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IMPACT OF LOW LATENCY ON 5G-BASED INTELLIGENT TRANSPORTATION SYSTEM

Master's thesis

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MADALA LATENTSUSE MÕJU 5G-PÕHISE INTELLIGENTSE TRANSPORTSÜSTEEMI NÄITEL

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Author’s declaration of originality

I hereby certify that I am the sole author of this thesis. All the used materials, references to the literature and the work of others have been referred to. This thesis has not been presented for examination anywhere else.

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Abstract

The fifth generation of wireless communication systems (*5G*) is the next generation in wireless communications which is standardized by the Third Generation Partnership Project (*3GPP*). It is expected that commercial deployments of 5G will start during 2019-2020. 5G will have significant improvements in terms of data rates, latency, massive connectivity and energy efficiency. With these capabilities 5G can realize a diverse variety of use cases proposed by 3GPP. However, this thesis concentrates on the Intelligent Transport System (*ITS*) use case.

Safety is the most important aspect when talking about ITS and this is the main reason we are focused on it. Another argument why ITS is discussed in this thesis is the interest stemming from a telecommunication operator since there are a lot of estimations for latency reduction in research papers without practical testing or simulations while considering specific use cases proposed for 5G.

The objective of this thesis is to investigate both the Fourth Generation Wireless Communication System (*4G*) and 5G networks and determine whether the 5G network is really needed for the ITS use case or can it also be realized with 4G.

As a result, the thesis serves up the Round-Trip Time (*RTT*) values in a 4G network and simulations for Vehicle-to-Vehicle (*V2V*) communication. This enables to estimate the RTT value for the User Equipment (*UE*) in the 4G network for the ITS use case and compare it with the estimated values proposed for 5G.

This thesis is written in English and is 30 pages long, including 5 chapters, 15 figures and 8 tables.

Annotatsioon

Madala latensuse mõju 5G-põhise intelligentse transportsüsteemi näitel

Viienda põlvkonna traadita sidesüsteem (*5G*) on järgmine põlvkond traadita sidesüsteemi hierarhias, mida standardiseeritakse kolmanda põlvkonna partnerlusprojekti poolt (*3GPP*). Eeldatakse, et 5G võetakse kasutusele ajavahemikus 2019-2020. 5G eelisteks loetakse, võrreldes eelmise põlvkonna traadita sidesüsteemide ees, kõrget andmeedastuskiirust, võimalikult madalat latentsust, massiivsest seadmete ühendamise võimet ja energiatõhusate seadmete kasutamist. Tänu nendele eelistele on 5G võimeline toetama 3GPP poolt välja pakutud kasutusjuhtusid. Antud lõputöö uurib ühte 3GPP poolt välja pakutud kasutuslugu - intelligentne transpordi süsteem (*ITS*).

Kõige olulisem aspekt, millel antud lõputöö keskendub on ITS kasutusjuhu turvalisus. Teine põhjus, miks antud töös intelligentset transpordisüsteemi uuritakse on telekommunikatsiooni operaatori poolne huvi, mis tuleneb sellest, et latentsuse vähendamiseks on avaldatud mitmeid teadustöid, kuid need ei hõlma praktilisi mõõtmisi ega simulatsioone spetsiifiliste 5G poolt välja pakutud kasutuslugude jaoks.

Antud lõputöö eesmärgiks on uurida nii 4G kui ka 5G-võrku ning teha järeldus, kas 5G-võrk on tõesti vajalik ITS kasutusjuhu jaoks või saab seda saavutada ka 4G-võrgus.

Antud lõputöö tulemusena esitatakse mõõtmistulemused edasi-tagasi viite (RTT) väärtused 4G võrgus ning simulatsiooni tulemused sõidukilt-sõidukile (V2V) kommunikatsiooni korral. Nende tulemuste põhjal on võimalik hinnata ITS kasutusjuhu latentsuse väärtust lõppkasutaja jaoks ning võrrelda saadud tulemusi hinnanguliste 5G väärtustega.

Lõputöö on kirjutatud inglise keeles ning sisaldab teksti 30 leheküljel, 5 peatükki, 15 joonist, 8 tabelit.

List of abbreviations and terms

1G	First Generation Wireless Communication System
2G	Second Generation Wireless Communication System
3G	Third Generation Wireless Communication System
3GPP	Third Generation Partnership Project
3GPP2	Third Generation Partnership Project 2
4G	Fourth Generation Wireless Communication System
5G	Fifth Generation Wireless Communication System
5GC	5G Core Network
5GS	5G System
5G-AN	5G Access Network
8PSK	Eight Phase Shift Keying
AMPS	Advanced Mobile Phone System
AV	Autonomous Vehicle
AWGN	Additive White Gaussian Noise
CDMA2000	Code Division Multiple Access 2000
CN	Core Network
C-plane	Control plane
DES	Discrete-Event System
DL	Downlink
E2E	End-to-End
EDGE	Enhanced Data Rates for GSM Evolution
eMBB	Enhanced Mobile Broadband
eNB	Evolved Node B
EPC	Evolved Packet Core
ETSI	European Telecommunications Standards Institute
E-UTRA	Evolved Universal Terrestrial Radio Access
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
FDD	Frequency Division Duplex
FM	Frequency Modulation
FSK	Frequency Shift Keying
GMSK	Gaussian Minimum-Shift Keying

gNB	Next Generation Node B
gNB-CU	Next Generation Node B Central Unit
gNB-DU	Next Generation Node B Distributed Unit
GPRS	General Packet Radio Service
GSMA Intelligence	Global System for Mobile Communications Intelligence
GSM	Global System for Mobile Communications
HSS	Home Subscriber Server
IARR	Interface-Aware Radio Resource
IoT	Internet of Things
IMT Advanced	International Mobile Telecommunications Advanced
IMT-2020	International Mobile Telecommunications 2020
ITS	Intelligent Transport System
ITU	International Telecommunication Union
ITU-T	International Telecommunication Union Telecommunication Standardization Sector
L3VPN	Layer 3 Virtual Private Network
LAN	Local Area Network
LSR	Label Switch Router
LTE	Long-Term Evolution
mIoT	Massive Internet of Things
MAC	Medium Access Control
MBH	Mobile Backhaul
MME	Mobility Management Entity
MPLS	Multi-Protocol Label Switching
MTC	Machine-Type Communications
MU-MIMO	Multi-User Multiple-Input and Multiple-Output
NGMN	Next Generation Mobile Network
ng-eNB	Next Generation eNode B
NG-RAN	Next Generation Radio Access Network
NMT	Nordic Mobile Telephone
NR	New Radio
NSA	Non-Standalone
OFDMA	Orthogonal Frequency-Division Multiple Access
OWD	One-Way Delay

PDN-GW	Packet Data Network Gateway
PE	Provider Edge
Q2	Second quarter
Q3	Third quarter
QoE	Quality of Experience
RAN	Radio Access Network
RAT	Radio Access Technology
RRC	Radio Resource Control
RSU	Road Side Unit
RTT	Round-Trip Time
SA	Standalone
SC-FDMA	Single-Carrier Frequency-Division Multiple Access
SDN	Software Defined Networking
SIU	Site Integration Unit
SR	Service Router
S-GW	Serving Gateway
TA	Time Advanced
TBS	Transport Block Size
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TTI	Transmission Time Interval
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunications Service
URLLC	Ultra-Reliable Low-Latency Communication
U-plane	User plane
VANET	Vehicular Ad-Hoc Network
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
W-CDMA	Wideband Code Division Multiple Access

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1 Introduction

The evolution of wireless communication systems over the past few decades has resolved many technical challenges to fulfil new requirements and support growing connectivity around the world. The evolution of wireless communication systems has been divided into separate generations. Each generation relates to a set of standards, diverse capacities, new techniques and aspects which distinguish generations from each other. The following sections give a short overview of the standards and techniques used in each generation.

The first generation of wireless communication systems (*1G*) used analog radio signals. 1G was the first generation that introduced mobile voice services. In the 1980s several analog telecommunication standards were published e.g. Nordic Mobile Telephone (*NMT*) and Advanced Mobile Phone System (*AMPS*). NMT was used in the Nordic countries, Switzerland, The Netherlands, Eastern Europe and Russia. NTM used full-duplex for transmission, Frequency Modulation (*FM*) for voice channel transmission and Frequency Shift Keying (*FSK*) modulation with a bandwidth of 25 kHz for signal transfer. AMPS was used in North-America and Australia. It used FDMA modulation with a 30 kHz bandwidth for FM-modulated voice channels. The data transfer rate for 1G was 2 Kbps [1].

The second generation of wireless communication systems (*2G*) was an upgrade from 1G and it used digital radio signals. The primary services for 2G were digital phone calls and short messaging. In the 1990s several standards were launched for 2G e.g. Global System for Mobile communications (*GSM*), General Packet Radio Service (*GPRS*) and Enhanced Data Rates for GSM Evolution (*EDGE*). GSM was standardized by the European Telecommunications Standards Institute (*ETSI*) and it defined protocols for mobile devices used in 2G. GPRS was standardized by ETSI and it used the Frequency Division Duplex (*FDD*) and the Time Division Multiple Access (*TDMA*) channel access methods. EDGE was standardized by 3GPP and it used the Gaussian Minimum-Shift Keying (*GMSK*) and the Eight Phase Shift Keying (*8PSK*) transmission techniques. 2G provided higher capacity, improved data rates and power efficiency for digital hardware. The average data transfer rate for 2G was between 14.4-64 Kbps [1].

The third generation of wireless communication systems (*3G*) was an upgrade from 2G. In the 2000s several standards were published for 3G e.g. Universal Mobile Telecommunications Service (*UMTS*) and Code Division Multiple Access 2000 (*CDMA2000*). The primary services for 3G were phone calls, messaging and data transfer. The UMTS was standardized by 3GPP and it defined the complete network system for 3G. The Radio Access Technology (*RAT*) used for UMTS was Wideband Code Division Multiple Access (*W-CDMA*). UMTS was developed based on GSM and it was used in Europe, Japan and China. CDMA2000 is a second version of UMTS and it was standardized by the Third Generation Partnership Project 2 (*3GPP2*). CDMA2000 was developed to be used in North-America and South-Korea. The maximum data transfer rate for 3G was 2 Mbps [1].

4G is an upgraded version of 3G that was defined by the International Telecommunication Union (*ITU*) and the International Mobile Telecommunications Advanced (*IMT Advanced*) in 2008. The primary services for 4G are IP-services, including voice messaging. Standardized by 3GPP, the Long-Term Evolution (*LTE*) is a standard for wireless broadband communications, developed based on 3G technologies. LTE Advanced was standardized by 3GPP in 2011 and it is an upgraded version of LTE which meets the initial 1 Gbps data rate requirement for 4G. The 4G RAT used for Downlink (*DL*) is Orthogonal Frequency-Division Multiple Access (*OFDMA*) and for Uplink (*UL*) Single-Carrier Frequency-Division Multiple Access (*SC-FDMA*). 4G is currently the most usable wireless communication system around the world with a maximum data transfer rate for 4G of 1 Gbps [1].

