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Vehicular Communication Aided By 5G Networks: A Latency Analysis

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ABSTRACT

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This thesis is a research into possible use of 5G in vehicular communication with emphasis on autonomous vehicles. Recent developments in road vehicles show a strong trend toward higher degrees of self-driving capabilities. These capabilities have a potential to improve road safety through exclusion of human factor from road traffic. They can also create new advantages for businesses through, for instance, truck platooning. To facilitate such capabilities and cooperation between vehicles and other traffic participants, mobile and reliable communication standard is needed. In this thesis we analyse 5G in the context of V2X systems, how it compares to another alternatives, and whether it is able to match the latency requirements for safety-critical applications of self-driving scenarios.

Contents

Glossary

3GPP 3rd Generation Partnership Project. 10

5G Fifth Generation Standard. 1

AVs Autonomous Vehicles. 1

C-V2X Cellular Vehicle-to-X. 6, 10, 29

DSRC Dedicated Short Range Communication. 6

ECDF Empirical Distribution Function. 35

eMBB Enhanced Mobile Broadband. 13, 17, 43

FSD Full Self-Drive. 2, 5, 24

IEEE Institute of Electrical and Electronics Engineers. 25

IoT Internet of Things. 12, 15

LoRa Long Range. 20

LoRaWAN Long Range Wide Area Network. 20

MIMO Multiple-Input and Multiple-Output. 12, 18, 30

mMTC Massive Machine-Type Communications. 15, 17

RSU Road Side Unit. 7

RX Receive. 18, 31

SAE Society of Automotive Engineers. 4

SINR Signal to Interference & Noise Ratio. 29

TX Transmit. 18, 31

UE User Equipment. 7

URLLC Ultra Reliable Low Latency Communications. 8, 16

V2I Vehicle-to-Infrastructure. 10

V2V Vehicle-to-Vehicle. 10

V2X Vehicle-to-X. 1

WAVE Wireless Access for Vehicular Environments. 6

Nomenclature

c speed of light in a vacuum

dB decibel

h Planck constant

Hz hertz

m meter

$Mbps$ megabit per second

mm millimeter

ms millisecond

1 Introduction – State of The Industry

With a roll-out of Fifth Generation Standard (5G) networks more and more users get access to the features and technical specifications enabled by these networks. By leveraging expanded bandwidth, low latency, high communication density, and improved reliability 5G can provide unique conditions for next steps in vehicular development. Even at this early stages of 5G roll-out we can already see how transport industry uses 5G to enable massive IoT connectivity. In particular, maritime industry was one of the first to see potential benefits. Port of Rotterdam, Netherlands was early to take advantage of 5G networks in order to automate container operations during supply chain crisis and improve connectivity previously based on Wi-Fi and 4G networks (DeGrasse 2020).

In automotive industry, on the other hand, implementation of modern technologies traditionally faced obstacles that arise from a number of factors, such as strict safety regulations and standards in road vehicles or lack of incentive to take risks associated with new technologies. However, conservative approach that might work well with a mechanical part of the vehicle, where well tested designs might be more reliable and hence more popular, can be a disadvantage in a world where cars become more and more connected. Nowadays, manufacturers realise that taking the biggest risk factor in modern road traffic, the driver, from the wheel and allowing automatic systems to take care of driving might dramatically improve road safety. According to European Truck Accident Causation Study conducted by International Road Transport Union 85.2% of the studied road accidents are caused by a human error. In-depth analysis, IRU (2007) shows that in accidents caused by a driver the leading reasons are: speeding and vehicle maneuvering violations including road sign violations.

In light of this, Autonomous Vehicles (AVs) can potentially solve the problem by providing advanced prediction and accident avoidance through next level connectivity of Vehicle-to-X (V2X) systems. In this thesis we focus on technical aspects of 5G application in autonomous road vehicles and how 5G compares to the alternative wireless communication protocols. By conducting this research we would like to define whether the features of 5G can enable next levels of autonomy and connectivity in road vehicles.

1.1 Use Cases

High degree of autonomy in automotive transportation requires higher awareness of vehicles that can be achieved through constant V2X connectivity. While Full Self-Drive (FSD) might not require advanced connectivity features and can even successfully work completely offline at this point, future of autonomous vehicles involves deeper integration with the surroundings. Thus, leading automotive manufacturers will need to master connectivity to tackle the challenges of autonomous driving.

The following requirements are based on 5GCAR (Fifth Generation Communication Automotive Research and innovation) use cases outlined in *'On the Needs and Requirements Arising from Connected and Automated Driving'*. Based on Antonakoglou et al. (2020), these requirements reflect possible use cases for vehicles in both solo and cooperative environments. All these cases work together to complement and enhance overall awareness and safety of road users as well as provide more efficient utilization of infrastructure resources.

- **Cooperative maneuvers** – to optimize decision making in a group of vehicles and use infrastructure resources more efficiently connectivity between vehicles and infrastructure must be established. Optimization of trajectories, early route planning, and decentralization of conflict resolution are possible cases where wireless connectivity plays key role. Low latency and high connection density capabilities is in focus here as decisions in high traffic must be made without a delay and critical decisions must be prioritized.
- **Cooperative perception** – is about both making a vehicle more aware of its immediate surroundings through a mesh of other users but also extending

this awareness far beyond the field of view of own sensors. The information is gathered from locally installed radars and sensors as well as equipment of other road users along the planned route. This feature allows for enhanced awareness that extends far beyond the line of sight of the vehicle.

- **Cooperative safety** – early detection and prevention of accidents is a key to improved road safety. Both local detection equipment, infrastructure, and prioritisation help autonomous vehicles to recognize potential risks associated with for example vulnerable road users like pedestrians and cyclists. Cooperative perception helps to handle edge cases where some road users might deviate from a normal behaviour. Pedestrians might jaywalk, another car might jump a red light etc. This aspect of connectivity can be significantly improved if all users including pedestrians and cyclists have handheld devices that become cooperative parts of network and share information with other road users.

- **Intelligent autonomous navigation** – by using local sensors, information from other users along the route, and maps the real-time picture of the road network. We already see cooperative traffic guidance where navigation apps monitor all the users and typical traffic patterns for the given time to redirect traffic flows and distribute flows of vehicles evenly throughout the road network. This feature complemented with more advanced sensors and radars installed on autonomous vehicles and in infrastructure as well as modern data analysis can significantly improve traffic situation in congested areas without the need to rebuild road network completely.

- **Remote driving** – while autonomy is the main focus of this thesis, some remote control features can still be facilitated by wireless communication. When autonomous vehicle becomes involved in complex traffic situation, remote operator can intervene and drive the vehicle. In this case reaction time and reliability are extremely important, hence low latency is a key here again. Autonomy also comes at different levels with some requiring some input from the driver at certain stages, more on levels of automation in the following paragraph.

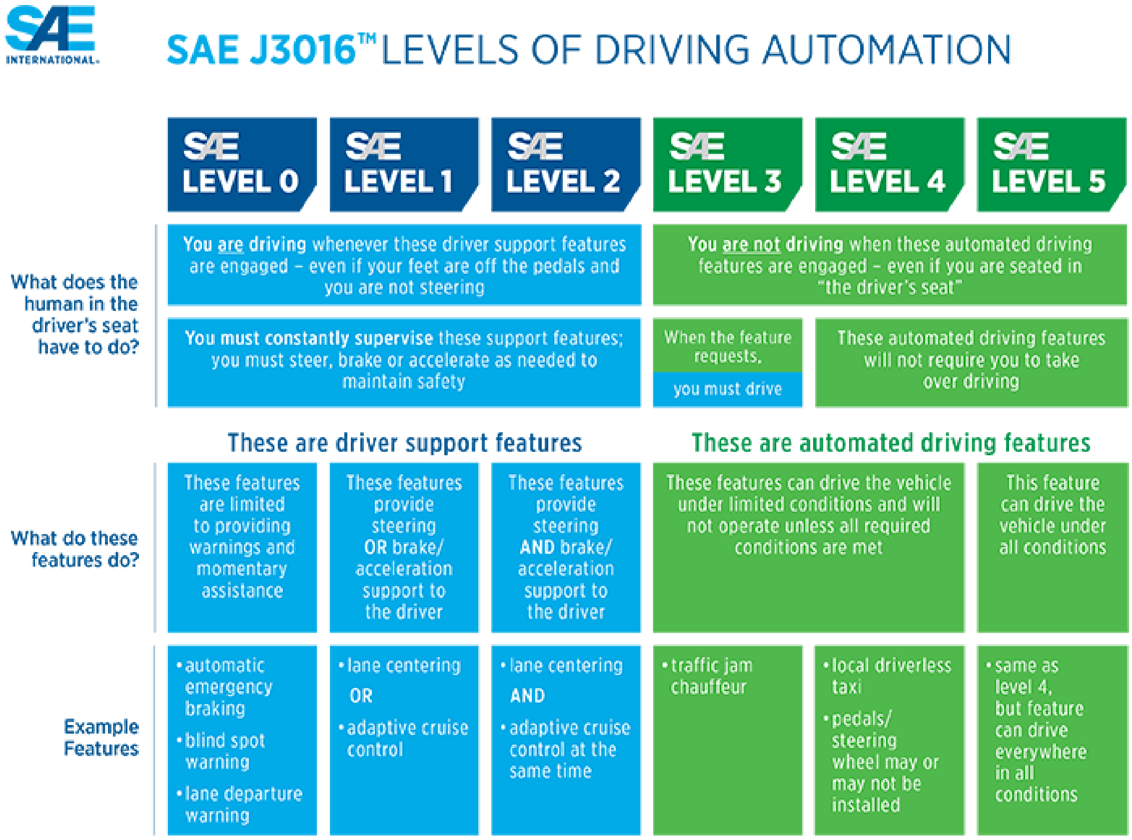

Figure (1) Society of Automotive Engineers (SAE) J3016 Levels of Driving Automation. (SAE 2021)

Society of Automotive Engineers' classification gives a system of reference for manufacturers to better understand their development in the field of autonomous driving. According to SAE's classification there are 6 levels of driving automation of which levels 3-5 can be considered true automation as 0–2 require input from the driver and only support driver's activities (see Figure 1). Level 3 vehicles can carry out point A to point B driving under presence and supervision of the driver who can take over in case of emergency. Level 4 do not require human input and are almost completely autonomous but only in certain areas with speed limitations and outside of extreme weather conditions. This is why Level 4 vehicles still might require operators input even if done remotely. Out of 6 only Level 5 can be considered fully automated and doesn't require any input from passengers or remote operators. This level is currently unavailable and its development might not be yet possible with the current technologies.

