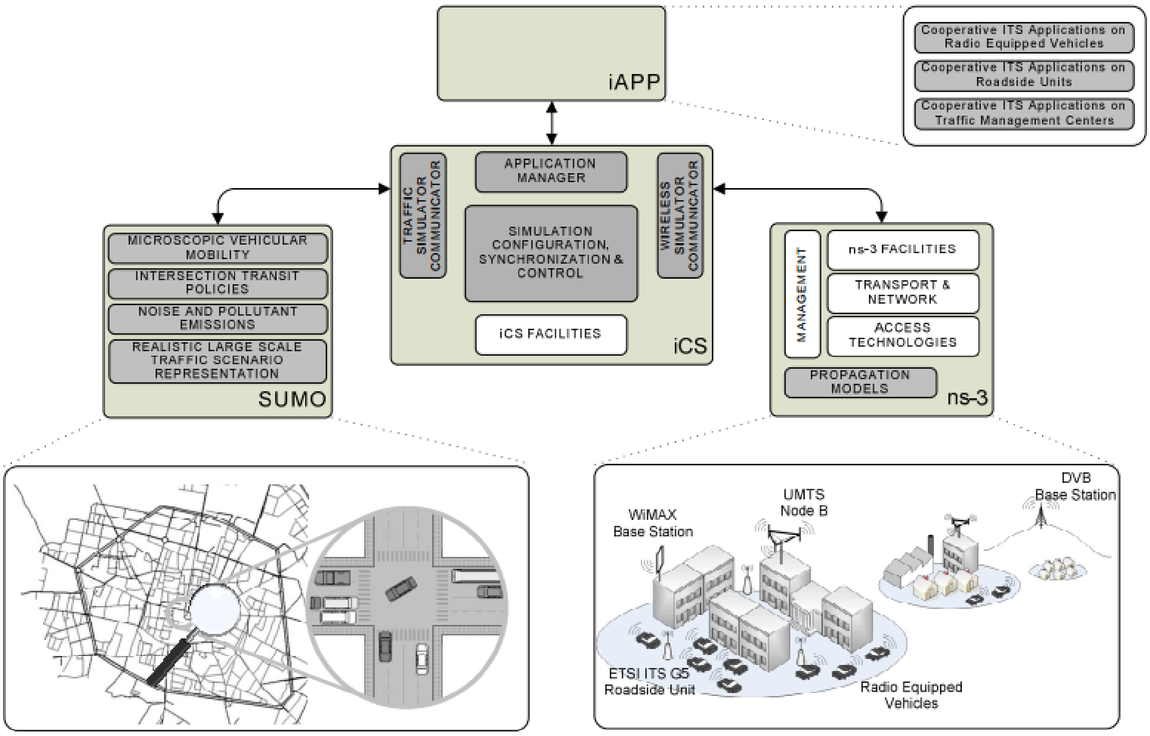

Figure 31 iTETRIS Architecture (Michele Rondinone, 2010)

The architecture of iTETRIS is presented in Fig.31. Cooperative ITS applications running on vehicles, RSUs or TMCs are implemented in external blocks referred to as iTETRIS Applications (iAPP). SUMO models and simulates transportation aspects like vehicles' mobility at microscopic level, road intersections transit policies, pollutant and noise emissions produced by the vehicles, as well as their fuel consumption. It also supports detailed representation of real-world large-scale traffic scenarios in terms of road networks, traffic demands and traffic lights management. Ns-3 supports accurate and realistic modelling and simulation of wireless transmissions for cooperative ITS systems in heterogenous communications scenarios. It also provides suitable models to emulate the radio propagation effects and reproduce functionalities and protocols for every layer of the communications protocol stack. The iCS provides some supporting functionalities for the cooperative ITS applications implemented on the iAPP. The implementation of the ITSC Facilities has been split between ns-3 and iCS. More specifically, the facilities more closely related with the ITS applications (require a higher interaction with the iAPP) are implemented on the iCS Facilities part in the architecture, while those needed to support communication sessions have been implemented in ns-3 (iCS Facilities in Fig.31). the implementation approach results in that the iCS and ns-3 do not have to call from an external block the Facilities needed for their internal operations, which significantly reduces the exchange of messages between ns-3 and the iCS, the required computing resources and the simulation time.

