Master’s Thesis

3GPP LTE vs. IEEE 802.11p/WAVE: Competition or Coexistence?

By

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Abstract

The cooperative awareness messages referred to as Beacons in intelligent transport systems enable the cooperative safety applications. These safety applications require strict beacon delay and highly reliable communication of beacons. The technology that has already been designed for vehicular communications is IEEE 802.11p/WAVE, this technology has some technical shortcomings in terms of beacon delay and beacon loss ratio at congested traffic scenarios. The shortcomings of WAVE open the door to testing new wireless communication technologies for vehicular communications. The best available commercially launched wireless communication technology right now is 3GPP LTE. In comparison to WAVE, the fundamental difference of LTE is that it is an infrastructure based technology. In this thesis, we are going to test the performance of LTE and WAVE in a rural highway traffic scenario. The evaluations are done on the basis of supporting the strict cooperative vehicular safety applications in terms of beacon delay and beacon loss ratio. The simulations for both LTE and WAVE model for vehicular communications are done in NS-3. The effect of beaconing frequency and beacon size on the network is also analyzed. On the basis of our simulation results, a comparative analysis was done between LTE and WAVE. Our conclusion is that, although LTE has performed better than WAVE, its primary responsibility is wireless telephony, therefore it is not wise to completely eradicate WAVE, so the best possible solution for the vehicular safety application support would be coexistence of LTE and WAVE.

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CHAPTER 1

1 Introduction

The last decade can arguably be classified as the most extraordinary decade of development of Science and technology, especially in the fields of wireless and mobile communications. The exponential growth of the number of cellular phone users has changed the social fabric of society and now the effect of this great technological boom can now be seen on different industries e.g. entertainment, advertising, automotive. In the automotive industry more and more research is in process to improve the safety features of vehicular transportation by the use of wireless communication technology. This has given birth to a new concept called Intelligent Transport Systems (ITS) which involves; the utilization of synergistic technologies and systems engineering concepts to develop and improve the transportation systems of all kinds [1]. ITS basically combines and gathers all the information about each vehicle and road environment in one network. Nowadays vehicle already have complicated electronic systems with a number of different computers installed in them on-board. For the implementation of ITS the additional wireless communication system is required to be installed on vehicles which will enable them to exchange the information with each other within the vicinity of communication range. The most important advantage of this system would be the enhancement of automotive cooperative safety applications e.g. collision avoidance, emergency brakes [2].

1.1 Overview of WAVE for Vehicular Communication

The field of vehicular communication which falls under the umbrella of ITS is being dominated by the vehicle to vehicle (V2V) communication which is based on the IEEE standard 802.11p/1609 WAVE (Wireless Access in Vehicular Environment), it inherited the features of WLAN with some new properties to sustain the vehicular environment. Direct Short Range Communications (DSRC) standard frequency band of 5.85 to 5.89 GHz is being assigned for WAVE. This standard 802.11/p is specifically designed for the ITS communication but still there are some technical, social and economical issues. Therefore, it has been the topic of continuous and vigorous research and discussion among academia and industry [3]. One important technical feature of WAVE is that it has no central server or node so the network management is difficult and the economical perspective is, it requires infrastructure in place before being commercially launched.

1.2 Overview of LTE for Vehicular Communication

The economical and technical limitations of WAVE leads to look for the new technology for vehicular communication and the best contender right now is latest cellular technology LTE (Long Term Evolution) developed by 3GPP (3rd Generation Partnership Project). One of the benefits of LTE is the high mobility support for its users, so it suits very much vehicular communications. From an economic point of view this cellular network infrastructure is already present and deployed on the ground and its devices are easily available in the market. On the technical aspect the LTE features include high data rate, accommodation of a greater number of users in cell, larger coverage area of cell, low latency etc. these mentioned technical features are very important for the cooperative safety applications of vehicular communication. The architecture of LTE is certainly very different from 802.11p as in the access network it has a centralized node called Evolved Node B (eNB) which communicates with all the User Equipments (UEs) within the coverage area of the cell and on the backhand the eNB is connected to the core network called Evolved Packet Core (EPC), so with this kind of centralized network the management of the network is much easier. Figure 1depicts the basic architecture of LTE, the detail analysis of the LTE architecture will be discussed in later chapters.