5G is the next generation of wireless communication systems which is standardized by 3GPP. It is expected that commercial deployments of 5G will start in 2019-2020 and 5G will have significant improvements in terms of data rates, latency, massive connectivity and energy efficiency. With these capabilities 5G can realize a diverse variety of proposed use cases. These scenarios are often divided by several standardization organizations e.g. International Mobile Telecommunications 2020 (*IMT 2020*) into three main groups – Enhanced Mobile Broadband (*eMBB*), URLLC and Massive Machine Type Communication (*mMTC*). 5G introduces multiple frequency bands: low (700 MHz-3.5

GHz), mid (3.5-6 GHz) and high (6-100 GHz) with the maximum data transfer rate envisioned to be up to 20 Gbps. The previously mentioned statements show that 5G is not an incremental improvement over 4G, but rather it facilitates an exponential growth in the evolution of wireless communication systems [2].

1.1 Standardization activities for 5G

From the previous overview we can see that each generation of wireless communication systems is relying on a specific set of standards. The focus of this thesis is on 5G which makes it essential to give an overview of the pertinent standardization activities done so far.

The worldwide technical standards for telecommunication are coordinated and standardized by the ITU. This means that all proposals from other standardization bodies e.g. 3GPP, ETSI etc. are not considered to be used worldwide until the International Telecommunication Union Telecommunication Standardization Sector (*ITU-T*) has standardized them. ITU has named the 5G standard as “IMT-2020 and beyond” and all ITU recommendations are called as standards only after they have been approved by ITU Member States.

3GPP has divided 5G standardization into two main stages. Release 15 defines Phase 1 and Release 16 defines Phase 2. One more phase is planned, in Release 17, but the features for this have not yet been clarified.

Phase 1 defines the fundamental aspects e.g. the architecture, Core Network (*CN*), critical communications, Machine-Type Communications (*MTC*), the Internet of Things (*IoT*), V2X communications, use cases, protocols, 4G improvements and other new features for 5G [3]. Release 15 has been divided into three distinctive stages – “Early Drop”, “Main drop” and “Late drop”. Additionally, release status “frozen” is used which means no additional functionality modifications can be added to the release. “Early drop” contains Non-Standalone (*NSA*) 5G specifications and it was frozen in March 2018. The “Main drop” contains Standalone (*SA*) 5G specification and it was frozen in September 2018. “Late drop” contains additional migration architecture and it will be frozen in June 2019. This means that phase 1 will finally be frozen in 2019 between second (*Q2*) and third quarter (*Q3*).

Phase 2 defines an extensive set of topics for 5G e.g. V2X application layer services, network automation, Local Area Network (*LAN*) support, satellite access, communication in vertical domains, novel radio techniques etc. No distinctive stages have been described for Release 16 which will be frozen in 2020 between Q2 and Q3.

Since nor 3GPP or ITU-T have concluded the standardization activities for 5G, this thesis only considers documents published by the mentioned organizations before January 2019.

1.2 5G at a glance

Due to rapid technology growth, many emerging new use cases and business models, it is estimated that there will be a massive increase in connectivity and traffic in the mobile domain and 5G is expected to be the enabler which guarantees this future connected society [4]. The Mobile Economy 2018 report estimates the mobile industry to have 6 billion unique mobile subscribers and 5 billion mobile internet users by 2025. When comparing these values with the 2017 results (Figure 1), an increase of 1 billion unique mobile subscribers and 2 billion mobile internet users can be observed. Additionally, it is estimated that 5G will have 1.2 billion connections by 2025 [5].

The report also states that the total number for cellular and non-cellular IoT devices will reach 25 billion. This growth for IoT devices is driven by new use cases e.g. smart cities, smart homes, connected devices and vehicles. Nowadays user’s digital engagement means that they are using their mobile phones to access internet-messaging, social-media platforms, entertainment content and other digitally delivered services. For 5G consumers are estimated to adopt new ways of capitalizing technologies e.g. augmented and virtual reality, building applications, drone delivery and autonomous cars. In terms of supporting these expectations and to satisfy the customers’ needs vast resources are globally allocated to the development of 5G in the upcoming years [5].

With regards to use cases the Next Generation Mobile Network (*NGMN*) Alliance created a 5G vision report in 2015 where twenty-five use cases were devised which were further divided into eight use case families: broadband access, broadband access everywhere, higher user mobility, Massive Internet of Things (*mIoT*), extreme real-time communications, lifetime communications, ultra-reliable communications and broadcast-like services. This report also states that for 2020 and beyond many applications e.g.

remote operation and control, automotive and healthcare require extremely low latency [4].

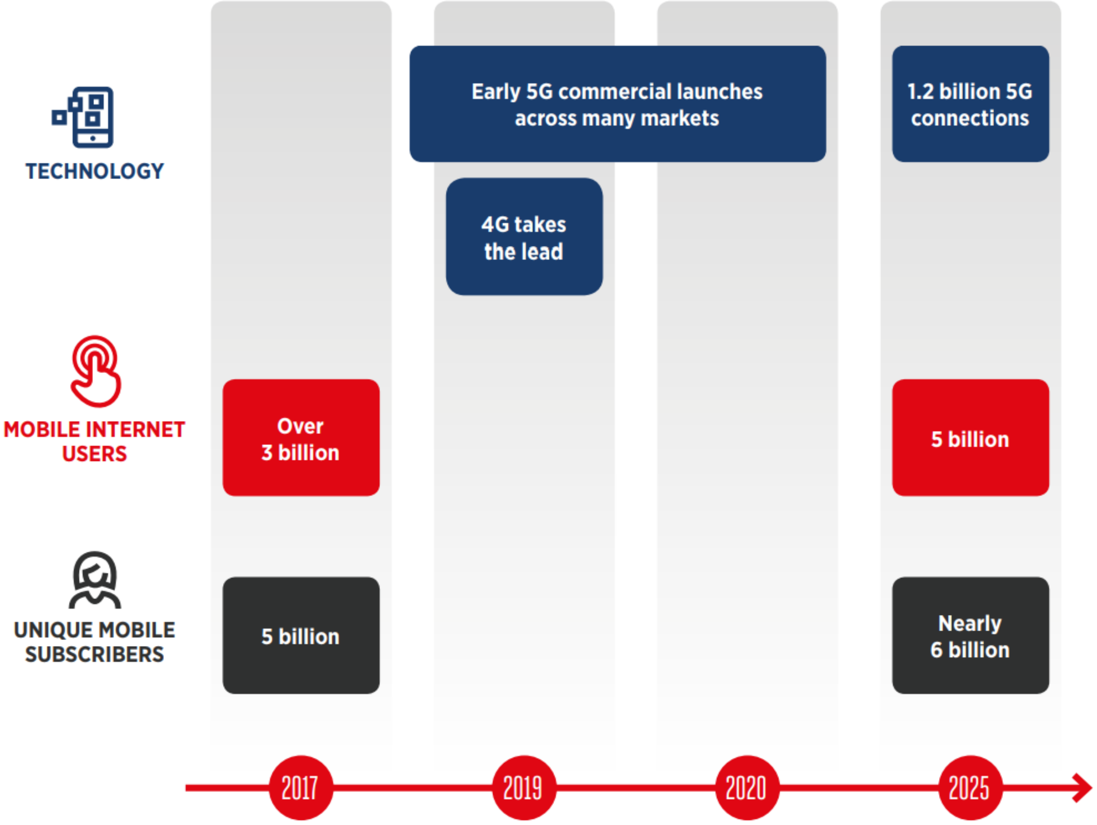

Figure 1. The Mobile Economy 2018 report - mobile industry milestones up to 2025 [5].

Automated traffic control and autonomous driving use cases improve traffic efficiency and increase road safety. For these applications V2V, Vehicle-to-Infrastructure (*V2I*) and communication with sensitive road users e.g. pedestrians and cyclists are envisioned to be implemented by 5G. It is also stated that to achieve End-to-End (*E2E*) low latency in the communication chain the use of URLLC is essential [4].

From a value creation point of view 5G changes the experience for consumers and enterprises. Higher data rates and lower latencies enable consumers to experience enhanced personalized services with 5G smartphones with increased battery lifetime. 5G also addresses the complex needs of enterprises when it comes to e.g. security, privacy reliability and latency. Increased data volumes through 5G will provide enterprises the possibility for enhanced data analytics and thus helps to improve their businesses [4].

1.3 Key aspects of 5G

ITU has published a figure to divide the key aspects of 5G into three directions – eMBB, URLLC and mIoT [6]. This is called the 5G key aspects triangle, seen in Figure 2. The ITU report “Setting the Scene for 5G: Opportunities & Challenges” released in 2018 is defining eMBB as one of the primary use cases for 5G which enables enhanced indoor and outdoor broadband for the users [6]. According to 3GPP, eMBB is defined as having advanced data rates, higher traffic throughput and increased user mobility. Different service areas e.g. indoor and outdoor, urban and rural areas, wide and local areas require appropriate connectivity deployments and are categorized into individual scenarios [7]. 3GPP TS 22.261[7] describes all the use cases for the eMBB.

The mIoT requirements must conform to a wide range of IoT devices and services foreseen in the 5G evolutionary plan [6]. Figure 2 is using the term mMTC in the 5G triangle, however ITU and 3GPP are using mIoT. Although the terms are different the meaning is the same. The mIoT term refers to its usage only in IoT use cases and applications and mMTC refers to a broader use in the 5G context. 5G is expected to transform the evolution of smart cities, homes and IoT. The built-in security and stability elements in 5G are also suitable for public safety and mission-critical services which are one of the main use cases for mMTC [6].

The third key aspect in Figure 2 is URLLC. The main services for URLLC defined by ITU are autonomous driving, smart grids, remote patient monitoring and automation in industries. 3GPP 4G network is not able to fulfil the low latency requirements needed for the mentioned services. Therefore, URLLC is considered a key enabler in 5G and it is important to investigate ways on how to achieve low latency values within the communication chain [8].

This thesis is only focused on URLLC within an ITS use case. Low latency is crucial for ITS as it is one of the fundamental aspects to achieve road safety. In a case of autonomous driving the car should react to changes in the environment near real-time. As an example, when an Autonomous Vehicle (*AV*) senses a collision, it should brake, turn or accelerate instantly to avoid the potential crash [6]. 3GPP TS 22.261 [7] describes all the use cases for URLLC.