Currently some car manufacturers offer limited level 2 and level 3 systems under certain conditions to general public and sometimes to users based on safety scores, for example, Tesla's step roll-out of FSD to users with better safety score first. In this thesis we consider 5G as a possible communication solution for levels 2-4. At these levels not only V2X connectivity plays important role but also remote operator's input might be required to take over in case autonomy cannot handle the situation. In both cases 5G features like low latency and high data rate might offer a viable solution.

1.2 Classification of Applications

While the latency offered by previous generation wireless networks is good enough for non-critical and some industry critical applications, a lot of applications like vehicle-to-vehicle communication related to collision avoidance, medical robots, and automated air traffic control require much lower latency with higher reliability to match the increased safety requirements associated with such applications.

In the classification used in this thesis we have safety-critical, industry-critical, and non-critical applications (Figure 2). It is important to distinguish between these to put wireless connectivity requirements for them in perspective. Non-critical applications in vehicles include entertainment systems, voice and video calls, environmental data transmission. Industry critical applications are directly linked to revenue business activities carried out by road vehicles and related infrastructure. For example, fleet telemetry for preventive maintenance or connectivity within transport hubs mentioned in the introduction. Both types of applications are not associated with safety directly and hence requirements for latency and reliability are not strict.

Safety critical applications, on the other hand, include the activities that might affect safety of people directly. Autonomous driving is one such application where giving driver's responsibilities to an automation system comes with high requirements for acquisition, processing, decision making times, and lower latency.

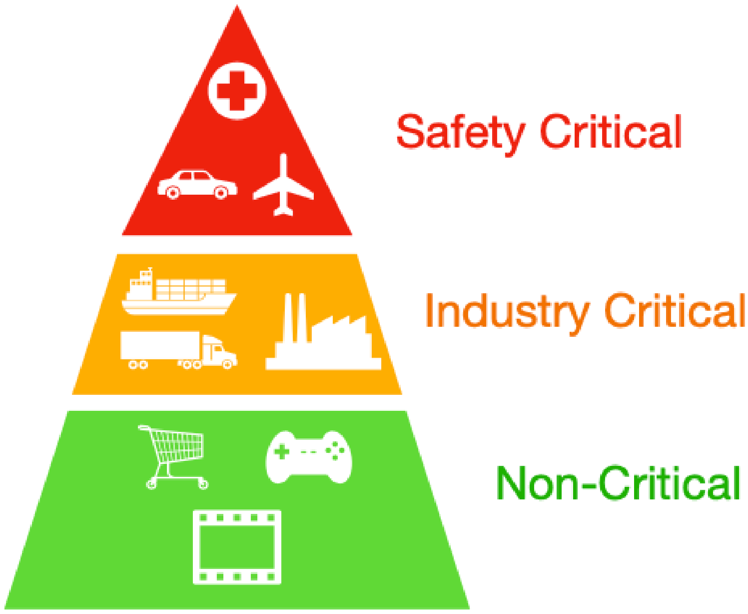

Figure (2) Types of communication by importance.

1.3 Technical Requirements

Currently the efforts for standardization of wireless communication for road vehicles and infrastructure led in two main direction that are supposed to target the same applications but have some differences. Dedicated Short Range Communication (DSRC) (defined by IEEE 802.11p: Wireless Access for Vehicular Environments (WAVE)) and Cellular Vehicle-to-X (C-V2X) (defined by 3GPP Releases 14, 15, 16) Both are designed to operate in intelligent transport systems but have some important differences. For example, in WAVE target latency is at 5 ms while in C-V2X it is at 20ms. At the same time data rates are higher in C-V2X at 150$Mbps$ and only 3-27$Mbps$ in WAVE. These are based on currently available technologies, however, Futere 5G in theory might offer much better specs with $<5ms$ end-to-end latency and up to 10$Gbps$ data rates (Usman et al. 2020). Both systems operate at 5.9GHz.

802.11p: WAVE (DSRC) has been developed to support vehicle-to-vehicle and vehicle-to-infrastructure communication based on IEEE 802.11. This development of 802.11 is designed to improve road safety through accident prevention enabled by V2X communications. Only 15,506 vehicles in US were equipped with the technology and due to lack of interest from manufacturers the lower 45MHz from 5.850GHz to 5.895GHz were allocated to unlicensed services (including Wi-Fi) in 2020 with the remaining 30MHz of spectrum allocated to C-V2X (Visnic, Bill and SAE 2020). The momentum in protocol has shifted toward C-V2X and its wider adoption among car manufacturers.

Vehicle-to-vehicle (V2V) communication according to 3GPP is a device-to-device communications defined in LTE releases 12 and 13 and refined for vehicular use cases, addressing high-speed (up to 250 Km/h) and high density of users. V2V cellular communication originally described in Release 14 to use the LTE. Later in Releases 15 and 16 3GPP elaborated on the use of 5G and 5G NR in V2V communications. In Release 16 sidelinking has been introduced in V2V communication mode. This allows for more connectivity between vehicles even with a lack of cellular coverage, hence the increased support for semi-autonomous and autonomous driving in the areas with no coverage. Real-time situational awareness and V2V sensor data transmission. Eventually, with enough connected vehicles on the road they can form a chain of connectivity to expand coverage to vehicles in remote areas (3GPP 2020a).

Table (1) Performance requirements for vehicles platooning and advanced driving (3GPP 2022).

Scenario	Degree of automation	Max end-to-end latency (ms)	Data rate (Mbps)	Min required communication range (meters)
Cooperative driving for vehicle platooning Information exchange between a group of User Equipment (UE) supporting V2X application.	Lowest	25		
	Low	20		350
	High	20	65	180
	Highest	10		80
Reporting needed for platooning between UEs supporting V2X application and between a UE supporting V2X application and Road Side Unit (RSU).	N/A	500		
Information sharing for automated driving between UEs supporting V2X application.	Lower	20		350
	Higher	20	50	180
Cooperative collision avoidance between UEs supporting V2X applications.		99.99	10	
Information sharing for automated driving between UE supporting V2X application.	Lower	100		700
	Higher	100	53	360
Information sharing for automated driving between UE supporting V2X application and RSU.	Lower	100		700
	Higher	100	50	360
Emergency trajectory alignment between UEs supporting V2X application.		3	30	500
Cooperative lane change between UEs supporting V2X applications.	Lower	25		
	Higher	10		

Release 16 also features new use cases for 5G in autonomous driving like vehicle platooning - the ability of a group of vehicles to form a platoon where a lead vehicle provides directions to following vehicles. Platooning also benefits from sidelinking feature to provide close range connectivity for cooperative maneuvering. To achieve these functionality NR V2X is aimed at significantly lower latency and higher reliability compared to LTE V2X and is intended to be future proof for possible road vehicles with advanced communication requirements. URLLC is one of the main directions for further 5G development in vehicle applications. In addition, features like network slicing can significantly improve latency and reliability of communication, some models offer simulation of network slicing 5G feature that shows an improvement in both latency and reliability compared to networks without network slicing (Ge 2019).

1.4 Importance of Low Latency

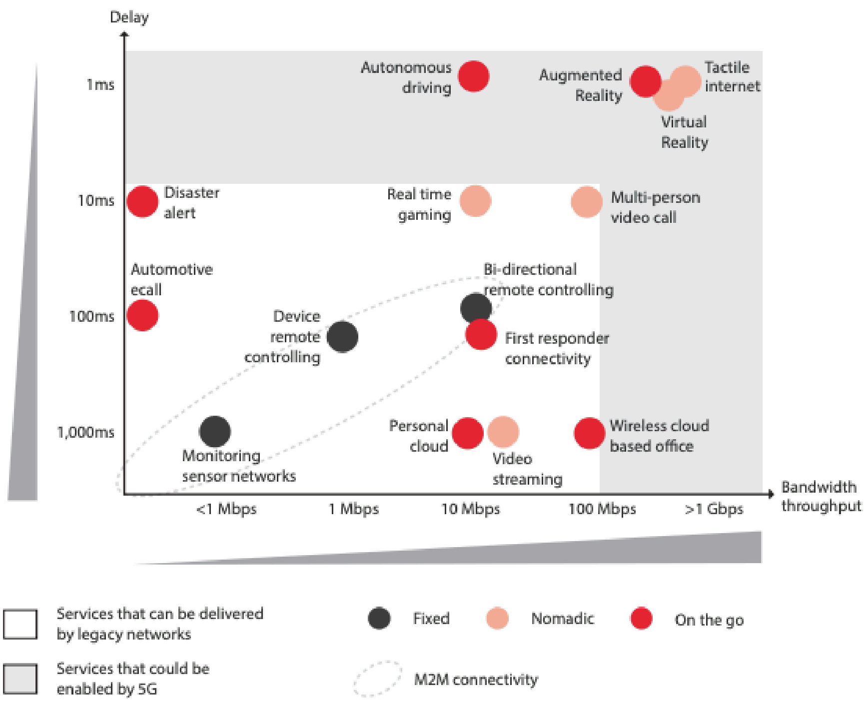

Figure (3) Bandwidth and latency requirements of potential 5G use cases. Source: GSMA Intelligence

Latency is the main technical parameter that we will consider as a result of our simulation as this parameter is critical to autonomous driving applications and associated road vehicle activities. Previous generations of cellular networks as well as alternative technologies have the ability to support the requirements for 5G. According to GSMA technical specifications for 5G are sub-1ms latency and <1 Gbps downlink speed, hence, the services and use cases that one of these can be considered 5G use cases (Warren & Dewar 2014). Level 3 and up autonomous driving requires both of these specifications as it is critically important to have low communication latency for better situational awareness and quicker decision making.

> ”We need to look at how long it takes for the message to be transmitted between sensors and then get to the computer in each car, and then how long it takes for the computer to make a decision, and all of this has to be in less time than a human would take to make a decision - 2 milliseconds,” Jane Rygaard, Head of Dedicated Wireless Networks Edge Clouds, Nokia (Russon 2018)

Table (2) Comparison between 4G and 5G standards (Kim 2019).

	4G	5G
Introduction year	2009	2018
Technology	LTE, WiMAX	MIMO, mm Waves
Bandwidth	100 MHz	30 GHz to 300 GHz
Latency	<100 ms	<10 ms (theoretically <1ms)
Data Rate (theoretical peak DR)	75 Mbit/s – 1 Gbit/s	5 Gbit/s – 20 Gbit/s
Advantages	Speed	Extremely high speeds, low latency

5G ultra low latency might even enable brain-controlled vehicles currently constrained by higher latency technologies like XBEE bluetooth. Both brain-controlled road and aerial vehicles can also benefit from wider area coverage and edge computing enabled by 5G networks (Hekmatmanesh et al. 2021). This integration can improve quality of life of disabled patients giving them easier access to personal transportation.