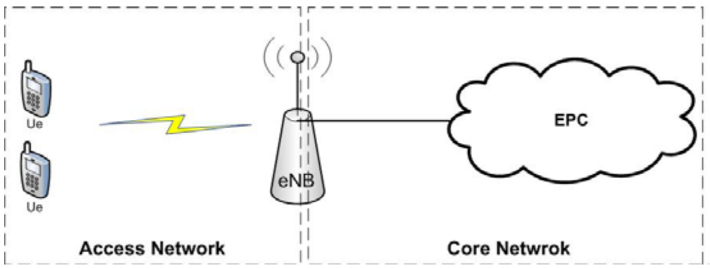

Figure 1. Basic LTE Architecture

Multiple operating frequency bands are dedicated to LTE which vary from region to region; in Europe the frequency bands of 800, 900, 1800, 2600 MHz are dedicated for the LTE. So the mentioned operating frequency bands give the edge to LTE over WAVE as 5.9 GHz band of WAVE is a relatively high frequency band when compared to LTE frequency band and it is known that high frequency bands have low penetration power and it required line of sight communication for optimum performance, therefore LTE due to the lower operating frequency band performs better than WAVE in non-line of sight condition between transmitter and receiver. On the other hand the communication pattern in WAVE is more direct i.e. V2V which is very helpful in maintaining the low latency while in LTE the communication pattern is V2I (Vehicle to Infrastructure) since the vehicle sends the information to a central server or node and then this central node will transmit the information to the dedicated receiving vehicle. Therefore LTE is still needed to be researched and discussed more under the different traffic scenarios for the ITS applications before finally approving it for the vehicular communication.

1.3 Goal of the Thesis

The above discussion between LTE and WAVE proves that LTE does have technological edge over WAVE and its functionalities are very good for vehicular communications, which enable us to test LTE for vehicular communications. The main goal of our thesis is to evaluate the performance of both LTE and WAVE in relation to the strict requirements of vehicular safety applications. Furthermore the effect of different network work parameters will also be analyzed. The main goal of the thesis can be redefined in the following research question:

- Which technology (3GPP LTE or IEEE 802.11p/WAVE) is able to support vehicular safety applications?

The following analytical research questions will lead us to the main goal of our thesis:

- What is the effect of beaconing frequency in LTE and WAVE?
- What is the effect of beacon packet size in LTE and WAVE?
- What percentage of beacons can fulfill the strict delay requirement of cooperative safety application?

The above mentioned research questions will help us to conclude the coexistence or competition of the two technologies for vehicular communication with respect to cooperative vehicular safety applications.

In our thesis project we will analyze the working of the above mentioned technologies for the highway traffic scenario. The main exclusive point of this thesis is that cellular technology LTE is being first time ever simulated for the vehicular communication scenario in the discrete event networking communication tool called Network Simulator – 3 (NS-3). The simulations has included complete communication pattern i.e. downlink and uplink transmission. The research provides the simulation framework which compares the features of both the technologies (LTE and WAVE) regarding the automotive cooperative safety applications under the different network parameters.

1.4 Organization of the Report

The rest of the report is structured as follows; In Chapter2 overview of related background work along with the literature study is presented about the topics related to the thesis which includes ITS, LTE and WAVE. In Chapter3, simulation scenario is explained along the introduction of NS-3 simulator and especially the LTE design in the simulator is discussed in detail with the system model of our simulation. The Chapter4 deals with all the results of our simulations and their detail analysis to find out the answers of our research questions. In Chapter5 the conclusions have been drawn on the basis of simulation results and the future work has been proposed.