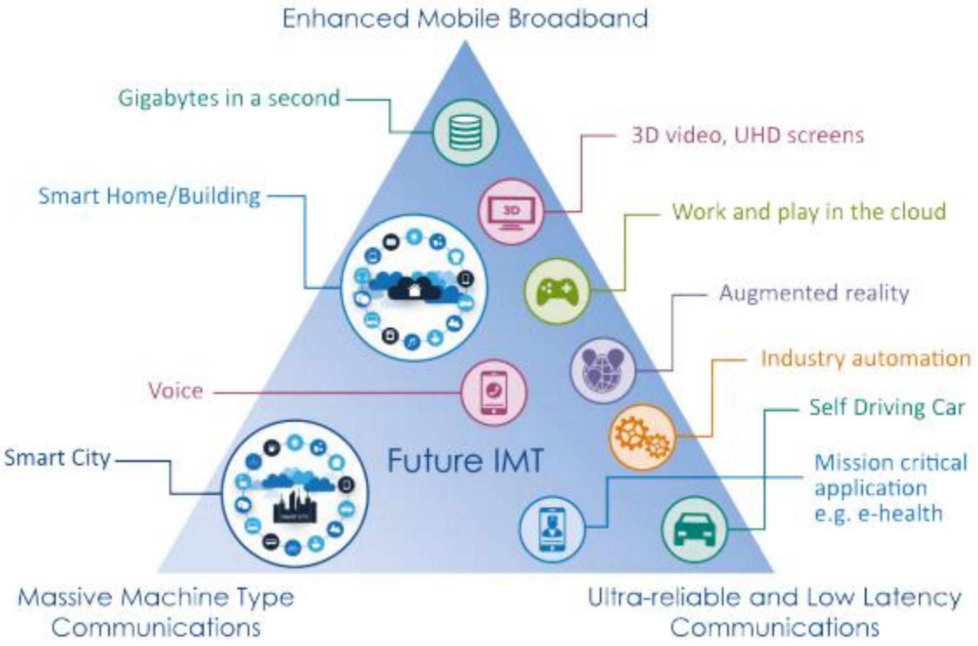

Figure 2. 5G key aspects triangle representing the main three benefits of 5G [6].

1.4 Motivation behind the ITS use case and problem statement

Safety is the most important aspect when talking about the ITS use case and this is the main reason why this thesis is focused on it. In a highway environment receiving data with a delay can cause errors in vehicles' safety applications, culminating in a serious traffic accident. This necessitates the testing of V2X environments for the ITS use case to ensure safety and reliability of the communication. The priority of testing V2X is high due to high risk and requirements stated for this environment [9].

Another reason why ITS is discussed in this thesis is the interest of a telecommunication operator since there are a lot of estimations for latency reduction in research papers without practical testing. With this thesis, we want to obtain actual latency data for 4G and compare the latency values between 4G and 5G. This comparison gives us feedback on how much latency reduction will be needed for the operator in the future.

With regards to latency reduction current research papers only consider specific algorithms or methods for radio air interface or for the core network (will be discussed in more detail in Chapter 2.4). There are limited number of research papers for URLLC use cases which consider the whole 5G network. In the context of this thesis we consider the whole 5G network to be:

- UE;
- Next Generation Radio Access Network (*NG-RAN*);
- transport network;
- 5G Core Network (*5GC*).

The goal of the master thesis is to calculate the total RTT value for one use case where the latency in 5G is a critical issue and based on this see, whether this use case is possible to achieve in 4G network. The expected outcome is to determine the total value of RTT for UE. In this thesis, only one-use case has been chosen for consideration – intelligent transport system. Simulations are run for V2V communication and for the 4G network. Simulations results are found by using MATLAB program and measurement results for 4G network are found by using telecommunication operators input after which the results for total RTT values for 4G network are found and as a result comparison between 4G and 5G networks is presented.

The rest of this thesis is organized as follows: Chapter 2 describes the State of the Art regarding latency in 4G and 5G networks. Chapter 3 describes the 4G and 5G network architectures and the ITS use case. Chapter 4 describes the ITS use case simulations and represents the results. Chapter 5 concludes the thesis and considers future work based on the work done.

2 State of the Art for low latency in 4G and 5G

There are different types of latency definitions which are used in telecommunication systems. Differences between latency definitions depend on how the source, destination and the transmitted information is described. In simple words, latency can be described as the interval it takes a data packet to be transmitted from source to destination [10]. According to 3GPP documents, there are two types of latency which are used in cellular communication. These are Control Plane (*C-plane*) and User Plane (*U-plane*) latency [11]. There are also several different definitions used for C-plane and U-plane latencies in the literature and these are defined differently in 4G and 5G. The following sections describe the various definitions used for latency.

2.1 The basics of latency in 4G and 5G

Latency definitions for 4G:

- **U- plane latency:** U-plane latency for 4G is defined in [12] as the time it takes for a small IP-packet to travel from the terminal through the network to the internet server back to the terminal. In other words, U-plane latency is called an RTT, see Figure 3. RTT is defined as the time it takes a data packet to be sent from the UE though the Evolved Node B (*eNB*), Serving Gateway (*S-GW*) to a server and the same route back towards the UE [12]. It is also often called a ping time. U-plane latency is defined in [13] as One-Way Delay (*OWD*), which is available at the IP-layer until it shows up in the UE. In [14], U-plane latency is defined as OWD between a packet being accessible at the IP-layer in the UE/Radio Access Network (*RAN*) edge node or in the RAN edge node/UE. The U-plane latency requirement for 4G is 5 ms.

Figure 3. Latency definition according to [12] – RTT.

- **C-plane latency:** C-plane latency in 4G is defined as a transition time from camped-state to active mode. In other words, camped-state is called idle mode. Idle mode is a battery efficient state and active mode represents the start time for data transfer [15]. Idle mode means that the UE does not have a connection to a Radio Resource Control (*RRC*) protocol. RRC protocol is a communication link between the UE and eNB. If the UE reaches the RRC connection, then we call it active mode. The active- "dormant" state means that the UE cannot detect the cell. Figure 4 illustrates the mentioned states for C-plane latency. Latency for C-plane consist of two parts which need to be added, to find the total value. The transition time from the camped state to active state is required to be lower than 50 ms and the transition time between the active and active – "dormant" state is required to be lower than 10 ms [16].

- **E2E latency:** Several sources in literature have referred to E2E delay as half of the RTT value. This means that this is a time required for one packet to be transmitted across the network from source to destination. Another term used for E2E is OWD.

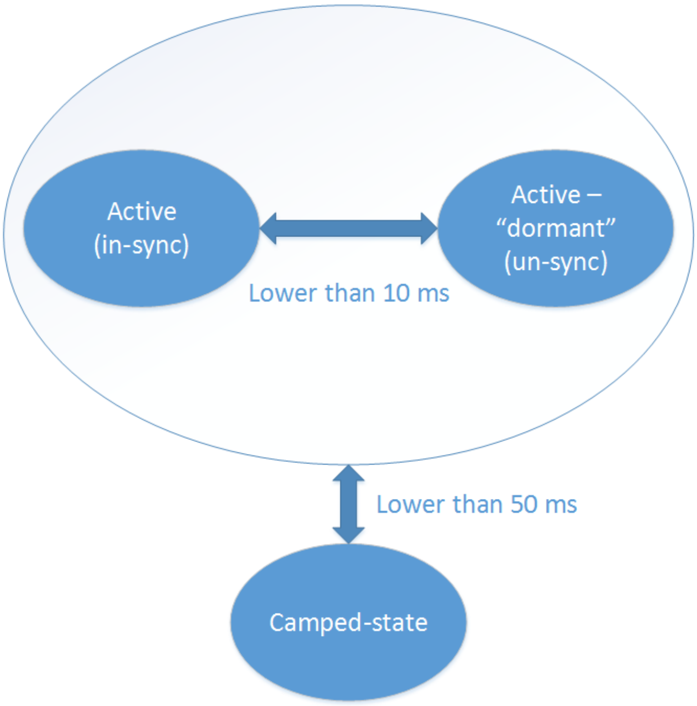

Figure 4. C-plan transition states [16].

Latency definitions for 5G:

- **C-plane latency**: C-plane latency is defined as the time gap for a UE to move from idle mode to active mode. The target value for C-plane latency in 5G is 10 ms [17].
- **U-plane latency:** Is defined as OWD to deliver an application layer packet from the radio protocol layer ingress point on the UE side to the egress point from the RAN side via the radio interface. For this definition both UL and DL are considered. The URLLC latency target for both UL and DL is 0.5 ms [17].
- **E2E latency:** 3GPP defines E2E latency as a time frame to transfer data from source to destination. It is measured at the application level from the time it is transmitted by the source to the time it is received at the destination [18].

Table 1. Comparison for C-plane and U-plane latency values in 4G and 5G.

Latency type	**4G**	**5G**
U-plane latency	5 ms [14]	0.5 ms [17]
C-plane latency	From camped to active state 50 ms [16] From active to active – “dormant” state 10 ms [16]	10 ms [17]

To conclude, a lot of different definitions are used in a various wireless communication systems standards, books and research papers and there is no common agreement or rule on using the latency definition. Due to this it is essential to clarify and explain the latency definition used in this thesis.

This thesis considers the total latency value to be RTT where the data packet is sent from the UE to the eNB, MPLS network and finally to the EPG and back to the UE (see Figure 5). This path is important for the telecommunication operator because from the end user standpoint, this RTT value ultimately guarantees the Quality of Experience (*QoE*) – the smaller the RTT value, the better the perceived experience for the costumer.

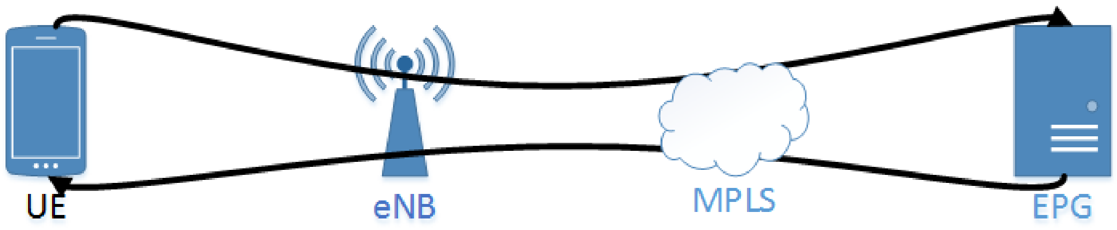

Figure 5. Path of the data packet used in this thesis to calculate the RTT value.