1.5 Vehicle-to-X

Vehicle-to-everything (V2X) refers to high-bandwidth, high reliability, and low latency communication of road vehicles and other road users. This term includes vehicles, pedestrians, road infrastructure and other sensors that can be used by vehicles to acquire information a about road situation. 5G mobile networks might provide key infrastructure to provide connectivity for Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications. 3rd Generation Partnership Project (3GPP) Release 14 describes the foundational principles for V2X communication for an exchange of safety messages. On the next step, Release 15 incorporated additional features to improved range and reliability for V2V communication. These features include transmission diversity and low packet delay of 10 ms. The 5G NR C-V2X in 3GPP Release 16 opens the possibilities for higher throughput, lower latency, and higher reliability of communication that is needed for safety critical applications. (3GPP 2020*b*)

The transfer of C-V2X from LTE-based V2X to 5G-based V2X supports existing non-safety-critical use cases and also adds additional functionality that can enable safety-critical applications in vehicle autonomy (5GAA 2019). Such functionality can improve road safety through direct V2V communication that can carry sensor data and road warnings from the road ahead. In general, ultra-low latency can make vehicles more aware of the situation around them. In the same way V2X infrastructure can become integral part of road safety, creating additional layer of sensors that can interact with vehicles and pedestrians making them more aware of the situation and warning them about possible accidents.

Travelling at high speeds road vehicles face a challenging environment for cellular networks. In such situations handover speed becomes important if we want to maintain uninterrupted connectivity at speeds exceeding 250 km/h. Improved signal design in C-V2X addresses this with an introduction of extra reference signal symbols that improves channel estimation. In situations where high density of vehicular traffic occurs, there could be congestion in radio resource allocations due to a number of users in small area. C-V2X implements resource allocation algorithms that track the available resources, sort them and pick the least loaded one. This is achieved through manufacturer-specific resource allocation methods.

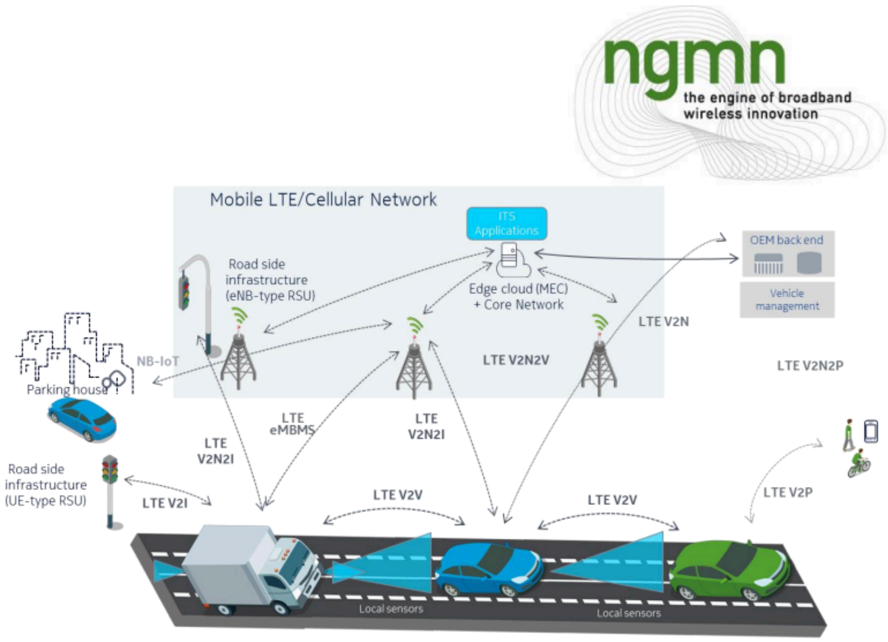

Figure (4) The hybrid use of the LTE technology to support intelligent transportation system. Source: NGMN Alliance V2X White Paper v1.0 (NGMN, 2018)

Eventually all the 'actors' in intelligent transportation will form a network that are capable of sending information from any node to any other node instantaneously and advanced algorithms will be able to monitor the situation on a scale of the whole city redirecting the traffic flow to distribute the load more evenly. Not only this will have huge benefits for safety but also allows smart route planning, decongestion, and, in case of prevalence of electric vehicles in the future, can make more optimised generation–to–consumption chain.

One of the examples of the national strategy in V2X wide deployment is Chinese "Smart Vehicles Innovation Development Strategy" issued in February 2020. Here, 90 cities have already partnered with local wireless operators, deploying tens of thousands of roadside units to demonstrate intelligent highways and urban intelligent networked roads (Qualcomm 2021). The estimation done by Qualcomm predicts that by 2025 approximately half of new cars in China will be ready for C-V2X connectivity. This is a big step toward developing a national standard for V2X technology and even wider use of such technology for improved road safety.

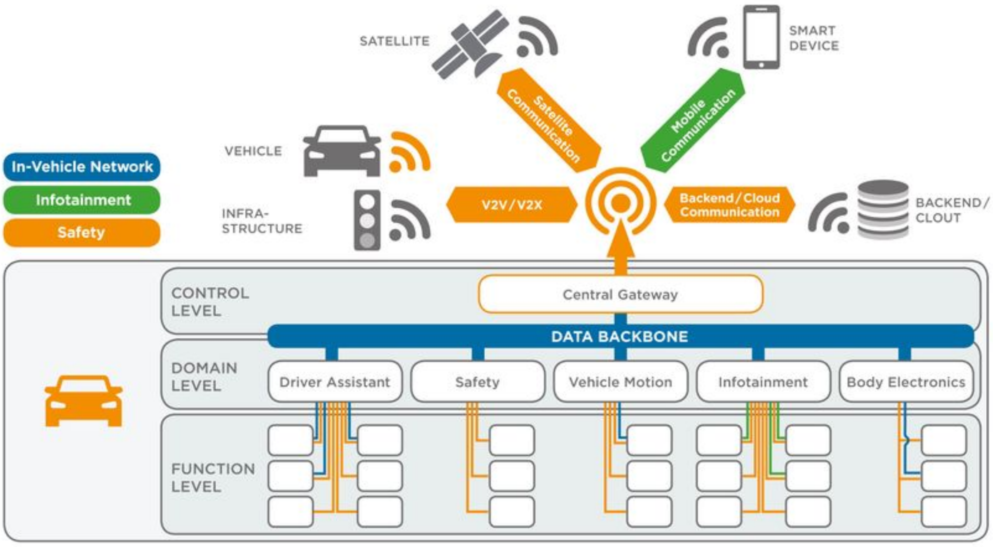

Figure (5) Functional domains for connected, autonomous vehicles with high speed in-vehicle networks. Source: TE Connectivity (IEEE Spectrum, 2018)

2 5G features

The advent of 5G creates unprecedented opportunities for industries, and these promising new opportunities are only possible with introduction of newer and better technological solutions. The significant step forward from 4G speeds and latency is enabled and supported by a number of new technologies and methods. The efforts to bring these technologies and methods can be outlined in the directions of increased network density, the use of full-duplex communication, massive Multiple-Input and Multiple-Output (MIMO), network slicing, and network resource virtualization. Such methods and technologies are implemented by communication service providers to achieve technical specifications for 5G where not only V2X communication must be reliable but other applications that share network resources with vehicles must fulfill with their own requirements. Large scale Internet of Things (IoT) setups can comprise of thousands of devices that might not require much resources individually, but as a massive cluster can put a strain on the network that can potentially interfere with network's ability to facilitate V2X safety-critical applications reliably. Table 3 shows the main 5G features and their corresponding enabling technologies that help 5G networks with increased network loads.

Table (3) Features and corresponding technologies in 5G (Hossain & Hasan 2015).

5G Feature	Correasponding Technology
Capacity and throughput improvement, high data rate (1000x of throughput improvement over 4G, cell data rate 10 Gb/s, signalling loads less than 1 100%)	Spectrum reuse and use of different band (e.g., mm wave communication using 28 GHz and 38 GHz bands), multi-tier network, D2D communication, massive-MIMO
Ultra low latency	Full-duplex communication, D2D communication
Network densification (1000x higher mobile data per unit area, 100 10000x higher number of connecting devices)	Heterogeneous and multi-tier network
Advanced services and applications (e.g., smart city, service-oriented communication)	Network virtualisation, M2M communication
Improved energy efficiency	Energy harvesting
Autonomous applications and network management, IoT	M2M communication

2.1 5G Triangle: eMBB, mMTC, uRLLC

In this section we consider 3 main 5G high-level use cases outlined by International Telecommunication Union in International Mobile Telecommunications-2020 (IMT-2020 Standard). These cases define the key advantages of 5G that can be used in more particular lower-level use cases including the cases in road traffic and autonomous vehicles.

2.1.1 eMBB

eMBB is a development of the existing LTE and LTE-Advanced networks that provides faster data rates and a overall better user experience for mobile subscription users compared to older mobile broadband services. Most of eMBB functionality can be offered to users even using the existing 4G infrastructure. In cases when data-driven use cases like vehicle communications require high data rates across wider coverage area, the existing legacy infrastructure can cover the needs of more demanding users while dedicated 5G infrastructure is being rolled out. As mentioned before most of the users of non-critical applications like gaming and streaming can benefit from increased speeds while not necessarily requiring other benefits of standalone 5G services like ultra low latency. The possibility to use the existing infrastructure allowed early adoption with 3GPP freezing Release 15 on June 2018. Release 15 elaborates on the first phase of 5G where eMBB services can be provided using both legacy and dedicated 5G equipment.

Within its use cases eMBB needs to addresses the following requirements:

- High mobility – will enable mobile broadband services in moving vehicles including cars, buses, trains and planes. This is also supported by the ability for fast handover in 5G networks. Targeted maximum user speed without losing defined quality of service is 500km/h (3GPP 2017).
- High capacity – areas with high connection density, both indoors and outdoors must have broadband access. The areas like city centres, office buildings or busy intersections with multiple users with different connection parameters must be covered by a reliable access.
- Enhanced connectivity – uninterrupted availability of broadband access is crucial in case of road vehicles where additional V2V communication capabilities can be used to support enhanced connectivity.

On physical level there are technologies and techniques introduced to facilitate eMBB. These technologies include carrier aggregation, cell densification, high order modulation transmission, and multiple-input multiple-output (MIMO) transmission. In order to achieve significant increase in resource capacity over the 4G systems, physical layer of 5G must utilise more advanced new spectral efficiency techniques enabled by ultra-high frequencies that were not available for previous generation of networks. For road vehicles the technologies and methods that enable eMBB functionality include full-dimension and massive MIMO, millimeter-wave communication, and spectrally-localised waveforms (Ji et al. 2018).

As can be concluded from the features and use cases the impact of eMBB on communication might be the most significant in terms of visibility to the most users who come across non-critical application on a daily basis. The main goal of eMBB implementation in road vehicles is to achieve higher data rates in both non-critical and safety-critical applications using both legacy infrastructure of previous generations of standards and equipment built specifically for 5G networks.