4.6.4 iTETRIS simulation process

The execution of iTETRIS simulations is controlled by the iCS. First, the iCS sets up the simulation environment by initialising the various iTETRIS configurable objects. A hierarchical XML configuration file structure (Fig. 32) is adopted to improve the readability of the simulation configuration and facilitate the customization of the different iTETRIS blocks.

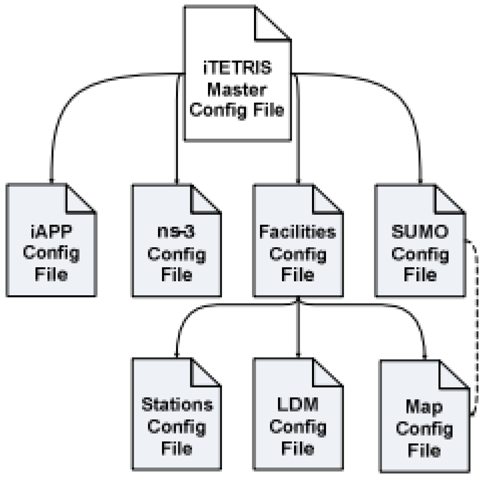

Figure 32 iTETRIS configuration files hierarchy (Michele Rondinone, 2010)

The master configuration file defines general parameters such as the duration (in seconds) of the simulation, the penetration rate of vehicles equipped with each simulated radio access technologies and the sockets' IP addresses and port numbers needed to communicate the iCS with ns-3, SUMO and the iAPP. When iTETRIS is started, SUMO and ns-3 are launched by the iCS with their executables registered in the system in separate threads so that, from that moment on, they can receive commands. At the same time, the iCS allocates dedicated execution threads for each of the simulated ITS applications (iAPPs) and reads the configuration file needed to create the iCS Facilities. SUMO and ns-3 configuration files are then read to prepare the traffic and wireless environments.

iTETRIS simulations, as described in (Michele Rondinone, 2010) consist of subsequent iterations of a loop, depicted in Fig.33. in which ns-3, SUMO and the iAPPs are sequentially triggered by the iCS to execute their tasks.

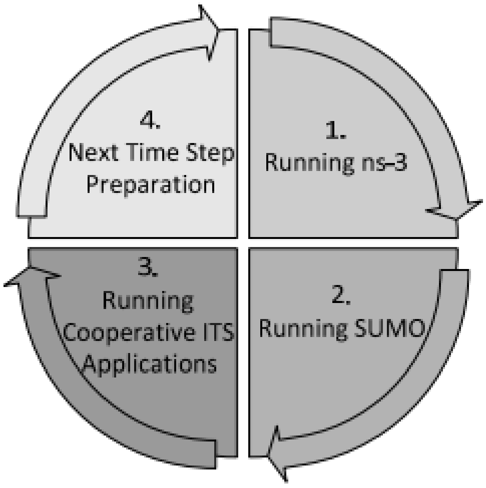

Figure 33 iTETRIS run-time loop iterations (Michele Rondinone, 2010)