Service latency depends on the radio interface, transmission in the 5G System (*5GS*) and data processing. The radio interface depends on the 5GS, because it includes new 5G hardware in the radio interface layer. The transmission latency in 5G systems depends on 5G network architecture (NSA vs SA) and the corresponding interconnections. Data processing depends on the 5G hardware and the transmission setup. To reduce the service latency suitable interconnections between the 5G system and service layer must be deployed [3].

The estimated latency values for 5G are very low. To understand if the estimated values are archivable we should initially look at these from a physics point of view. One of the main marketing notions for 5G is URLLC and how this makes remote surgery possible in the future. The haptic feedback in remote surgery requires the RTT to be 10 ms or lower [19]. Let’s assume that a doctor is performing remote surgery in the United States and the patient is in Spain. To see if this kind of setup is feasible we will calculate the latency for it, based on optical cables only. The result will show whether 5G is usable for these kinds of scenarios. Figure 6 shows a submarine cable map where the red line shows the underwater optical cable route from the United States to Spain. This calculation is done using a typical single-mode fibre optical cable, E9/125/250, OS2 / G.652.D which is used inside the submarine cable. The specification for the optical cable used is shown in Table 2 [20]. The distance of the cable is 6605 km [21].

Table 2. Optical cable specification [20].

Optical Fiber Type	**Wavelength**	**Refractive Index**
Single-mode fiber, E9/125/250, OS2/G.652.D	1310 nm	1.4676

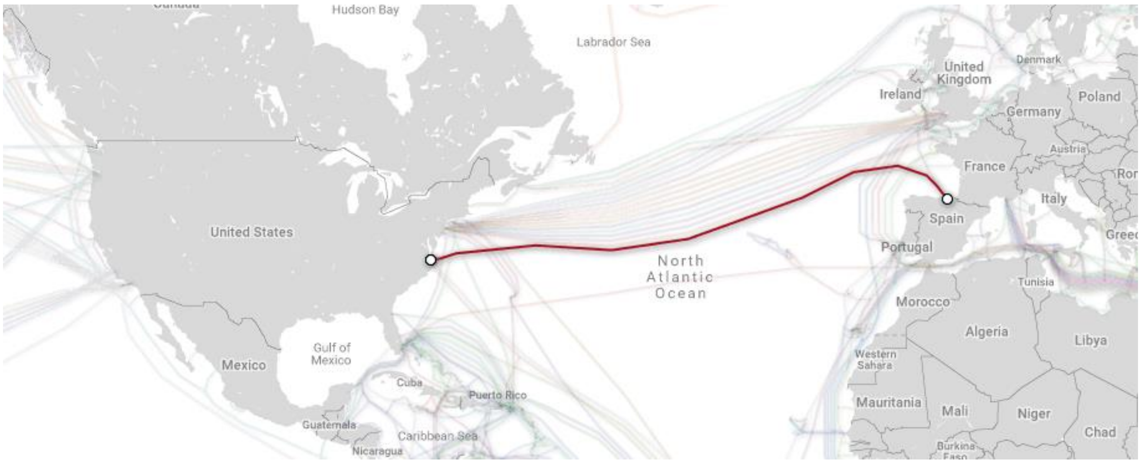

Figure 6. The submarine cable map showing the route from the United States to Spain [21].

To calculate the latency in the optical cable the following formula is used:

$$t_{fiber\_latency} = \frac{L}{c} \times n \text{ [17]}, \tag{1}$$

where L is the distance between the endpoints, c is the speed of light and n is the refractive index of the optical cable. The latency in one direction is calculated as:

$$t_{fiber\_latency} = \frac{6605000\ m}{3 \times 10^{8}\ \frac{m}{s}} \times 1.4676 \approx 32.3\ ms$$

To obtain the RTT value the previous result must be doubled thus giving a final value of 64.6 ms. Considering that the optical cable latency alone is 64.6 ms and we should add the delay of the 5GS to this value, it is clear that the RTT value of 10 ms cannot be achieved.

2.2 Research into latency reduction

Several research articles have discussed methods on how to reduce the latency in a 5G network. The research done in [22] shows how the required Time Division Duplex (TDD) latency can be achieved for the 5G physical air interface. To reduce the latency on the air interface, this paper proposes to use larger subcarrier spacing.

Paper [23] investigates how to reduce latency for the 5G CN while using Software Defined Networking (*SDN*) based solutions. As a result, this paper proposes a novel architecture based on SDN with reconfigurable control and data planes to reduce the E2E latency in the 5G CN.

The design principles and enabling technologies to deploy low latency in 5G has been done in [24]. The paper investigates the different latency components from the physical to the transport layer. Different methods on how to influence delay are discussed and three main technologies are proposed to support low latency: Multi-User Multiple-Input and Multiple-Output (*MU-MIMO*), millimeter wave and full duplex.

The research in [25] investigates how to use short processing time and short Transmission Time Interval (*TTI*) length for latency reduction. As a result, this paper proposes to restrict maximum Time Advance (*TA*) and Transport Block Size (*TBS*) to achieve short processing time. To shorten the TTI length, this work recommends using a 2-symbol TTI.

The goal of paper [26] is to investigate how to achieve high reliability, reduce the number of retransmissions and packet latency for a 5G network. As a result, this work presents an Interface-Aware Radio Resource (*IARR*) allocation algorithm which can reduce latency up to 10% compared to traditional schemes.

As discussed in the previous sections and mentioned in the first part of the thesis we can conclude that there are a limited number of research papers for URLLC use cases which consider the whole 5G system. This confirms the need to investigate the core topic of the thesis.

3 4G and 5G network architectures and the ITS use case

This thesis concentrates on latency values for the ITS use case and the goal is to measure the real-life values for the 4G network and simulate different scenarios for the ITS use case while using these obtained values:

- **From the UE to the eNB** – these values are found by simulating the V2V and V2I use case.
- **From the eNB to the CN** – these values are measured from the operators' 4G network.

Since the latter scenario involves measurements done in an existing 4G network and analysis is done for 5G, it is essential to understand the nature and architecture of both networks.

3.1 4G network architecture

The radio access network in 4G is called Evolved Universal Terrestrial Radio Access Network (*E-UTRAN*) which facilitates the wireless radio connection between the UE and the eNB. The three main parts for the radio infrastructure are the mobile terminals, the radio interface and the eNB. The 4G mobile terminals, in other words UE-s are all devices what support the LTE standard. The radio interface is the wireless connection between the eNB and the UE. The eNB-s are connecting mobile terminals via the radio interface to the CN. The Site Integration Unit (*SIU*) is a mobile site router which acts like a cell-site gateway. The main task of the SIU is to combine and optimize all traffic from different sites to be sent towards the backhaul, thus acting like a mobile site router and aggregation unit. The site switch is a switch between the SIU and the Multi-Protocol Label Switching (*MPLS*) switch. In a real network more than one SIU is connected to a single site switch, but to simplify the 4G network architecture in Figure 7, only one SIU is drawn. The MPLS core is a part of the mobile core and its task is to perform label switching for the incoming and outgoing packets.

MPLS is an advanced data forwarding method. All data packets are labelled with an MPLS header. Label Switch Routers (*LSR*) are MPLS routers which check the data packet labels and send them to the next LSR. The incoming label in LSR is replaced with an outgoing label depending on which is the most efficient data packet route. The data packet is then forwarded to the next LSR [27]. There are three types of LSR-s – ingress, egress and intermediate. The ingress LSR's task is to insert a label to the packet that is not labelled and then send it to a data link. The egress LSR's task is to remove the label from a previously labelled packet and send it to a data link. The intermediate LSR's task is to perform an operation for incoming labelled packets and send them to a correct data link. Often LSR-s are termed as Provider Edge (*PE*) routers and intermediate LSR-s as provider routers [28]. The 4G network architecture used in this thesis adopts the PE and provider terms instead of LSR and intermediate LSR. The MPLS switch is a switch which is a part of the MPLS core, and it sends the packets towards the MPLS core where packet labelling takes place as explained previously.

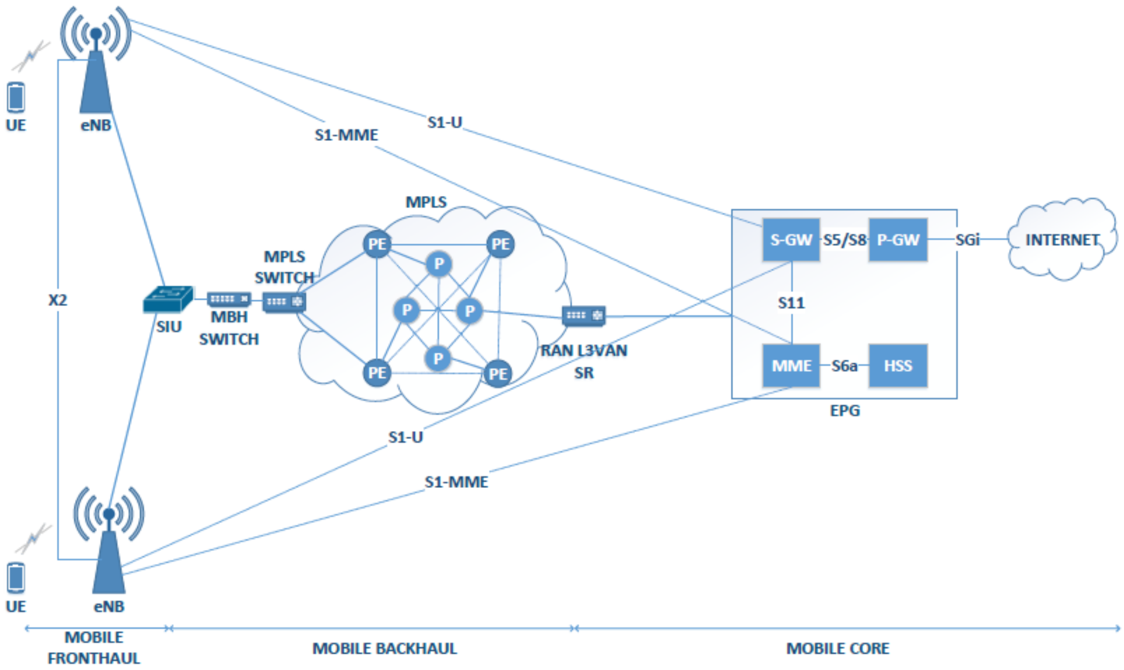

Figure 7. Simplified 4G network architecture.

The Evolved Packet Core (*EPC*), MPLS Service Router (*SR*) and internet are connected to the MPLS core. The EPC contains a S-GW, Packet Data Network Gateway (*PDN-GW*), Mobility Management Entity (*MME*) and a Home Subscriber Server (*HSS*). The MME is a control-plane node and its tasks are to handle security keys, manage the carrier's connections to the terminals and handle idle and active mode transitions. The MME is paging and tracking the UE in idle-mode. The S-GW is the user-plane node which connects the EPC with the E-UTRAN while transporting IP-data between the UE and external networks. The PDN-GW connects the EPC to the internet and allocates IP-addresses and prefixes to data packets. The PDN-GW also performs policy and charging control. The HSS is a database which contains the subscriber's information, it also supports mobility management, call and session setup and user authentication [29], [30].