1.5 Organization of Responsibilities

Throughout the thesis both team members have worked in close coordination with each other. The responsibilities were defined in such a way that Syed Muhammad Asif Qamar was more focused on the theoretical literature review, designing the test environment and result analysis while Zoraze Ali main area of responsibilities includes implementation in NS-3 by using C++ programming language, executing the simulations and troubleshooting the error and bugs in NS-3. It is also important to highlight that both of us kept helping each other in the execution of our responsibilities and at sometimes even swap responsibilities between each other, so this thesis is the result of diligent team work. As far as the report writing is concerned the introduction, literature review and performance evaluation chapters are compiled by Asif and the system modeling chapter is compiled by Zoraze. In the end the report was edited by both of us according to the instructions of supervisor and examiner.

CHAPTER 2

2 Literature Review

In recent years lots of work is done in the field of vehicular communications, especially in enhancing and testing the different features of vehicular cooperative safety applications. The cooperative applications have always been associated with WAVE/ 802.11p, as in [4] three different safety applications are evaluated by testing WAVE in different real world scenarios and it shows that at high speed of vehicles and at congested traffic scenarios the WAVE still needs advancement in communication techniques to cope with the extreme requirements of cooperative safety applications. Throughput, packet delay and collision probability are the important parameters on the basis of which WAVE is evaluated in [5] and it shows again that in a high number of user scenarios the packet delay increases a lot and throughput decreases which is not good for cooperative safety application. So the limitations in WAVE give the idea to test the cellular networking technologies for the vehicular communication. Third generation communication technology Universal Mobile Telecommunication System (UMTS) communication properties is being tested for inter vehicular communication and the findings shows that latency or message delivery time is not up to the requirements of safety applications in [6]. Now the focus is on fourth generation technology LTE and there is very little research available in which LTE is being analyzed for vehicular communication, the most recent research we find is [7] where different downlink scheduling strategies of LTE is evaluated for vehicle to infrastructure communication and the primary evaluation criteria is packet delay from eNB to UE and the secondary is packet loss ratio, and the simulations are done in simulator called LTE-Sim, so this paper [7] specifically deals with the downlink communication only and delay in the uplink communication is not accounted. The other research papers which deal with the topic of LTE for vehicular communication are [8] and [9]. In [8] the performance study on cooperative vehicular services with LTE is presented and the research shows that the capacity of the LTE network is directly affected by downlink data channel because of the periodic transmission of awareness messages. But contradictory to the results in [8] the research [9] focuses on the uplink transmission and concluded that uplink transmission is the bottleneck of the network. Radio Network simulator a propriety tool by Ericsson is used for the LTE simulations in [8] while in [9] the author has used his own simulator developed in Delphi programming language.

2.1 Intelligent Transport Systems (ITS)

The phenomenon of accumulating different telecommunications and information technologies to transport infrastructures and vehicles in an effort to enhance the quality, efficiency, reliability and above all safety is called Intelligent Transport Systems (ITS). ITS services also covers the area of better and optimized fuel consumption, since the energy requirements are increasing in today's world and the resources of energy are stretched to limits and new research efforts are in process to find the new and renewable energy sources, so in this environment of less and expensive energy resources ITS plays a vital role in better and optimum fuel consumption. The improvement of ITS and the terms of subsequent services are not limited to the road transport only, but it includes other domain of transportation industry such as maritime, railways and aviations. The diverse types of ITS rely on wireless and radio communication technologies [10]. The complete range of ITS communication is shown in Figure 2.

In our thesis the focus will be on the Cooperative ITS, since in C-ITS vehicles communicate with each other directly (vehicle to vehicle/V2V) or through the infrastructure (vehicle to infrastructure/V2I) which tremendously enhances the quality and reliability of the information about the vehicles, including their location and overall traffic environment on the road. The introduction of this system will definitely minimize the human and machine error related to the vehicle safety and this is the main reason that it has the potential to bring the major economical and social benefits for the commuters and transporters, and leads to the improvement in the efficiency and the safety of transportation [11].