2.1.2 mMTC

mMTC means large-scale connection where thousands of devices can remain connected in relatively small area without compromising connection quality. 5G-enabled connectivity is able to promote integration of industries with a large number of connected devices. Such vertically-integrated industries smart manufacturing, smart agriculture, smart cities and Industrial IoT require a large number of devices not only to stay connected reliably but also to be able to move quickly while retaining connection. This is where 5G with its features can make a difference compared to other wireless standards. mMTC is designed to support connectivity for a massive number of devices with requirements for narrow-bandwidth and infrequent uplink and downlink connections with a small volumes of data. These devices might operate in difficult conditions with obstacles and a number of noise sources. Road infrastructure devices and pedestrians' wearable devices form a network with relatively narrow-bandwidth requirements, high communication density, and need to overcome high interference that can be found in highly populated areas. These devices in large V2X systems can be supported by mMTC.

Although 4G communication standard facilitated a major step toward higher bandwidth the real obstacle was always a large scale. Initial success of 4G can be attributed to a step-up in mobile internet connectivity from 3G. Such quality improvement allowed for new use cases that require higher bandwidth and download speeds like video calls. The new requirements of the industry, however, assume that large number of devices must stay reliably connected for possible short data transmission sessions. Smart cities are typical example of such environment and integration of V2X systems only increases the load on the infrastructure (Wang & Gao 2020). In this case we talk about non-safety-critical applications of vehicle autonomy that increase awareness through the network of sensors. Although it may not require as much data transmission rate and bandwidth as entertainment applications, it needs to maintain a large amount of data and support high concurrency, multi-channel data transmission and processing capabilities (Han et al. 2021).

Due to its key role in 5G applications, mMTC has attracted great attention from researchers in academia and industry. There are two main challenges that engineers faced to bring mMTC from a concept to reality. The first one is how to achieve its massive connections. As we discussed previously, 3GPP suggests connectivity of 10^6 devices/km^2. High frequency band is not available for mMTC due to limited transmission distance. Meanwhile, the available low frequency band is scarce (Wang & Ma 2019). This problem is addressed by using a combination of frequencies for connections and applying different access schemes that help optimise network resources in mass connectivity scenarios.

2.1.3 URLLC

URLLC is a service category introduced in 3GPP Release 15 to address the requirements of ITU-R M.2083. It is one of the key pillars of 5G New Radio (NR) that supports the services such as vehicle remote control and autonomous driving. Both services are safety-critical and hence the requirements for latency are high. As discussed previously the latency of 4G LTE networks has been significantly improved compared to 3G networks but still some critical applications in transportation and medicine require much lower latency values. Due to fundamental incompatibility of communication in 3G and 4G networks with mission-critical applications of autonomous vehicles and high end-to-end latency, all layers of the network must be changed significantly in order to facilitate high levels of vehicle autonomy. Virtual network slicing as well as creation of private networks only for V2X can be implemented in order to ensure low latency and high reliability in safety-critical applications. (Ji et al. 2018).

By using the dedicated network infrastructure, latency can be reduced significantly. A large portion of the transmission latency comes from the control signalling (e.g. grant and pilot signal) and it takes almost 0.4 ms per scheduling, this is the reason why incorporation of URLLC in 4G networks is not possible. To support URLLC, therefore, significant fractions of the physical layer must be adjusted to newer demands and standalone access points are required (Foukas et al. 2017). In addition, to achieve the requirements of URLLC, new numerologies defined in 5G and determined by subcarrier spacing and symbol length are used. 5G numerologies allow base stations to manage allocation of radio resources for users that require ultra-low latency with more flexibility.

Scheduling schemes and multiple radio interfaces are used to minimise transmission latency of URLLC packets along with the physical layer changes. Considering the fact that autonomous vehicles are mobile and hence can travel to the areas with variable 5G coverage, the ability to interface with multiple radio standards is important. At the basis of multiple interfaces is the ability of the user to choose radio access technology that provides minimum latency at the location among all possible options. Such options can include both licensed and unlicensed spectrum technologies which we discuss later in this thesis. The requirements for latency, however, might disqualify many technologies that simply cannot provide such low values.

One of the technologies that support enhanced reliability of connection in 5G networks is Hybrid Automatic Repeat reQuest (HARQ). This is an extended feature for sidelink communication in NR which is provided by the medium access control layer. Both unicast and groupcast communication is supported by HARQ procedure (Harounabadi et al. 2021). While certain level of reliability can be achieved without dedicated 5G NR infrastructure, URLLC is not possible without the development and implementation of it. (Singh et al. 2018). That means that unlike eMBB and mMTC URLLC is not readily available for rollout everywhere where 4G LTE infrastructure is present. This adds additional complexity to ensuring that autonomous vehicle has reliable access to low latency communication technology at all times. In addition, far from all the areas with heavy road traffic are covered by 4G even 10 years since its launch, this might give us a very long timeline for wider URLLC availability in safety-critical applications.

2.2 Beamforming and Massive Multiple Input Multiple Output (mMIMO)

To support high-density of connected devices in 5G networks there are two technologies we would like to highlight as having the biggest influence. Beamforming technology is important for 5G networks to handle massive number of connected devices through MIMO antennas. MIMO arrays equipped with dozens or hundreds individual antennas, benefit from beam forming because it enables more efficient use of spectrum in the area and as a result higher connection density can be maintained. Beamforming and MIMO are not new or unique to 5G, same technologies were available in the previous generations, however, higher frequency spectrum and other factors revisit beamforming and massive MIMO as more powerful tools than before.

Transmission of higher volumes of information using multiple antennas to high number of users is the primary goal of massive MIMO. The principle of operation for MIMO includes reflection and beamforming to form patterns. The use of complex signal-processing algorithms to find the best pattern improves packet movements and delivery times to the users (Nordrum 2017). Beamforming combined with multiple Transmit (TX)/Receive (RX) antennas allows for more simultaneously supported users and better network resource management.

Millimeter waves, which play important role in 5G networks, have one important disadvantage especially in comparison with lower frequency protocols: they are easily blocked by obstacles like concrete walls. This significantly limits the possibility to use millimeter waves in the cities. This problem is especially relevant to smart cities and the demand for reliable connectivity in the presence of different obstacles. Beamforming addresses this issue by focusing a signal and directing it to just one user. This is more efficient technique compared to omnidirectional broadcast in terms of resource utilisation. Beamforming makes a signal stronger for the particular user making chances of arrival of data without losses higher. Such method also reduces interference for other users in the network. This way we achieve better network resources allocation and more flexible network that can prioritise safety-critical connections over other users.

Important to notice that 5G adopts higher radio frequencies than previous generations and hence the physical size of the antenna required for high frequency is smaller than in lower frequencies. This is really useful when you have to build a cluster of antennas for MIMO communications and have a limited space. Due to higher frequency spectrum used in 5G networks the requirements for antenna size are smaller than for lower frequencies. That means more individual antennas can fit inside massive MIMO antenna. All these antennas can target their own users individually sending and receiving data with beamforming. Smaller individual antennas enable more flexible placement and main antenna unit design that can fit the exact location requirements more precisely.

Introduction of beamforming brings a lot of benefits for both telco companies and consumers. Users no longer need to move to get a better reception, this is now handled by the antenna using beamforming. Security is also considered in beamforming, now that user's data travels in the beam instead of throughout the entire arc of the antenna. That means that signal interception becomes more difficult and data remains more secure. For autonomous vehicles that means additional security and improved prioritisation of safety-critical cases over other connections as well as less interference in high-density scenarios.

2.3 Alternative technologies

There is a number of wireless technologies and standards widely used in IoT applications that potentially can compete with 5G as a standard for autonomous vehicles. In this section we are taking a look at some popular standards and comparing their features to 5G features through the prism of autonomous driving and V2X communication.

2.3.1 LoRaWAN

As stated in its name Long Range is one of the main features of Long Range (LoRa) technique uses spread-spectrum modulation techniques to achieve bidirectional connectivity. It is one of the popular technologies within Low Power Wide Area Networks (LPWAN). LoRaWAN is a protocol of LoRa that defines system architecture on a upper networking layer that LoRa is lacking. LoRaWAN is responsible for data rate management and frequencies, as well as device's power (LoRa Alliance 2022). The development of this protocol is oriented toward a growing IoT and industrial IoT markets and hence the main advantages are also addressing the needs of battery powered smart devices that need to stay connected with optimal power management and wide area coverage.

Key advantages of LoRaWAN compared to 5G are wider range, higher power efficiency, license-exempt. All these features attracted many customers from IoT vertical markets like smart metering, smart city, asset tracking and others. Where LoRaWAN lacks compared to 5G is in the field of data transfer and latency. While cellular standards like 4G and 5G have latencies in milliseconds as shown in Table 1 LoRaWAN total latency in end-to-end forwarding should be a few seconds (Delgado-Ferro et al. 2022). Achievable end-to-end delay is possible even below 400 ms but with lower spreading factors and at shorter distances (Pötsch & Hammer 2019). While these might be low enough values for latency in certain non-critical applications like message exchange more demanding applications like traffic conflict resolutions at a busy intersection can't rely on latencies this high.

Due to wider range covered by LoRaWAN and low cost of devices the introduction of this protocol for the applications in V2X might be a good solution. Another factor is the use of unlicensed band. In many countries 5G operators have problems with frequency allocation for proposed 5G networks and so the protocol that can avoid this might be very competitive. It might be concluded that LoRaWAN can work along with 5G and the addition of LoRaWAN to any vehicle doesn't require additional license, while providing benefits of wider area connectivity. Telemetry and alarms for vehicles might tolerate a delay of even seconds and hence LoRaWAN might become a good affordable solution for these applications in automotive industry (Santos Filho et al. 2020).

2.3.2 ZigBee

ZigBee is a specification for high-level communication of IoT devices that is based on IEEE 802.15.4 (operation of a low-rate wireless personal area network) standard and uses different frequency bands (868 MHz, 902–968 MHz and 2.4 GHz) for operation. It is mostly used for connections in local networks, hence a short physical range of up to 100 m with data rate of about 250 kbps (Wheeler 2007). However, mesh topology allows for data transfer beyond the line-of-sight using other connected devices in the network. ZigBee as LoRaWAN optimized for power efficiency and low data rate communication.

One advantage of ZigBee protocol is mesh network topology. While adding to latency due to complexity the reliability of mesh network can be of a great advantage when cellular network is out of reach. In emergency situations outside of cellular coverage critical information can be relayed via other road users. This way ZigBee can be used as an additional protocol for the matters unrelated to driving (Silicon Labs 2022).