3.2 5G network architecture

The 5G network architecture is named by 3GPP as a 5G system. It consists of three parts: the 5G Access Network (*5G AN*), the 5GC and the UE. The 5G AN is an access network which provides a connection between the NG-RAN or non-3GPP access network to the 5GC. The 5GC is a core network for 5G which is connected to the 5G-AN. The NG-RAN is a radio access network for 5G.

5G enables the option to integrate elements from various wireless communication generations in diverse configurations. The SA configuration contains only one radio access technology and the NSA combines multiple radio access technologies [31]. The configurations are as follows:

- **SA NR –** Next Generation Node B (*gNB*) is connected to the 5GC [32].
- **SA E-UTRA –** 4G Next Generation eNodeB (*ng-eNB*) is connected to the 5GC [32].
- **NR is the anchor with E-UTRA extensions –** the 5GC and NR gNB are used as masters and the 4G ng-eNB is an extension [32].
- **E-UTRA is the anchor with NR extensions –** the 5GC and 4G ng-eNB are used as masters and the NR gNB is an extension [32].

To conclude, the NG-RAN node can either be a gNB or an ng-eNB. The gNB connects the UE and NR U-plane and C-plane [33]. The NG, Xn and F1 are logical interfaces for the 5GC. In Figure 8 a connection between the NG-RAN and the 5GC is shown through the NG interface. A connection between the gNB-s is done using the Xn interface. The gNB consists of a gNB Control Unit (*gNB-CU*) and multiple gNB Distributed Units (*gNB DU*). The interface between the gNB CU and gNB DU is marked as F1 [34].

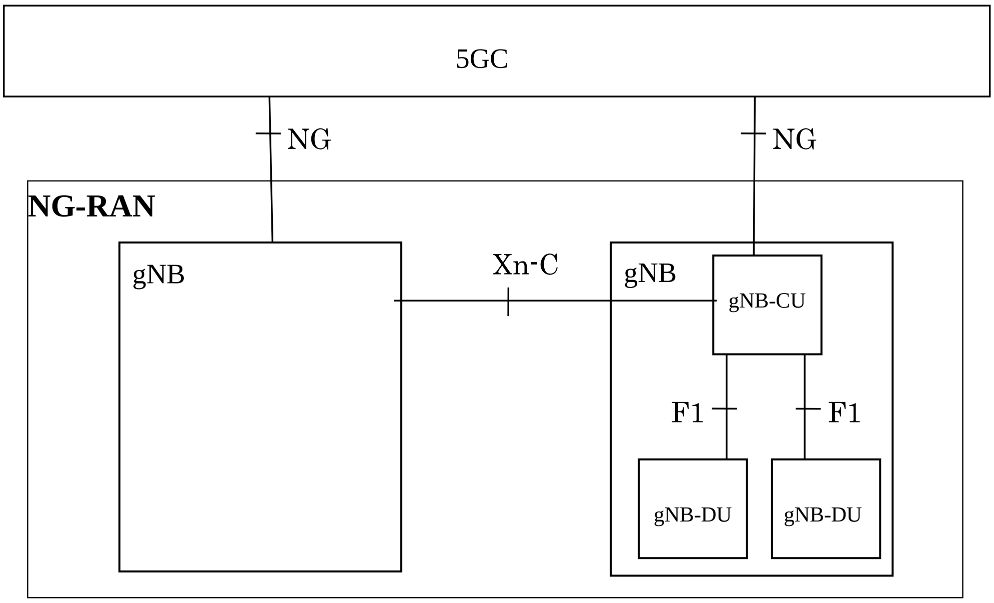

Figure 8. A helicopter view of 5G network [34].

3.3 The ITS use case

Although 3GPP states several use cases for NR URLLC, this thesis only considers one use case – the intelligent transport systems with a focus on V2X. ITS is defined by 3GPP as automation solutions created for the infrastructure which supports street-based traffic. This use case addresses several connections which are done in the road-side infrastructure e.g. how Road Side Units (*RSU*) relate to other infrastructure parts. To coordinate their movements and maneuvers, vehicles and RSU share their data with other vehicles nearby. 3GPP defines the RSU as a stationary infrastructure entity supporting V2X applications that can exchange messages with other entities supporting V2X applications [18].

In [35] 3GPP divides V2X scenarios into six subcategories which are: general aspects, vehicles platooning, advanced driving, extended sensors, remote driving and vehicle quality of service support. In the course of this thesis we are focused on advanced driving which enables semi-automated and fully automated driving.

The advanced driving use case group offers important benefits for the road users e.g. safer travelling, collision avoidance and improved traffic efficiency. The requirements to implement the previously mentioned benefits are stated in [18]. For this thesis only one scenario is under investigation – “cooperative collision avoidance between UE-s supporting V2X applications”. Performance requirements for this scenario are brought forth in Table 3 [18].

Table 3. Advanced driving performance requirements for a scenario used in this thesis [18].

Scenario description	**Payload (Bytes)**	**Tx rate (Message /Sec)**	**Maximum RTT latency (ms)**	**Reliability (%)**	**Data rate (Mbps)**
Cooperative collision avoidance between UEs supporting V2X applications	2000	100	20	99.99	10

Service requirements for V2X services which are supported by 4G are described in [35]. There are four V2X application types: V2V, V2I, Vehicle-to-Network (*V2N*) and Vehicle-to-Pedestrian (*V2P*) (see Figure 9).

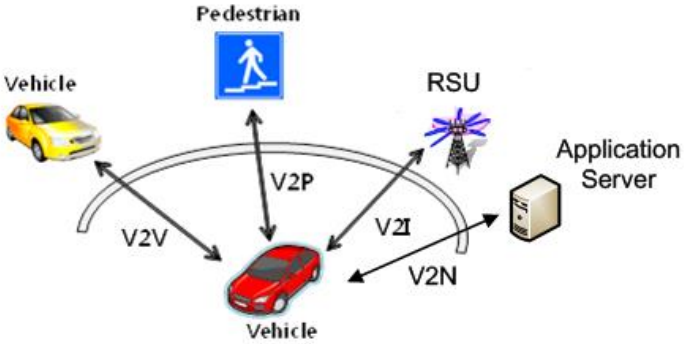

Figure 9. V2X application types [30].

For V2V applications it is expected that UE-s are near each other to transfer the application information. 3GPP states that UE-s need to have valid subscriptions and they must be authorized by the network operator to transport messages including V2V application information e.g. location, dynamics and attributes. Message transport between the UE-s is done directly or UE-s are directed, due to limited direct communication range, towards the infrastructure supporting V2X communication e.g. an RSU or application server. To transmit V2I messages the UE-s must support V2I applications [35].

For V2N applications UE-s which support V2N can communicate with an application server. For V2P applications the UE-s which are nearby share V2P information with each other, however 3GPP states that UE-s need to have valid subscriptions and must be authorized by the network operator to transport the corresponding messages. V2P application information is also transmitted by a UE which has V2X application support in a vehicle [35].

3GPP TR 22.185 [35] states four latency requirements for V2X applications (see Table 4).

Table 4. Latency requirements for V2X applications proposed by 3GPP [35].

Latency requirement description	**Latency value**
E-UTRAN shall be capable of transferring messages directly or via and RSU between two UE-s supporting V2V or V2P application.	100 ms
For use cases e.g. pre-crash sensing, the E-UTRAN shall be capable of transferring messages between two UE-s supporting V2V application.	20 ms
E-UTRAN shall be capable of transferring messages between RSU and UE supporting V2I application.	100 ms
E-UTRAN shall be capable of transferring messages via 3GPP network between a UE and an application server both supporting V2N application.	1000 ms

4 Simulations and results

This chapter expands upon the measurements and simulations done to estimate the total RTT value for a data packet sent by a UE in the 4G network and compare this value with a value obtained within the 5G network. This comparison shows whether the 4G network can fulfill the requirements set for the ITS use case in 5G. To find the total RTT value within the 4G network, the following RTT values need to be measured or simulated (see Figure 10) and then added.

1. **V2V RTT** – This value we will obtain by simulating a V2V use case in MATLAB.
2. **V2I RTT** – This value we will obtain by simulating a V2I use case in MATLAB.
3. **Transport + CN RTT** – This value we will measure from a live 4G network.

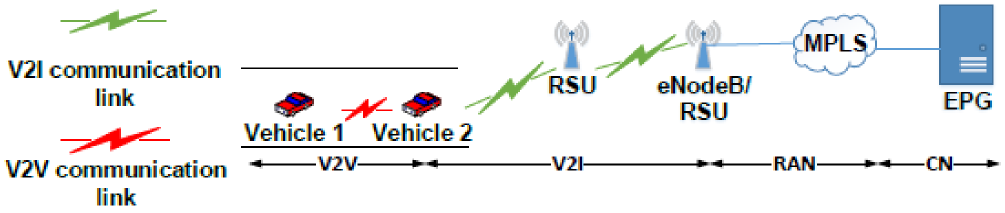

Figure 10. The different segments to estimate the total RTT value for the UE.

4.1 Simulation results

To find the RTT value for the V2I and V2V we are running simulations in MATLAB by using Vehicular Ad-Hoc Network (*VANET*) Toolbox [36]. Although the VANET Toolbox contains the RSU component, it is clarified during the simulation phase that this component is still under the development and therefore its functionalities cannot be used. We also studied other programs (open source) to be used for the simulations, however due to time and software development constrains, we decided to use a theoretical value. The theoretical RTT value used for V2I is proposed in [18] and it is 200 ms.

For obtain the RTT in the V2V scenario the VANET Toolbox is used for simulations [36]. VANET Toolbox is a MATLAB/Simulink based Discrete-Event System (*DES*) Vehicular network simulator. It is built based on the OSI-model for a vehicular network, which means that it contains an application, Medium Access Control (*MAC*) and physical layer. The application layer generates the message entity, in the MAC layer message entity is converted into a frame entity and from that a waveform entity is generated. This waveform entity is then sent to the physical layer. The physical layer is using a two-ray ground reflection model and an Additive White Gaussian Noise (*AWGN*) channel. From the physical layer the waveform is converted into a payload and then sent back to the MAC layer. From the MAC layer the payload is sent back to the application layer where it is received. The VANET Toolbox library is shown in Figure 11.