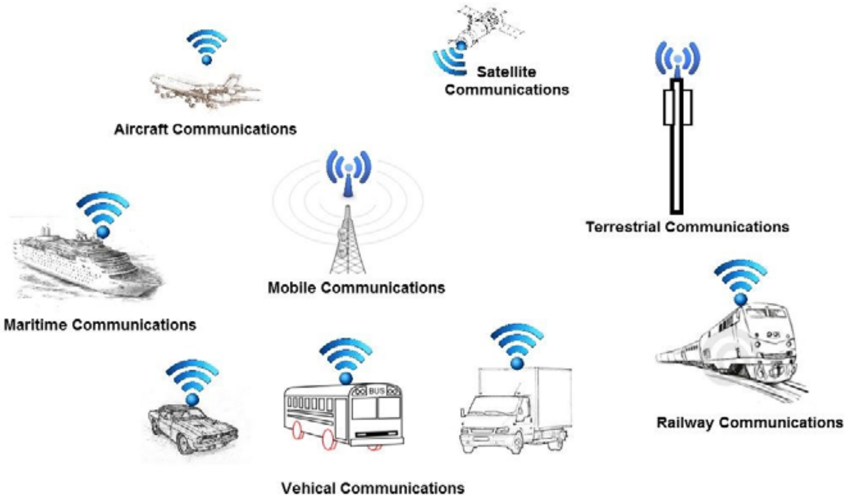

Figure 2. Intelligent Transport Systems (ITS)

2.1.1 European Telecommunications Standards Institute (ETSI)

ETSI is one of the most important and highly respected standardization organizations in the field of Information and Communication Technologies (ICT); it has produced standards for fixed telecom, mobile, radio, converged, broadcast and internet technologies. Although it is officially recognized by the European Union as a European Standards Organization, it has become worldwide famous because of its technical excellence and state of art standardizations. The domain of ITS also falls under ETSI and ETSI is responsible for the support of ITS with comprehensive standardization activities. There is a special technical committee in ETSI which takes care of the all standardization of ITS and this committee is called Technical Committee Intelligent Transport Systems (TC ITS). The main goal of TC ITS is to increase the safety of life through reducing the road accidents by focusing on the wireless communications for V2V and V2I communications. Since road accidents are a global issue, ETSI cooperates closely with other international standardization organizations such as European Committee for

Standardization (CEN), International Organization for Standardization (ISO), Institute of Electrical and Electronics Engineers (IEEE) etc. [10] [11].

2.1.2 ITS Messages

In ITS, two main messaging models are defined according to the road traffic environment and its requirements; Cooperative Awareness Message (CAM) and Decentralized Event Notification Message (DENM). These ITS messages have been standardized by the ITS, which are explained as follows.

2.1.2.1 Cooperative Awareness Message

The message communication pattern in which every vehicle in the network sends a message to every other vehicle within its range of communication periodically is defined as Cooperative Awareness Message (CAM). These messages generally consist of the geographical location of the vehicle, the velocity of the vehicle as well as the basic status of communicating vehicles to neighboring vehicles that are located within a single hop distance. The transmission interval of CAMs varies from 0.1s to 1s depending on the application but generally mostly applications uses 0.1s which is equal to 10 Hz frequency. All the vehicles within the system must be able to transmit and receive these messages. CAMs are the basic form of ITS messages and it constitutes the overwhelming majority of messages that are transmitted and received in the network [12]. One important point to note that these periodically transferred CAMs are also referred to as Beacons.

Figure 3 shows the CAMs scenario on the highway, just for the simplicity to define the whole messaging system of CAM, we will focus on only three cars which has been labeled as A,B and C. Car A is transmitting CAMs to B and C which is depicted by dark blue broken line, Car B is transmitting to C and A depicted by white broken line and Car C is transmitting to B and A depicted by dark red broken line and simultaneously they are all receiving the message from each other too.