As LoRaWAN, ZigBee has significantly higher latency compared to 4G and 5G which only increases with the increase in distance between users and the number of mesh users connected. In tests, when the number of cars reached 50 packet loss increased "significantly and the average end-to-end delay was more than 200 ms". As a consequence, it was concluded that ZigBee cannot be used for high connection density scenarios like crowded places in urban areas (Ahangar et al. 2021). Due to high latency the use of ZigBee in critical applications and in high connection density scenarios is limited but its performance is sufficient for non safety-critical applications in cars. One proposed use case is intra-vehicular monitoring systems that can benefit from the loss of wire (e.g. tyre pressure monitors) as well as non safety critical communication with infrastructure in close proximity or through mesh over the distance.

2.3.3 Wi-Fi

In April 2020 the US Federal Communications Commission made 6 GHz frequency band (5.925–7.125 GHz) available for unlicensed use. These new rules enable extended Wi-Fi 6, the next generation of Wi-Fi, to compete with 5G in many applications that require high speeds and low latency. Opening the 6 GHz band for unlicensed use increases the amount of spectrum available for Wi-Fi by nearly a factor of five (FCC 2020) and helps improve remote area connectivity. This legislative change also opens possibilities for wider use of 5G unlicensed (NR-U) in private networks without licensing and easier access for private V2X infrastructure as a consequence.

Wi-Fi 6 and 5G offer similar technical specifications, both can achieve gigabit speeds and low latency. The tests done for IIoT applications in downlink scenarios compared Wi-Fi 6, 5G unlicensed (NR-U), and 5G licensed (NR) measuring packet latency and reliability showed that Wi-Fi 6 can perform on par with 5G. With optimization and low load up to 0.16bps/Hz, Wi-Fi 6 can achieve URLLC performance with packet latency of < 1ms at 99.999% reliability (Maldonado et al. 2021). Higher loads can be handled as well but with relaxed latency requirements. That means that Wi-Fi 6 can, unlike previous alternatives considered in this chapter, match 5G's latency and bandwidth performance in safety-critical applications.

At the same time Wi-Fi has a lower cost to deploy, run, and scale networks. It will retain its role as the most popular wireless technology for static scenarios in home and some industrial setups. Devices with high data consumption in offices and homes don't require the ability to be mobile and hence additional features of newer generation of cellular networks like fast handover between base stations is not needed. The additional costs can be omitted in case of Wi-Fi 6 making it even more affordable option. For mobility purposes of moving vehicles cellular networks still remain a better option (Oughton et al. 2021).

For a more reliable network a hybrid use of both 5G and Wi-Fi can be implemented. Hybrid networks with 5G and Wi-Fi set up according to availability and predefined configurations and local demand (Abidi et al. 2018). These technologies will likely coexist as they do at the moment but much more advanced capacities now enable the use of wireless technologies for safety-critical applications like autonomous driving and V2X. Depending on availability situation of wireless services in a given location users can use both simultaneously or dynamically switch between two.

Figure (6) Possible applications of 5G and Wi-Fi 6 in hybrid environment. Source: Pxosys 2020

3 Significance and Methodology

In this chapter we explain the significance of our research in the context of modern automotive industry. The methods chosen to support the research and reach its goals are also outlined in this section.

3.1 Significance

The results of this thesis are needed primarily in automotive industry which, in general, is conservative when it comes to wide adoption of new technologies. The future of vehicles, on the other hand, demands better V-to-X communication and 5G might be the solution for applications that require ultra-low latency. The results can also be utilized as a basis for further research and reference for making the decision on communication technology to be used in high-demand autonomous vehicles.

The main benefit of this thesis is technical analysis of current state of communication protocols and comparison to 5G which is being widely adopted now for mobile subscribers in public and private networks. The topic of the thesis deals with an important issue in the field of communication and potentially contributes to faster adoption of game-changing technology in one of the biggest industries in the world. The demand for better connectivity of vehicles will only grow as FSD and other modern automotive technologies come to life.

As a secondary perspective this thesis can signify technical specifications of 5G standard that can contribute to increased road safety through faster and more reliable V2X communication and, as a result, better situational awareness of all road users.

3.2 Methodology

The main method used to achieve the research goals is a review of the existing research papers and reports in the field of autonomous driving, V2X systems, and

5G development. By analysing papers in specialized topics, e.g. comparison of 5G and Wi-Fi 6. In specific cases we extrapolate the results that researchers acquired in their simulations on possible application of 5G as a main wireless protocol in road vehicles and assess viability of such choice from technical point of view.

Another method of research is comparative analysis. Comparison of alternative wireless protocols is important to test the hypothesis and critically approach some technical features 5G offers that other protocols do not and vice versa. While some widely used protocols might seem like a good fit for automotive application, safety critical applications of AVs impose higher demand for network resources that cannot be provided by most of protocols that use low frequency spectrum. This requirement becomes definitive when we try to ensure low latency and high reliability in safety-critical applications.

Simulation is used in this thesis to test the ability of 5G to support low latency in challenging conditions of a city where density of users and presence of obstacles can affect the network's performance. Compared to theoretical analysis based on fundamentals of radio transmission it allows us to more precisely customize the conditions and assess how 5G would behave in real-life situations. Without any doubts any simulation model, including the one we use in this thesis, is not perfect and has its limitations, but adding real-life variables in scenarios like city might give us a much better insight in 5G behaviour in challenging situations with multiple users and obstacles.

3.3 5G Role in Automotive Industry

While 5G standard has been developed and is in active deployment phase now its utilization in automotive industry is very slow and requires customization of existing protocols. Namely protocols for communication must be updated according to modern demands. Relevant information is available and harmonizing current protocols with possible new requirements should not create any additional problems (e.g. Institute of Electrical and Electronics Engineers (IEEE) 802.11p IEEE 1609.1-4

SAE 2735).

5G is still in initial deployment state and will be for the next 3-4 years at least. This means that we can expect some changes in protocols and in enabling technologies. Another challenge is conservative approach to new technologies taken by major car manufacturers which can lead to unpredictable choices of communication technology not solely based on superior technical specifications that can facilitate future autonomous driving requirements.

The main parameters considered while choosing communication technology for safety critical application are latency, bandwidth, and possible connection density. All these parameters are investigated and compared from perspective of autonomous vehicles with emphasis put on latency as the definitive parameter. Some unpredictable results might come from the fact that 5G is not be the best standard to use from economic perspective in every case. 5G equipment is still very expensive and it usually takes time for more manufacturers to come to market with their offers driving prices down. Infrastructure costs is a major factor that might affect comparison. It depends on specific individual starting points. (e.g. availability of already installed 4G LTE equipment for 5G deployment)

It is important to give enough details on underlying demands and why for example low latency is extremely important in safety critical applications with many actors and variables. V2X connectivity is one of such applications. This is just one of the features to be considered in context of demands but without the context it might be difficult to understand the reasoning behind the arguments for certain technology. Human factor can be considered in terms of decision making regarding which technology will become an industrial standard. It can also be considered as a factor in dis-/misinformation surrounding 5G roll-out.

Important part of this thesis is a simulation based on System Level Simulator developed by Vienna University of Technology. The simulator will allow us to investigate how network can maintain low latency specifications needed for autonomous vehicles in simulated scenarios. This is why we set the scenario to have randomly distributed users in conditions with multiple obstacles that can interfere with a signal. The simulator also allows us to compare 5G and previous generations of communication standards.

4 Simulation

This chapter is dedicated to the simulation we conduct to assess the behaviour of 5G in real-life scenario. The main goal is to define whether 5G can deliver low enough latency in the situation where network resource allocation becomes challenging, namely, city centre with multiple users and obstacles.

4.1 Vienna 5G System Level Simulator

To gain insight in how 5G network performs in a large-scale scenario without using costly real-world measurement approach we can use simulation. System level simulators developed according to 3GPP standard provide us with such opportunity. Vienna 5G System Level (SL) Simulator is a popular choice among researchers working in a field of wireless communication. The Vienna 5G SL Simulator is particularly useful for simulation of V2X related scenarios because it offers the possibility to simulate scenarios with a large number of users. Due to the simulator's open-source nature and wide cooperation in development, the model was improved and adjusted along the development of communication standards. The simulation is done in Matlab and due to the use of Object Oriented Programming the code is easily expandable and custom scenarios can be created either from the provided examples or from scratch (Pratschner et al. 2019).

In the process of simulation the networks with an arbitrary layout are generated. It is possible to combine several tiers of base stations and various user classes in the same simulation. To reflect average network performance the simulator performs Monte-Carlo simulations. Simulation therefore averages over many spatial constellations and channel realizations and thus obtain results for average throughput per user/BS, average SINR performance and ratio of successful transmissions (Müller et al. 2018).

4.2 Limitations and Assumptions

The simulator doesn't provide us with latency calculations, however, we can use throughput and packet size to find latency for the given simulation. While throughput of $n - th$ user in Mbit/s is given as an output of the model packet size is the assumption we have to make. We can use throughput to divide packet size in Mbit to get latency in seconds. Multiple papers and articles that analyse C-V2X use 193 bytes as a packet size for the protocol, this is the value we are using in our simulation (Gonzalez-Martin et al. 2018) (Garcia et al. 2021).

At the basis of latency calculation is Shannon channel capacity equation that defines the maximum amount of information, or data capacity, which can be sent over any channel or medium including radio. The data rate in the equation is directly proportional to channel bandwidth and Signal to Interference & Noise Ratio (SINR) (Cao et al. 2021).

$$\frac{D_k}{Wlog(1 + \Gamma_k)} \leq T, \forall k \tag{1}$$

Where:

D_k : data size (in bits) of k-th user

W : channel bandwidth

Γ_k : SINR of the k-th user

$Wlog(1 + \Gamma_k)$: uplink transmit rate of the k-th user

T : latency[1]

Hence our equation for latency based on the Shannon channel capacity equation is the following:

$$\frac{D_k}{t} = T \tag{2}$$

[1]The terminology 'latency' refers to the over-the-air uplink transmission delay

Where:

$$D_k : \text{packet size [Mbit] of } k\text{-th user}$$
$$t : \text{throughput [Mbit/s]}$$
$$T : \text{latency [s]}$$

Not all the 5G features were simulated using SLS, in particular we did not implement MIMO in the scope of this simulation. Another consideration is that according to a manual the simulator was developed before 5G standard was complete, this means certain assumptions had to be made by developers on different aspects of 5G network. However, these limitations do not prevent us from assessing the behaviour of 5G networks in the conditions similar to a city centre with different types of users like pedestrians, infrastructure, vehicles and with presence of obstacles.

4.3 City Scenario

The base scenario that is used to simulate situations with multiple users and obstacles typical for cite centres is Manhattan Scenario, one of the optional scenarios provided with the simulator. This scenario simulates streets and buildings with base stations located on the rooftops. Users randomly distributed along the streets with various travel speeds assigned to them depending on the type (e.g. pedestrian or vehicle). We change the parameters for base stations and users to cover different possible situations as well as compare different communication standards.