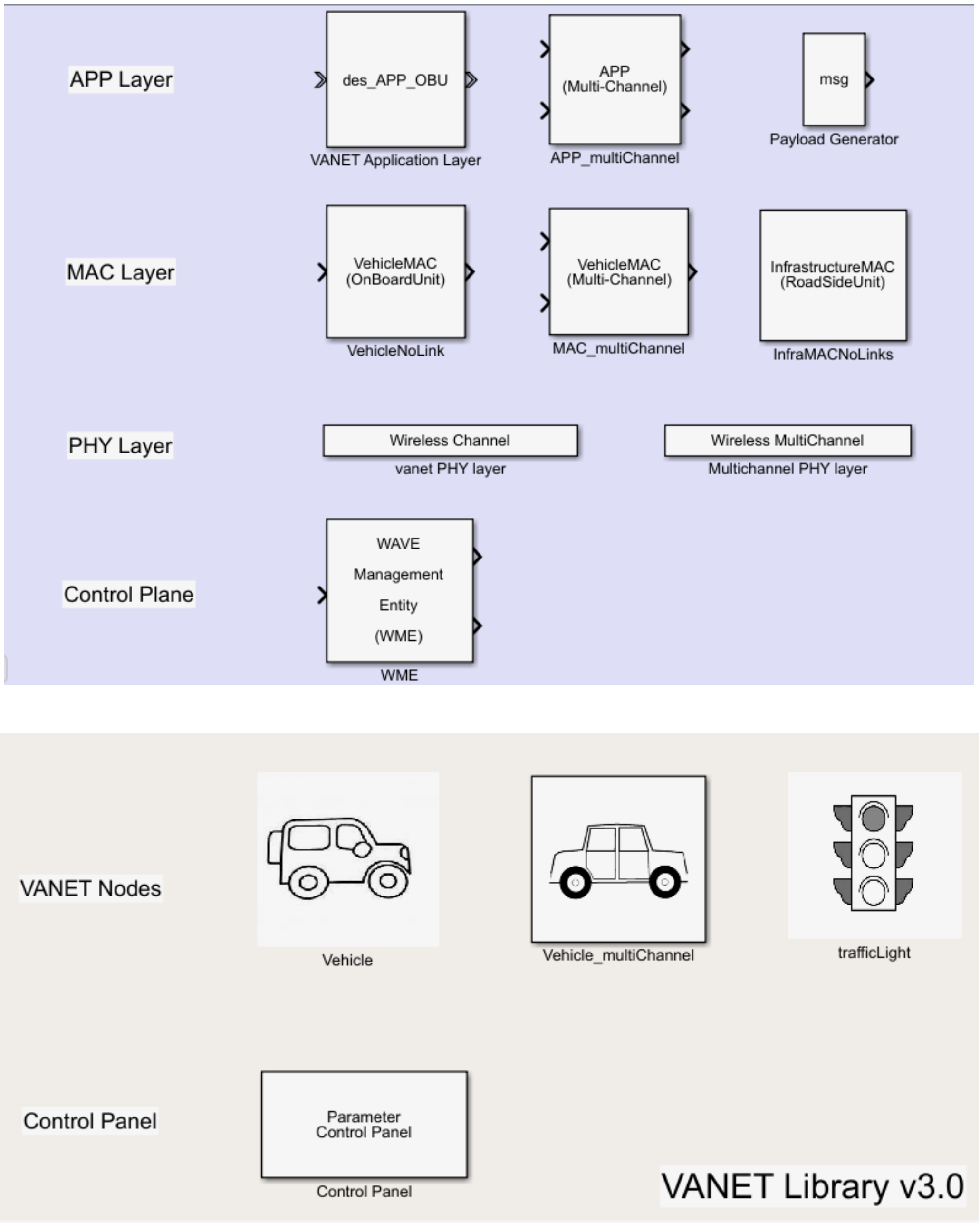

Figure 11. VANET Toolbox library [36].

From the VANET Toolbox library we are using suitable blocks to create our own simulation model. The respective model for the V2V scenario is shown in Figure 12. For the V2V simulation we are using two vehicles, a wireless channel and control panel blocks. The parameters used for the control panel and vehicles are as follows:

1. **Road type:** highway;
2. **Speed limit:** 90 km/h;
3. **Speed for vehicles 1 and 2:** 90 km/h.

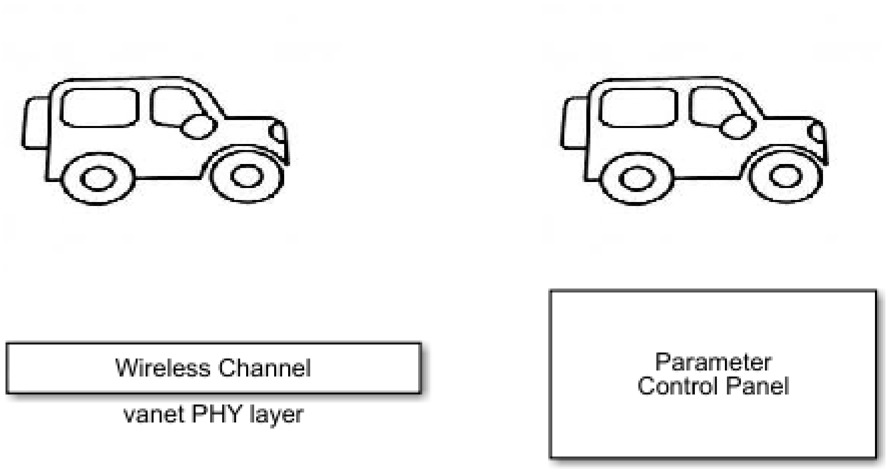

Figure 12. V2V Simulink model.

The essence of the V2V simulation is to generate a data packet in vehicle 1 and send it to vehicle 2 where that data packet is received successfully. The E2E latency is the time between sending and receiving the data packet. The simulation results in an E2E time of 1 ms which means that the RTT value is 2 ms. The log for this simulation is shown in Appendix 1.

4.2 Measurement results for the 4G network

To obtain the measurement results in the 4G network a pinging method is used. To collect the latency data, following three measurements are done as described in Table 5. Appendix 2 shows the pinging output for the three mentioned measurements and Table 6 shows the measurements results collectively.

Figure 13 shows which nodes are considered for the first measurement. We are using an eNB in Tabasalu which is an area near Tallinn. The measurement shows the latency value for the mobile core and the mobile backhaul. The red line represents the E2E path from the EPG to the eNB and the green line represents the E2E path from the eNB to the EPG. The RTT value for measurement 1 is 1.045 ms.

Table 5. The detailed description for the measurements in the 4G network.

Measurement number	**Start node**	**E2E target node**	**End node**	**Packet route between the nodes**
1	EPG	Tabasalu eNB	EPG	EPG→ L3VPN SR→ P4→ MPLS switch→ Mobile Backhaul (*MBH*) switch→ SIU→ Tabasalu eNB→ SIU→ MBH switch→ MPLS switch→ P4→ L3VPN SR→ EPG
2	EPG	Tartu eNB1	EPG	EPG→ L3VPN SR→ P4→ P1→ MPLS switch→ MBH switch→ SIU→ Tartu eNB→ SIU→MBH switch→ MPLS switch→ P1→ P4→ L3VPN SR→ EPG
3	L3VPN SR	EPG	L3VPN SR	L3VPN SR→ EPG→ L3VPN SR

Figure 14 shows which nodes are considered for the second measurement. We are using an eNB in Tartu which is a town in South-Estonia. The measurement shows the latency value for the mobile core and the mobile backhaul. The red line represents the E2E path from the EPG to the eNB and the green line represents the E2E path from the eNB to the EPG. The RTT value for measurement 2 is 4.956 ms.

Figure 15 shows which nodes are considered for the third measurement. The measurement result shows the latency value for the mobile core. The red line represents the E2E path from the Layer 3 Virtual Private Network (*L3VPN*) SR to the EPG and the green line represents the E2E path from the EPG to the L3VPN SR. The RTT value for this measurement is 0.24 ms. Low latency value in this scenario is expected because the packet is only sent via the L3VPN SR to the EPG, without sending it towards the mobile backhaul.

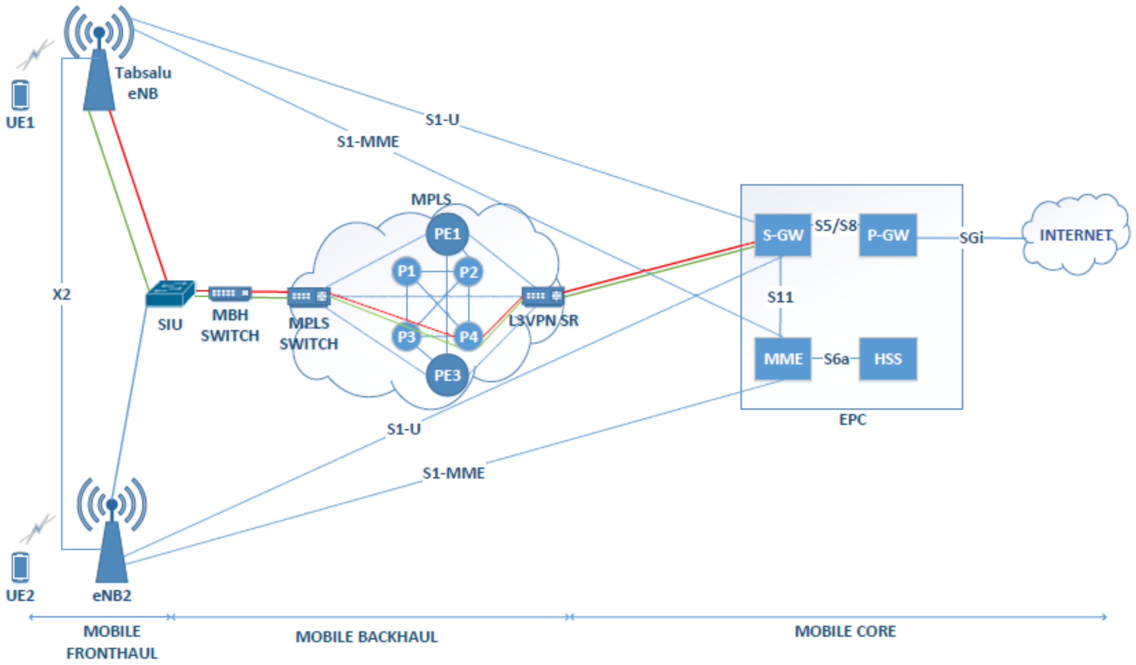

Figure 13. Measurement 1 – The RTT value measurement at Tabasalu eNB.