The simulated time period is divided into simulation time steps of one second. For each simulation time step, the different iTETRIS blocks simulate all the applications, traffic or wireless communications events scheduled for the corresponding time step. The entry point in the run-time loop is the simulation of the transmission of wireless messages in ns-3. The application's payload for these messages is created and store in the iCS. When the iCS schedules message transmissions in ns-3, a reference to these payloads is passed to ns-3. Once ns-3 has simulated all the events scheduled for the current time step, the iCS retrieves the simulation results as lists of successful wireless transmissions. The iCS can then match the received messages with the previously store payloads, and update specific communications-related iCS Facilities, which can then be accessed and used by the applications implemented in the iAPP. In the following stage of the run-time loop, SUMO simulates all the traffic mobility events and then, provides as outcome the updated position and speed of active vehicles, along with the position and speed of vehicles entering the simulated scenario in the current time step. For the new vehicles, the iCS establishes whether they are equipped with a given communications technology. If a vehicle is equipped with a communications technology, it can then run ITS applications and a structure of this vehicle is created at the iCS in order to link its SUMO and ns-3 representations. Upon retrieving the SUMO simulation outcomes, the iCS updates the mobility-related iCS Facilities to store the information related to active or new vehicles that could be used by the applications implemented in the iAPPs. The iCS passes then the simulation token to the iAPP block (3rd step). iAPP is asked by the iCS Application Manager to “subscribe” to the SUMO and ns-3 simulation results they need for the execution of the application implemented in it. Based on these subscriptions, the iCS forwards the needed information to the iAPP, After executing the applications implemented in the iAPPs during the corresponding simulation time step, the iCS retrieves the iAPPs’ results that in turn may generate new actions to be executed over SUMO or ns-3. The last stage of the run-time loop is devoted to preparing the execution of the next time step in ns-3. More specifically, the iCSs’ Wireless Simulator Communicator schedules the transmission of new messages, commands ns-3 to update the position of nodes based on SUMO’s outcomes and instructs ns-3 to create the new connected vehicles that have just entered the simulation scenario. To end the simulation, the iCS cleans up the objects in the memory, closes logging files, shuts down the connections with ns-3, SUMO and the iAPPs, and eliminates the threads in which they were executed.

5 CONCLUSION

The new, fifth generation of cellular networks is to start deploying in 2020. With it, it brings a lot of improvements, a lot of opportunities, but a lot of difficult challenges too. The focus of this thesis is to introduce cellular network, their requirements, as well as the applications and services they can offer.

Vehicular networks are one of the most trending technologies and are expected to be one of the main consumers of the services that the 5th generation cellular networks offer. These networks will help improve road safety, provide infotainment in the vehicles and will greatly support the faster development and deployment of the autonomous driving vehicles.

The autonomous vehicles generate an immense amount of data because of the many onboard sensors they have. To exploit it, this data is exchanged between vehicles and road infrastructure, creating a technology called Vehicle-to-Everything. V2X technology will enable many different use cases in the vehicular networks, such as: platooning, emergency vehicle warning, collision detection, assisted driving and many more.

The vehicular networks are a very particular type of communication networks because of their requirements of low latency and very high reliability, that are derived from the predominant type of messages they exchange - safety messages. On top of that, we have very fast-moving network nodes (5G should support speeds up to 500 km/h) in very dense scenarios, making things even more difficult. The networks we have are not able to satisfy these stringent requirements. In order to address the problems and satisfy the conditions the vehicular networks produce, we must come up with state-of-the-art solutions.

Testing and evaluating new solutions needs to be done in large-scale traffic scenarios, that portray the real-world. The best way to do this is using simulators. In this thesis work, we describe four different simulators that can be used for testing Cellular V2X performance and analysing new services and applications. Each of them is developed with a different interest in mind. For example, SimuLTE is created as a result of the lack of LTE simulators at the time and can be further improved by adding the Device-to-Device and Vehicle-to-Everything capabilities. The LTEV2Vsim simulator is created with a more definite purpose, to test the resource allocation for Vehicle-to-Vehicle scenarios. On the other hand, iTETRIS and VSimRTI are both envisioned to be able to integrate different types of network communication simulators and traffic simulators, and as a result, we get a V2V-capable simulator.

In conclusion, the vehicular networks are a very important addition to the regular networks, providing many benefits, creating greener, safer and smarter roads. They will be the core technology behind autonomous vehicles. That is why we need to know what challenges we are facing, how to solve them, and finally, how to move forward.

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