Channel model in the simulation is represented by additive white Gaussian noise (AWGN) that takes into account signal with added noise, noise with the same power across all frequencies, and a Gaussian distribution for random events. Certain assumptions in time and frequency domains are made for the model. In the time domain channel is assumed to be constant with one value calculated. In the frequency domain channel is assumed to be constant as well, and values for all sub-carriers are calculated.

Table (4) Simulation Parameters

Carrier Frequency	2.4 / 5.9 GHz
Antenna Height	25 m
Antenna Tx Power	40 W
Number of BS Antennas Tx/Rx	1/1
Cell Association	Max Received Power
User Distribution	Poisson Point Distribution SISO
Simulation Area [x,y,z]	300 x 300 x 35 m

For base stations we run tests with 2.4 GHz and 5.9 GHz as 5G frequency introduced in 3GPP Release 14 for communication between vehicles. For base station we use 1 TX and 1 RX omnidirectional antennas with transmit power of 40 Watts. The base height of a base station is set at 25 meters.

For users we set single antenna mode with 1 TX and 1 RX antenna and transmit power of 1 Watt. Poisson distribution of users has a density parameter of 0.006 and user height parameter at 0.01. We also need to take into consideration the fact that some users we be inside and not taking part in road traffic, yet they still require network resource allocation. Indoor probability parameter is set to 0.1 to simulate that.

As we discussed higher frequencies significantly reduce the ability of a signal to overcome obstacles like buildings. To take this into account we set parameters for typical obstacles that can be found in the city. Street width is set to 35 meters, block length and width to 50 meters, and maximum building height is set at 25 meters. Loss of signal due to walls is set to 10 dB.

4.4 Simulation Results

After running simulations for different frequencies and with different configurations of base stations and user parameters we acquired the following results for 2.4 GHz, 5.9 GHz with 3 base stations and 5.8 GHz configurations with 4 base stations.

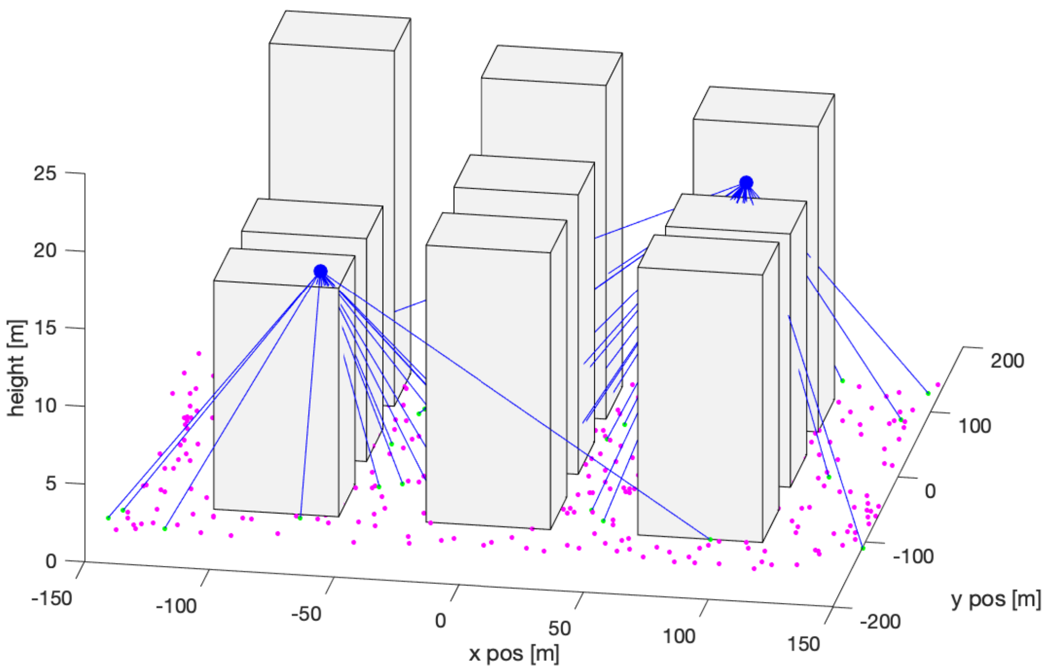

Figure (7) 2.4 GHz base stations distribution. Purple dots - users, blue dots - base stations, blue lines - links.

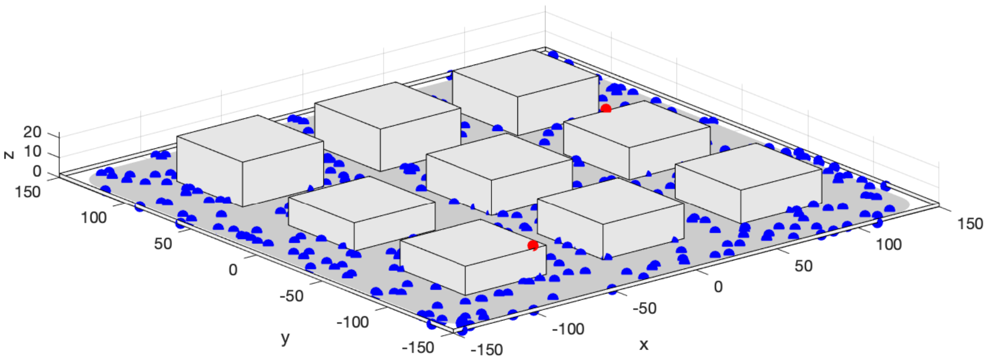

Figure (8) 2.4 GHz users distribution. Blue dots - users, purple dots - base stations.

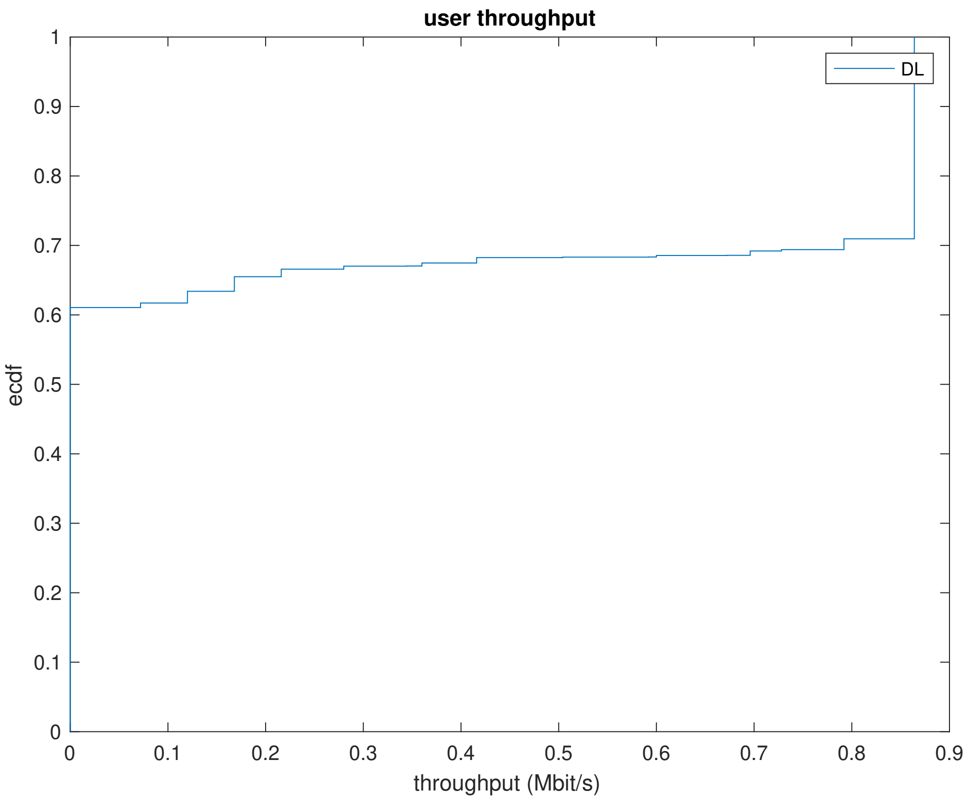

Figure (9) 2.4 GHz throughput ECDF.

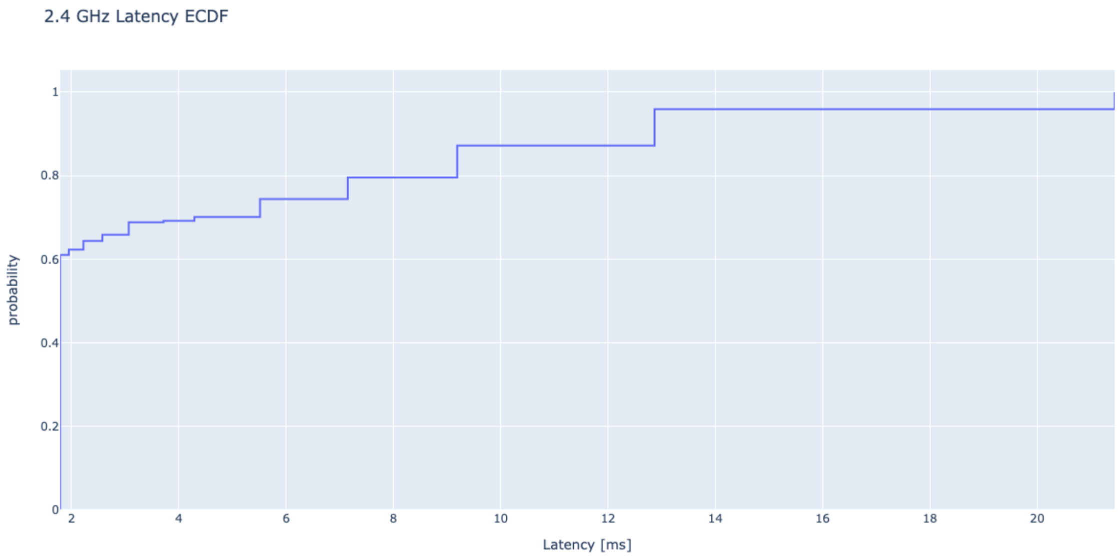

Figure (10) 2.4 GHZ latency ECDF.

For simulation of 2.4 GHz frequency we generate 2 base stations and 524 users on the area of 150 m x 150 m with six building blocks. This arrangement reflects the real-life possibility of signal blockage for some users as well as reliable signal reception in the line of sight cases. Output for throughput (Figure 9) is given as Empirical Distribution Function (ECDF) that shows the share of users at different throughput values. As explained at the beginning of this section we take throughput values and packet size of 193 bytes to calculate latency, the parameter we are mainly interested in for the purpose of this thesis. Latency results (Figure 10) show us that significant share of users (around 60%) have latency lower than 2 ms, however, no users have latency below 1.8 ms.