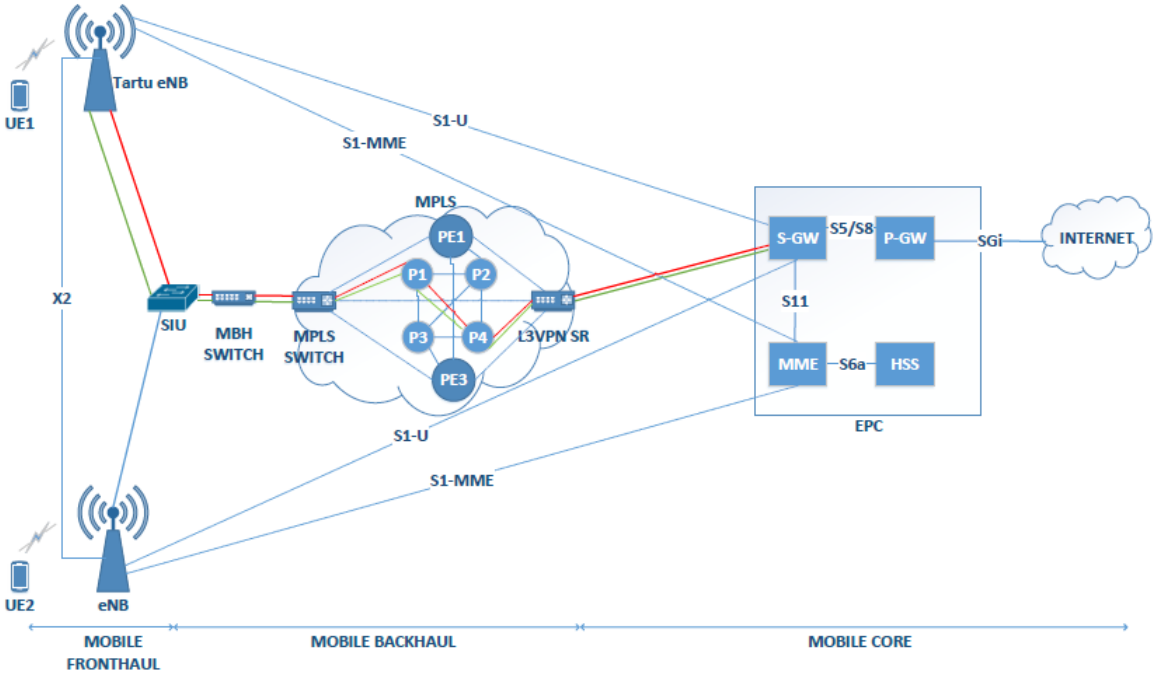

Figure 14. Measurement 2 – The RTT value measurement at Tartu eNB.

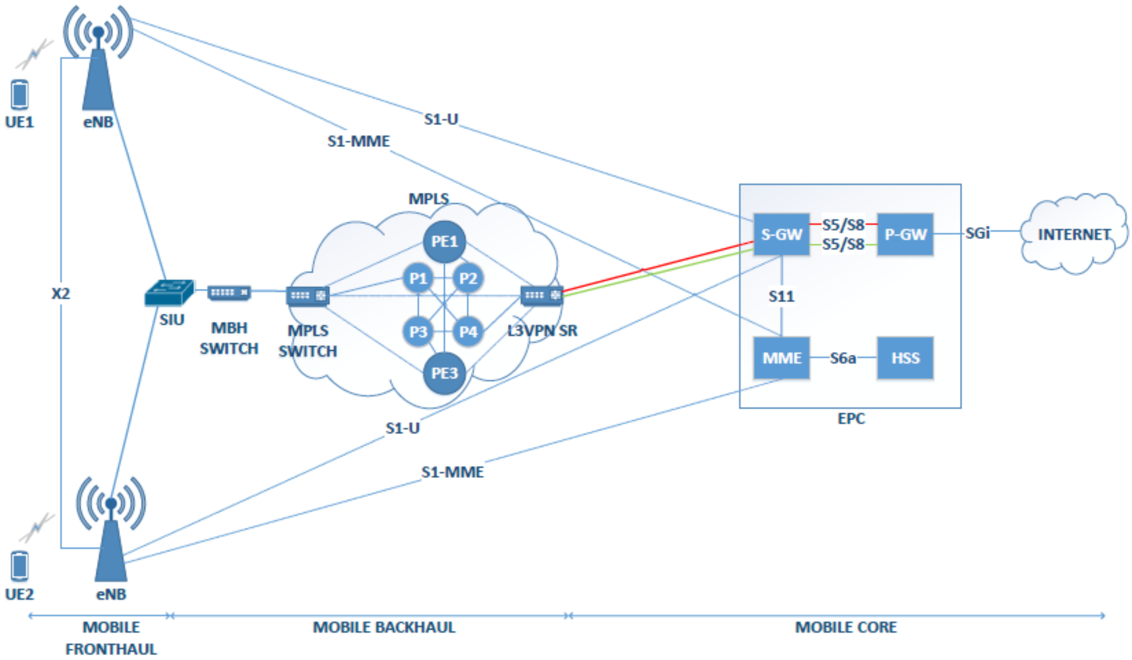

Figure 15. Measurement 3 – The RTT value measurement in the mobile core.

Table 6. The average RTT values for the three measurements.

Measurement number	**RTT average value/ms**
1	1.045 ms
2	4.956 ms
3	0.24 ms

4.3 RTT values for a UE in 4G and 5G

To find the total value of the RTT for the UE in the 4G and 5G network all the measured and simulated latency components are added. The results are shown in Table 7 and Table 8. Table 7 shows the total RTT values for the 4G and 5G network while using the eNB in Tartu which, from the core network point of view is the furthest eNB in our scenario. The data in table 8 is like that of Table 7, however the eNB is located in Tabasalu which is the nearest eNB in our scenario.

Table 7. The RTT values for the UE in the 4G and 5G network (furthest eNB is used).

	4G	5G
V2V RTT	2 ms	20 ms
V2I RTT	200 ms	200 ms
Transport + CN RTT	5.196 ms	5.196 ms
UE RTT	**207.196 ms**	**225.196 ms**

Table 8. The RTT values for the UE in the 4G and 5G network (nearest eNB is used).

	4G	**5G**
V2V RTT	2 ms	20 ms
V2I RTT	200 ms	200 ms
Transport + CN RTT	1.285 ms	1.285 ms
UE RTT	**203.285 ms**	**221.285 ms**

Following the measurements and simulations done and based on the data presented in Tables 7 and 8 the subsequent conclusions and notions must be emphasized:

- The total RTT value for UE in 4G and 5G networks is roughly equal considering that the simulation results found in Chapter 4.1 for V2V only considers two vehicles, which means that it does not consider the traffic density aspect. The traffic density cannot be considered for the simulations done in 4G because there is no detailed description in [18] for the traffic density requirement. The RTT given for 5G is currently 20 ms and this value is theoretical.
- The V2I RTT values are theoretical which are proposed by 3GPP.
- The used transport and core RTT values are identical since there is no separate transport network build for 5G. The transport architecture built for 4G is applicable for 5G since the data volumes in 5G are virtually non-existing.

- There are very few simulation tools which can be used for 5G and these are mostly still under development.
- In case of V2V the wireless communication network is insignificant.
- All the measurements done, and results obtained only apply for the use case considered in this thesis. For any other use case the total RTT value for the UE cannot be obtained based on these measurement results due to different requirements stated for each use case.

5 Conclusions and future work

5G is the next generation in wireless communications which is standardized by the 3GPP and it will pave the way for significant improvements compared to 4G in terms of data rates, latency, massive connectivity and energy efficiency. 5G is not an incremental improvement over 4G, but rather it facilitates an exponential growth in the evolution of wireless communication systems.

Since the standardization work for 5G is still ongoing, an overview of 5G standardization activities was given in the first part of the thesis. Only documents published by standardization organizations before January 2019 were considered.

The focus of this thesis was on URLLC within an ITS use case. The specific use case chosen was called “Cooperative collision avoidance between UEs supporting V2X applications” where the E2E latency defined by 3GPP was 10 ms.

The reason why ITS was discussed in this thesis was the interest of a telecommunication operator since there are a lot of estimations for latency reduction in research papers without practical testing. A corresponding analysis of existing research papers revealed that there are only a limited number of papers for URLLC use cases which consider the complete 5G system (UE, RAN, transport, core). The objective was to investigate both the 4G and 5G networks and estimate whether a 5G network is really needed for the mentioned use-case or can it also be realized on 4G.

In Chapter 2 the definition of latency in 4G and 5G networks was discussed. Many different definitions are used in various wireless communication systems standards, books and research papers and there is no common agreement or rule on using this term. This thesis considered the total latency value to be the RTT. Since the goal of the thesis was to compare specific values obtained in 4G and 5G networks, the corresponding network architectures were elaborated upon in Chapter 3.

Measurements and simulations were done in Chapter 4 to estimate the total RTT value in the 4G network and compare this value with a value obtained within the 5G network. Simulation and measurement results were found for V2V communication and for the 4G CN. The rest of the RTT values used in calculations were theoretical.

The RTT value for the V2V scenario was found by running simulations in MATLAB, using the VANET Toolbox. Although the VANET Toolbox contains the RSU component (needed to simulate the V2I scenario), it was clarified during the simulation phase that this component is still under development and therefore its functionalities could not be used. After a study of different simulation programs, we saw that there are very few simulation tools which can be used for 5G and all of these are still mostly under development. The theoretical RTT value used for V2I communication was proposed in [18] and it was 200 ms. The simulation results for V2V resulted in an RTT value of 2 ms.

To obtain the measurement results for the RTT values in the 4G network, input from a telecommunication operator was used in the form of pinging. To get the total value of the RTT for the UE in the 4G and 5G network we added all the measured and simulated latency components and two results were presented: for the furthest (Tartu) and nearest (Tabasalu) eNB. In the case of Tartu, the RTT value for 4G was 207.196 ms and for 5G 225.196 ms. For Tabasalu, the RTT values for 4G and 5G were 203.285 ms and 221.285 ms respectively. Hence, the total RTT values for the UE in both networks was roughly equal. It is important to note however that the simulation results found in Chapter 4.1 for V2V only considered two vehicles, which means that the traffic density aspect was neglected. The traffic density was not considered for the simulation results because no detailed information for traffic density requirements was given in [18].

The used transport and core RTT values were identical since there is no separate transport network built for 5G. The transport architecture built for 4G is currently applicable for 5G since the data volumes in 5G are virtually non-existing.

Considering the results of this thesis, we must assert that all the results obtained only apply for the specific use case considered. For any other use case the total RTT value for the UE cannot be obtained based on these measurement results due to different requirements stated for each use case.

Additionally, we can state that based on the results which considered the available 5G standards until the end of 2018, there is no clear difference whether the investigated ITS use case is implemented on a 4G or 5G network.