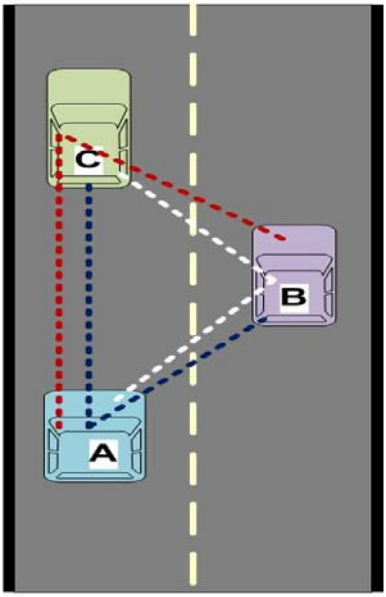

Figure 3. Cooperative Awareness Messages (CAM)

2.1.2.2 Decentralized Event Notification Message (DENM)

The messages that are only generated when certain hazardous event (e.g. accident) has taken place on the road are called Decentralized Event Notification Message (DENM) as it is obvious by name that the generation of these messages is dependent on the happenings of certain events and they are not routinely transmitted as CAMs. DENMs are also termed as event-triggered messages and they don't have any fixed schedule of transmission but the value of information of DENMs is much more than that of CAMs since it is directly related to the road safety applications. It is also important to note that DENM is only generated by the specific vehicle that has met some emergency event and its main aim is to aware and warned the other vehicles within the vicinity to take appropriate actions to avoid the mishap. The broadcasting of DENM continues till the event that triggered the generation of DENM is present, generally the DENM are generated with high frequency of 20 Hz and it has a very stringent time delay limits from source to destination [13]. In Figure 4 the scenario is depicted in which a red car has met an accident and now it is transmitting the DENMs to the other vehicles within the vicinity.

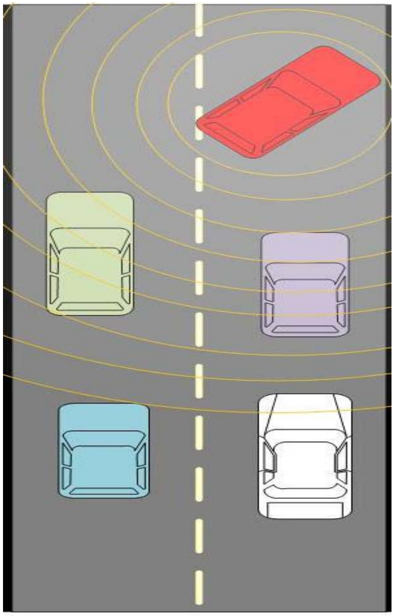

Figure 4. Decentralized Event Notification Message (DENM)

2.1.3 ITS Applications

There are numerous different ITS applications depending on the nature of the overall traffic environment and needs of the information about the particular vehicle for the insurance of smooth and normal traffic flow without any hiccups. The ETSI has standardized the ITS applications in four categories [14]. The detailed description of these four classes along with their time delay requirements and usage is presented in Table 1.

Table 1. Basic ITS Applications definition [14]

Application Category	***Applications***	***Use case***	***Latency***	***Beaconing Frequency***
Cooperative road safety	Cooperative awareness	Emergency vehicle warning, Slow vehicle indication, Intersection collision warning	50 ms To 100 ms	10 Hz To 20 Hz
	Road hazard warning	Emergency electronic brake lights, Wrong way driving warning, Accident, Traffic condition warning, Signal violation warning, Roadwork warning, Collision risk warning		
Cooperative traffic efficiency	Speed management	speed limits notifications	100 ms To 500 ms	1 Hz To 5 Hz
	Cooperative Navigation	Traffic information, Enhanced route guidance and navigation, Limited access warning		
Cooperative local services	Location based services	Point of Interest notification, Automatic parking management,	>500 ms	On demand
Global internet services	Communities services	E-commerce	>500 ms	On demand
	Vehicle life cycle management	Vehicle software update		