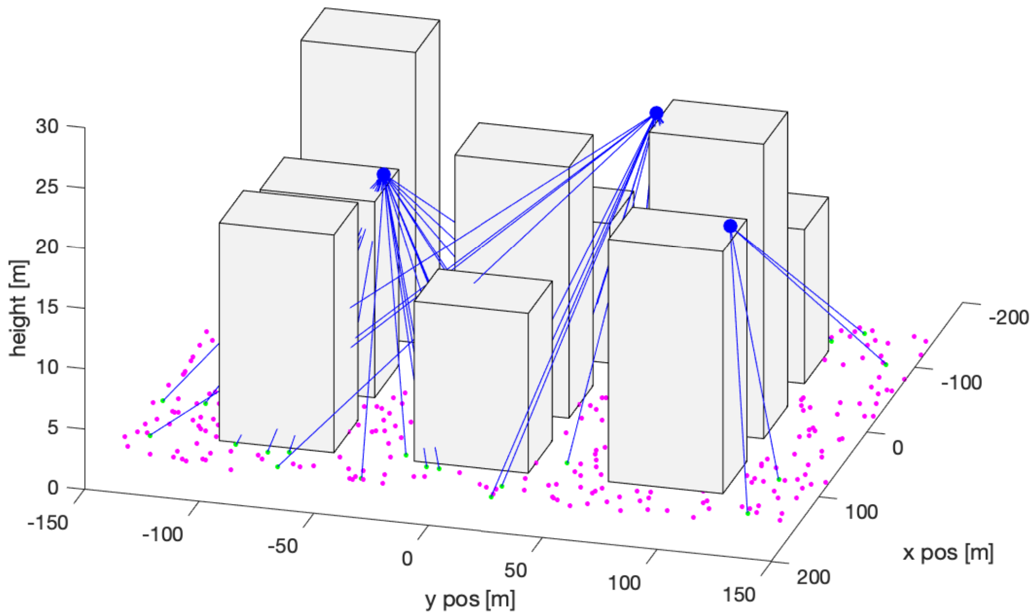

Figure (11) 5.9 GHz 3 base stations distribution. Purple dots - users, blue dots - base stations, blue lines - links.

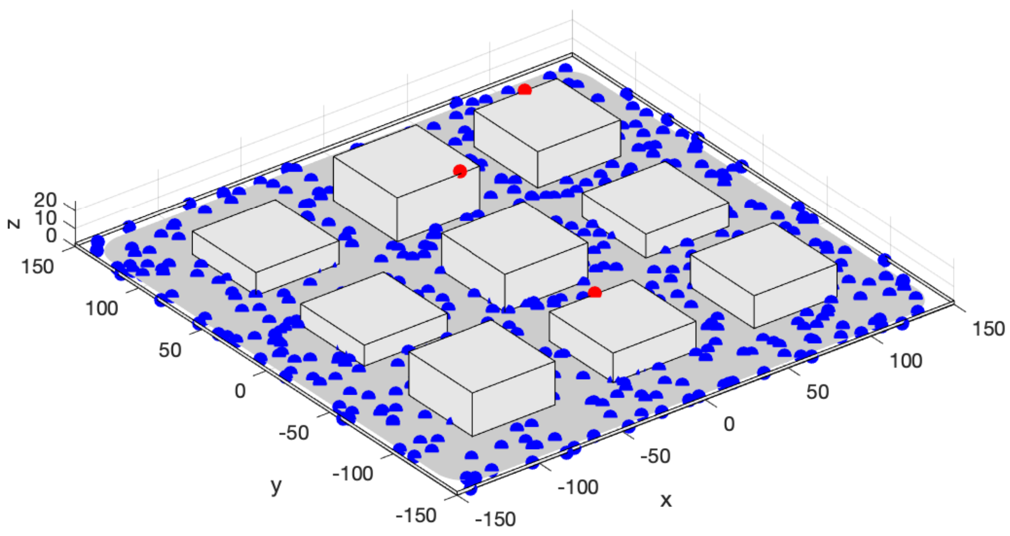

Figure (12) 5.9 GHz users distribution for 3 base stations. Blue dots - users, purple dots - base stations.

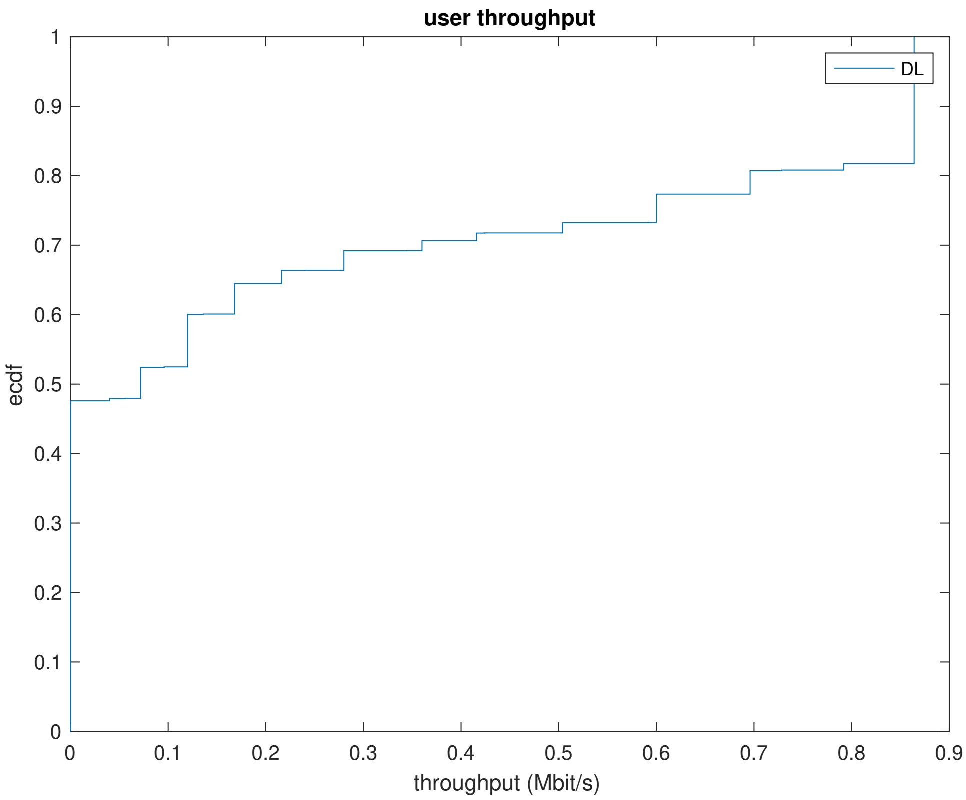

Figure (13) 5.9 GHz throughput ECDF for 3 base stations.

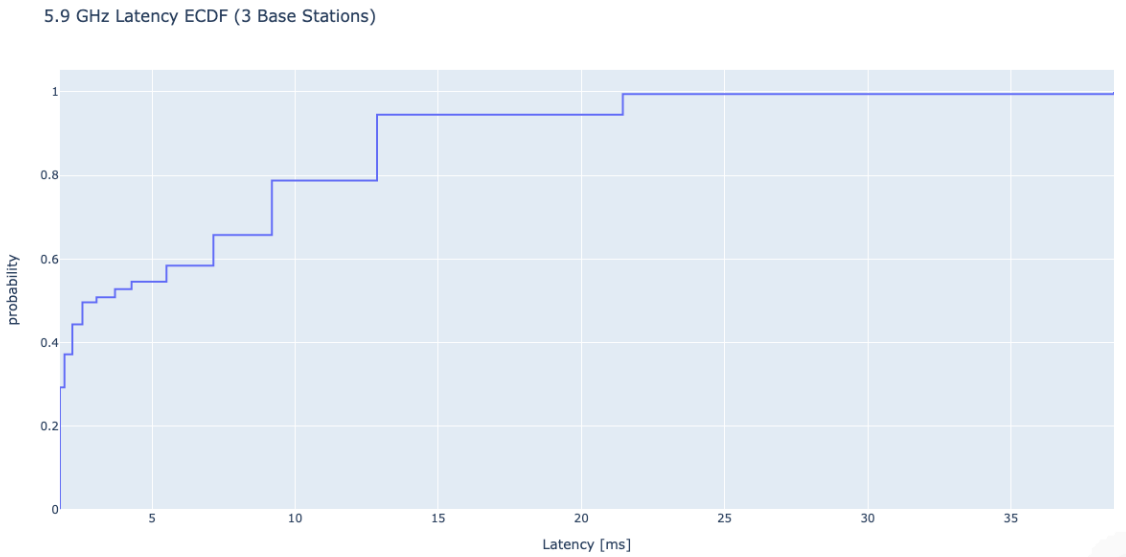

Figure (14) 5.9 GHz latency ECDF for 3 base stations.

In the next simulation we increase frequency to 5.9 GHz to represent CV2X standard for automotive 5G applications. The same arrangement for blockages as in the previous simulation is used here. Throughput values this time show bigger share of users have higher throughput with around 50% of users having throughput lower than 0.1 Mbit/s, an improvement from 2.4 GHz where it was more than 60%. Latency, on the other hand, doesn't show definitive improvement. While we now have around 25% of users having latency below 1.25 ms the share of users below 2 ms is lower than in the previous simulation run. This might be explained by the fact that higher frequencies of 5G are more sensitive to obstacles than 4G and hence users out of line of sight might experience more significant quality of service issues. Another test with more base stations for 5G can clarify if using more stations can improve the latency values for 5G.

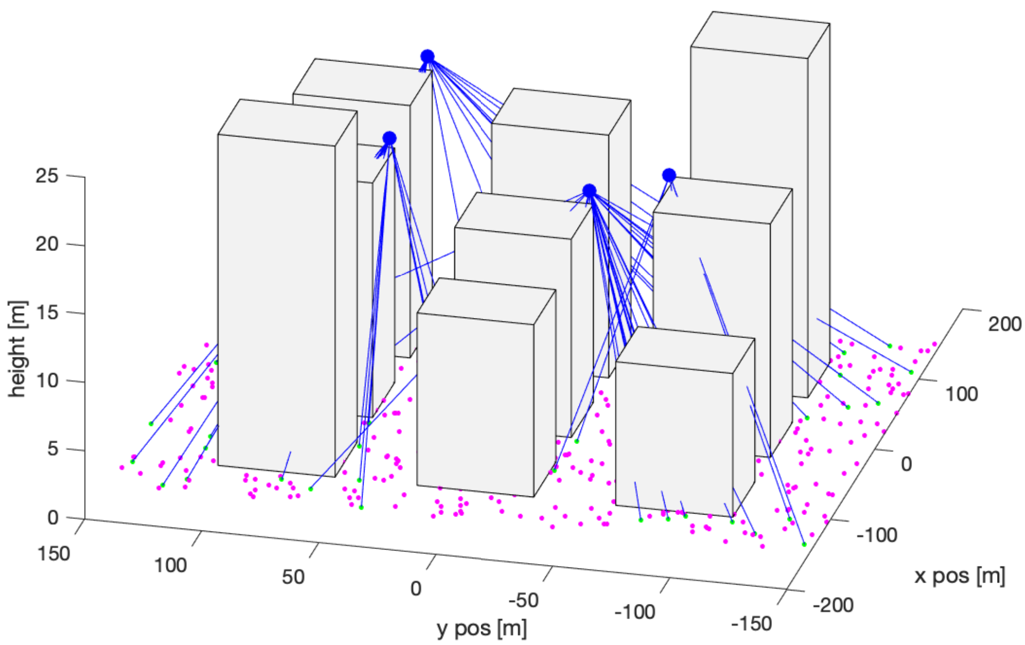

Figure (15) 5.9 GHz 4 base stations distribution. Purple dots - users, blue dots - base stations, blue lines - links.