Considering the results presented we see that further investigation is needed in the following areas:

- Development of simulation programs for the complete 5G system environment to investigate the 5G URLLC ITS use cases in more detail.

- As demonstrated in the thesis, the air interface had the highest latency values. This means that continued work is needed to elaborate on methods for latency reduction in the RAN. Additionally, it is crucial to start integrating these methods into live 5G networks.

- For the V2V communication scenario, further investigation regarding traffic density is needed to clarify if and how much it will impact the latency values.

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Appendix 1 – V2V simulation log

```
T= 5500.001ms,  node1: frame56 generated.
T= 5500.001ms,  node1: frame56 forwarded AC2
T= 5500.001ms,  node1:  frame56(AC2) sense idle channel, defer
access AIFS_AC2 0.071ms
T= 5500.002ms,  node2: frame56 generated.
T= 5500.002ms,  node2: frame56 forwarded AC2
T= 5500.002ms,  node2:  frame56(AC2) sense idle channel, defer
access AIFS_AC2 0.071ms
T= 5500.072ms,  node1:  Frame 56(AC2) listen idle
channel,backoff 4 timeslots;
T= 5500.072ms,  node1-------AC2 Backoff left:4----------
T= 5500.073ms,  node2:  Frame 56(AC2) listen idle
channel,backoff 3 timeslots;
T= 5500.073ms,  node2-------AC2 Backoff left:3----------
T= 5500.085ms,  node1-------AC2 Backoff left:3----------
T= 5500.086ms,  node2-------AC2 Backoff left:2----------
T= 5500.098ms,  node1-------AC2 Backoff left:2----------
T= 5500.099ms,  node2-------AC2 Backoff left:1----------
T= 5500.111ms,  node1-------AC2 Backoff left:1----------
T= 5500.112ms,  node2-------AC2 Backoff left:0----------
T= 5500.112ms,  node2,  select destination: node 0
T= 5500.112ms,  node2:  waveform56 sent.
T= 5500.112ms, <---Channel--->: New Data waveform from node2
received.
T= 5500.124ms,  node1-------AC2 Backoff left:0----------
T= 5500.124ms,  node1:  frame56(AC2) sense busy channel, listen
to another slottime 0.013ms
T= 5500.137ms,  node1:  frame56(AC2) sense busy channel, listen
to another slottime 0.013ms
T= 5500.15ms,  node1:  frame56(AC2) sense busy channel, listen
to another slottime 0.013ms
T= 5500.163ms,  node1:  frame56(AC2) sense busy channel, listen
to another slottime 0.013ms
T= 5500.176ms,  node1:  frame56(AC2) sense busy channel, listen
to another slottime 0.013ms
T= 5500.189ms,  node1:  frame56(AC2) sense busy channel, listen
to another slottime 0.013ms
T= 5500.202ms,  node1:  frame56(AC2) sense busy channel, listen
to another slottime 0.013ms
T= 5500.215ms,  node1:  frame56(AC2) sense busy channel, listen
to another slottime 0.013ms
T= 5500.228ms,  node1:  frame56(AC2) sense busy channel, listen
to another slottime 0.013ms
T= 5500.241ms,  node1:  frame56(AC2) sense busy channel, listen
to another slottime 0.013ms
T= 5500.254ms,  node1:  frame56(AC2) sense busy channel, listen
to another slottime 0.013ms
T= 5500.267ms,  node1:  frame56(AC2) sense busy channel, listen
to another slottime 0.013ms
T= 5500.28ms,  node1:  frame56(AC2) sense busy channel, listen
to another slottime 0.013ms
```

```
T= 5500.293ms,  node1:  frame56(AC2) sense busy channel, listen
to another slottime 0.013ms
T= 5500.306ms,  node1:  frame56(AC2) sense busy channel, listen
to another slottime 0.013ms
T= 5500.319ms,  node1:  frame56(AC2) sense busy channel, listen
to another slottime 0.013ms
T= 5500.332ms,  node1:  frame56(AC2) sense busy channel, listen
to another slottime 0.013ms
T= 5500.345ms,  node1:  frame56(AC2) sense busy channel, listen
to another slottime 0.013ms
T= 5500.358ms,  node1:  frame56(AC2) sense busy channel, listen
to another slottime 0.013ms
T= 5500.371ms,  node1:  frame56(AC2) sense busy channel, listen
to another slottime 0.013ms
T= 5500.384ms,  node1:  frame56(AC2) sense busy channel, listen
to another slottime 0.013ms
T= 5500.397ms,  node1:  frame56(AC2) sense busy channel, listen
to another slottime 0.013ms
T= 5500.41ms,  node1:  frame56(AC2) sense busy channel, listen
to another slottime 0.013ms
T= 5500.423ms,  node1:  frame56(AC2) sense busy channel, listen
to another slottime 0.013ms
T= 5500.436ms,  node1:  frame56(AC2) sense busy channel, listen
to another slottime 0.013ms
T= 5500.449ms,  node1:  frame56(AC2) sense busy channel, listen
to another slottime 0.013ms
T= 5500.462ms,  node1:  frame56(AC2) sense busy channel, listen
to another slottime 0.013ms
T= 5500.475ms,  node1:  frame56(AC2) sense busy channel, listen
to another slottime 0.013ms
T= 5500.488ms,  node1:  frame56(AC2) sense busy channel, listen
to another slottime 0.013ms
T= 5500.501ms,  node1:  frame56(AC2) sense busy channel, listen
to another slottime 0.013ms
T= 5500.5056ms,  node1:  receives 1 data.
T= 5500.5056ms,  node1: frame 56 received from broadcast
correctly!  No ACK needed.
Vehicle 1 at lane<1> receives BSM from car 2 at lane<1>
acceleration 5.5556
T=5500.5056ms. car1 at 180 0 detect car 2 at 136.5092 0
CAR 1 carFollowingMode at speed of 90
T=5500.5056ms: vehicle1is 990 meters to front car0> brake
distance 64.8269at speed of 90
T= 5500.514ms,  node1:  frame56(AC2) sense idle channel, defer
access AIFS_AC2 0.071ms
T= 5500.585ms,  node1: frame 56 resumes backoff!
T= 5500.585ms,  node1-------AC2 Backoff left:0----------
T= 5500.585ms,  node1,  select destination: node 0
T= 5500.585ms,  node1:  waveform56 sent.
T= 5500.585ms, <---Channel--->: New Data waveform from node1
received.
T= 5500.9786ms,  node2:  receives 1 data.
T= 5500.9786ms,  node2: frame 56 received from broadcast
correctly!  No ACK needed.
```

Appendix 2 – Pinging output results for LTE network RTT latency measurements

```
#L3VPN-router - EPG ping

L3VPN-router# ping router "RAN" 10.70.117.193 source
10.70.113.139 count 10
PING 10.70.117.193 56 data bytes
64 bytes from 10.70.117.193: icmp_seq=1 ttl=254 time=0.241ms.
64 bytes from 10.70.117.193: icmp_seq=2 ttl=254 time=0.243ms.
64 bytes from 10.70.117.193: icmp_seq=3 ttl=254 time=0.240ms.
64 bytes from 10.70.117.193: icmp_seq=4 ttl=254 time=0.238ms.
64 bytes from 10.70.117.193: icmp_seq=5 ttl=254 time=0.260ms.
64 bytes from 10.70.117.193: icmp_seq=6 ttl=254 time=0.243ms.
64 bytes from 10.70.117.193: icmp_seq=7 ttl=254 time=0.241ms.
64 bytes from 10.70.117.193: icmp_seq=8 ttl=254 time=0.238ms.
64 bytes from 10.70.117.193: icmp_seq=9 ttl=254 time=0.243ms.
64 bytes from 10.70.117.193: icmp_seq=10 ttl=254 time=0.241ms.

---- 10.70.117.193 PING Statistics ----
10 packets transmitted, 10 packets received, 0.00% packet loss
round-trip min = 0.238ms, avg = 0.242ms, max = 0.260ms, stddev =
0.006ms

#EPG - Tabasalu eNB1 ping

EPG#ping 10.72.232.9 10 verbose
PING 10.72.232.9 (10.72.232.9): source 10.70.113.136, 36 data
bytes,
timeout is 1 second
44 bytes from 10.72.232.9: icmp_seq=0 ttl=254 time=1.097 ms
44 bytes from 10.72.232.9: icmp_seq=1 ttl=254 time=1.044 ms
44 bytes from 10.72.232.9: icmp_seq=2 ttl=254 time=1.022 ms
44 bytes from 10.72.232.9: icmp_seq=3 ttl=254 time=1.106 ms
44 bytes from 10.72.232.9: icmp_seq=4 ttl=254 time=1.028 ms
44 bytes from 10.72.232.9: icmp_seq=5 ttl=254 time=1.036 ms
44 bytes from 10.72.232.9: icmp_seq=6 ttl=254 time=1.056 ms
44 bytes from 10.72.232.9: icmp_seq=7 ttl=254 time=1.005 ms
44 bytes from 10.72.232.9: icmp_seq=8 ttl=254 time=1.045 ms
44 bytes from 10.72.232.9: icmp_seq=9 ttl=254 time=1.015 ms

----10.72.232.9 PING Statistics----
10 packets transmitted, 10 packets received, 0.0% packet loss
round-trip min/avg/max/stddev = 1.005/1.045/1.106/0.033 ms


#EPG - Tartu eNB1 ping

EPG#ping 10.72.234.10 10 verbose
PING 10.72.234.10 (10.72.234.10): source 10.70.113.136, 36 data
bytes,
timeout is 1 second
44 bytes from 10.72.234.10: icmp_seq=0 ttl=63 time=5.128 ms
```

```
44 bytes from 10.72.234.10: icmp_seq=1 ttl=63 time=4.881 ms
44 bytes from 10.72.234.10: icmp_seq=2 ttl=63 time=4.868 ms
44 bytes from 10.72.234.10: icmp_seq=3 ttl=63 time=4.842 ms
44 bytes from 10.72.234.10: icmp_seq=4 ttl=63 time=4.877 ms
44 bytes from 10.72.234.10: icmp_seq=5 ttl=63 time=4.954 ms
44 bytes from 10.72.234.10: icmp_seq=6 ttl=63 time=4.980 ms
44 bytes from 10.72.234.10: icmp_seq=7 ttl=63 time=4.929 ms
44 bytes from 10.72.234.10: icmp_seq=8 ttl=63 time=4.910 ms
44 bytes from 10.72.234.10: icmp_seq=9 ttl=63 time=5.188 ms


----10.72.234.10 PING Statistics----
10 packets transmitted, 10 packets received, 0.0% packet loss
round-trip min/avg/max/stddev = 4.842/4.956/5.188/0.115 ms
```