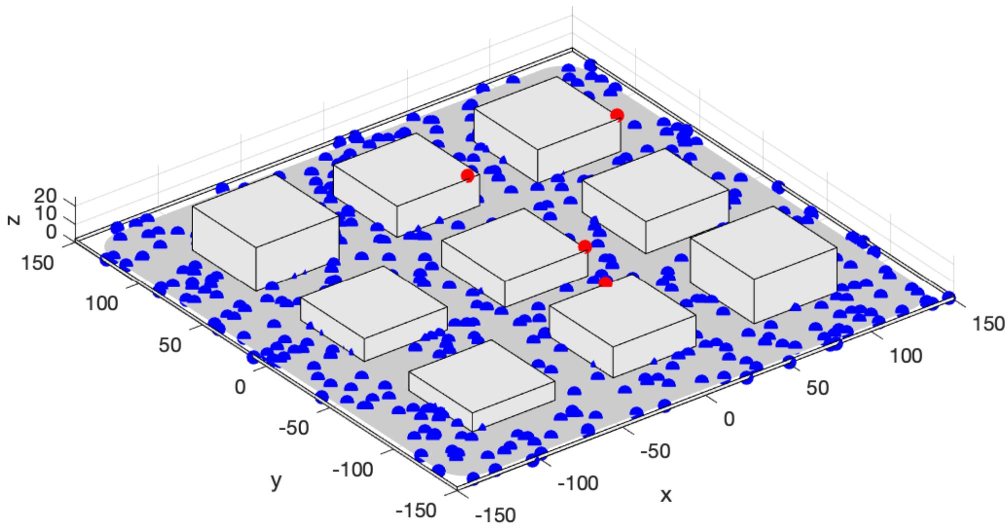

Figure (16) 5.9 GHz users distribution for 4 base stations. Blue dots - users, purple dots - base stations.

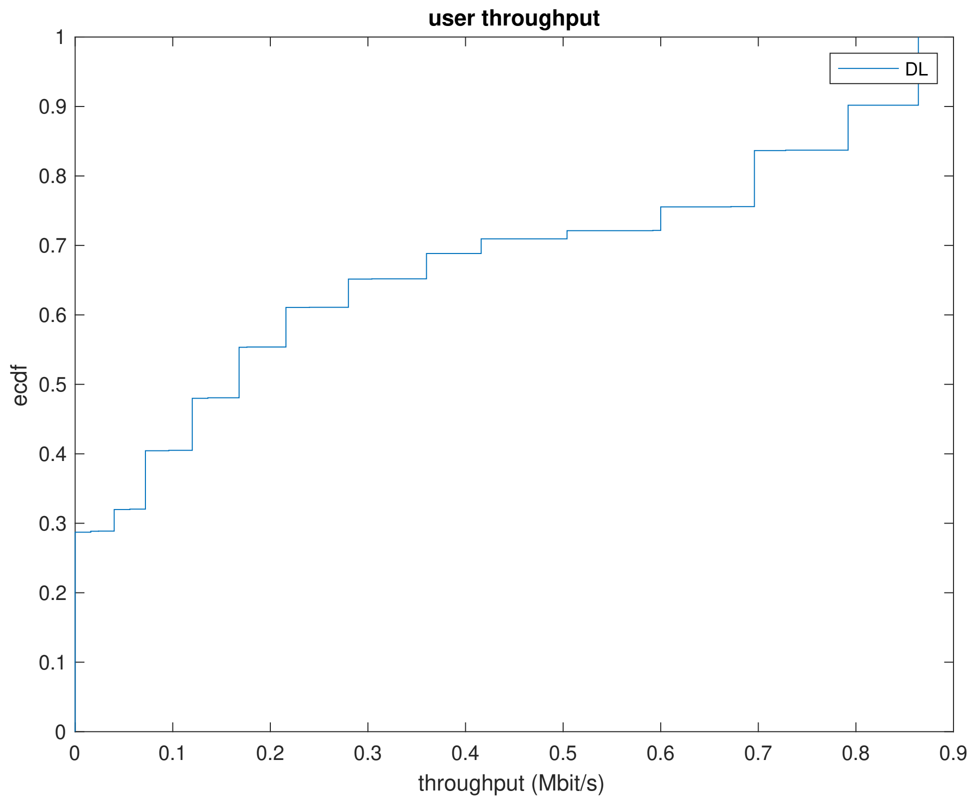

Figure (17) 5.9 GHz throughput ECDF for 4 base stations.

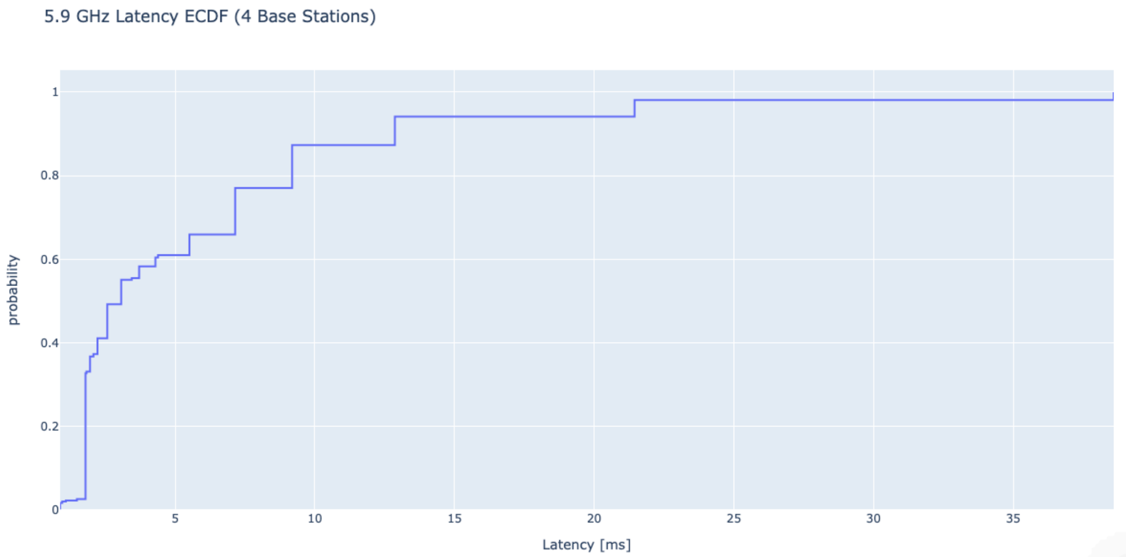

Figure (18) 5.9 GHz latency ECDF for 4 base stations.

Now with 4 base stations instead of 3 in the previous simulation we can see the influence of throughput and latency. Same arrangement for blockages is used in this run. With 4 base stations over 60% of users have latency <5 ms and about 50% have latency <2.5 ms. We can also observe that the share of users with <1 ms latency significantly dropped. This might be attributed to a specific generation, to make more decisive conclusions larger scale runs are required. Large scale simulations will allow to reduce the impact of outliers in random generations and highlight statistically significant differences in communication standards.

5 Discussion

In this thesis we tried to research the case of 5G in a context of autonomous road vehicles. While current levels of driving autonomy require significant input from the driver, the course on reaching higher levels of autonomy poses some questions regarding communication technology that is capable of providing low enough latency and high enough reliability. Remote driving is no exception, if we are going toward self-driving road vehicles either for the sake of economy or improved safety, we have to be sure that the signal reaches the vehicle fast leaving enough time for decision making process in critical situations. Safety-critical nature of road traffic puts very strict requirements on how much time autonomous vehicle has to detect and avoid road accidents. To help with this V2X communication is necessary for enhanced awareness and planning.

The fact that 5G is considered as a communication standard in CV2X emphasises possible key role of 5G in the industry in the future. 3GPP releases 14-16 describe this role and use cases in more details elaborating on cases of autonomous driving and vehicle platooning. Based on these specifications we were able to compare 5G to alternative standards both in licensed and unlicensed spectrum. In this comparison factors like infrastructure costs, available bandwidth, and latency were considered. For example, LoRaWAN and ZigBee can be used for non-safety-critical applications that do not require low latency and high bandwidth while 5G can cover both safety-critical and non-safety-critical applications. This way we utilise strengths of each technology and optimise network resources.

Simulation indicates that even in city scenario with multiple obstacles and signal blockages ultra low latency in 5G is possible for multiple users. In the environment where V2X communication might experience maximum interference and correct network resource allocation becomes crucial, 5G was able to support multiple users with <2 ms latency while, as expected, lower frequencies cannot provide the same performance. The latency results for some users fit within the range of requirements set by 3GPP TS 22.186 version 17.0.0 Release 17 including 3 ms requirement for emergency trajectory alignment (See Table 1). It must be noted that our simulation only considered V2X users and the results reflect the channel performance with limited load, hence, the acquired values for latency are lower than what can be expected in real situation.

Implementation of any technology in automotive industry is a complex process and there are some obstacles that 5G faces upon its roll-out. Economic factors delay the deployment of 5G networks especially in remote areas due to current high costs of standalone equipment. This factor limits the locations where 5G for autonomous driving can be tested as well as implementation of 5G in safety-critical aspects of autonomous driving. On the other hand some 5G features like eMBB can be implemented using legacy infrastructure from 4G networks. High costs of equipment can also be attributed to higher number of base stations needed to cover a unit of area compared to 4G. The topic of security of cellular networks is not thoroughly discussed in this thesis but it also contributes to the decision on what standard to use for which application. For non-safety-critical applications alternative communication technologies can provide a cheaper solution that doesn't require any infrastructure for V2X connectivity.

Collaborative efforts of manufacturers of radio equipment and vehicle to harmonise and unify development of RAN equipment can also reduce research and development costs. Open and interoperable solutions in RAN might create a platform for CV2X development where car manufacturers can join efforts to create common V2X communication environment. Such collaboration would promote progress toward level 3-5 autonomous driving and as a result toward safer road traffic.

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