2.2 Wireless Access in Vehicular Environment (WAVE)

WAVE is a commercial name of IEEE 802.11p standard, as it is obvious by the name this standard belongs to the family of famous Wireless Local Area Network (WLAN) standard called IEEE 802.11, so it is basically an extension of WLAN. To improve the 802.11 standard, keeping in view the requirements of mobile user, changes were developed in the physical and media access control (MAC) layer of 802.11 by the IEEE Task Group p (TGp of the IEEE 802.11 working group) and those changes were declared as new standard called IEEE 802.11p. Since 802.11p only focuses on the physical and MAC layer, there was a requirement to cover the other layers of the protocol suite, so IEEE working group 1609 undertook this task and defined the specifications of other layers of a protocol suite for the mobile user. IEEE 1609 defines the standards set which is consist of four standards and their names are IEEE 1609.1 "Core System" , IEEE 1609.2 "Security" , IEEE 1609.3 "Network Services" and IEEE 1609.4 "Channel Management". Combining together the standards of IEEE 802.11p and IEEE 1609.x they formulate the Wireless Access in Vehicular Environments because on the whole it acquired the goal of facilitating provisions of wireless access in vehicular environments [15]. Figure 5 depicts the WAVE communication stack and it is important to note that resource manager and security services do not correspond to any layer of OSI model [15].

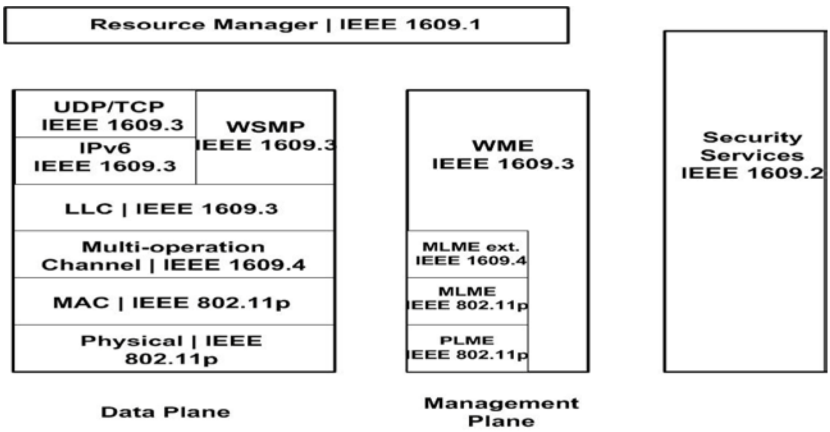

Figure 5. WAVE protocol stack

In Table 2, the protocols of WAVE are defined and their correspondence to particular OSI layer and IEEE standard is also mentioned.

Table 2. WAVE protocols with definitions

Protocols	***IEEE standards***	***Definition***	***OSI layer***
PHY and MAC	802.11p	Specification of the PHY and MAC layer according to the requirements of standard.	Physical(1) and MAC(2)
Multichannel Operation	1609.4	Enhancement of 802.11p MAC to support multichannel operation	MAC(2)
Networking Services	1609.3	Addressing and routing services within system	MAC(2), Network(3) and Transport (4)
Resource Manager	1609.1	Application that allows the interaction between device on vehicle with limited resources and complex process running outside the device	N/A
Security Services	1609.2	Formatting of messages and the processing to make them secure	N/A

Since WAVE belongs to the family of WLAN, it has a number of merits which it has directly inherited from WLAN such as ease to use, simplicity, straightforward changes required in WLAN hardware and software to make it work for WAVE, and as a technology it is stable as it belongs to WLAN which is very well established and tested. Still there are some problems directly dependent on physical conditions of vehicular communication environment; one of those main problems is high latency and there is also an issue of packet loss because of the nodes, inability to sense other node transmitting to the same destination node, these problems are mainly dependent on the physical layer and MAC layer of the OSI model, therefore it is very important to understand the features of 802.11p/WAVE physical and MAC layers.

2.2.1 WAVE MAC Layer

IEEE 802.11p/WAVE MAC layer uses the enhanced version of the distributed coordination function from 802.11 called Enhanced Distributed Channel Access (EDCA). The EDCA is same as used in 802.11e, it basically depends on multiple access scheme know as Carrier Sense Multiple Access Scheme with Collision Avoidance (CSMA/CA) which works on the principle of wait and check the channel before start sending and if some other node is sending then wait till the channel is available or free for transmission, in simple words it can be said “listen before start talking and if someone else is talking then just wait for your turn to talk”. In vehicular communication it works in this way, a vehicle is only permitted to start transmission when it detects that the channel is available or idle for a dedicated time duration in seconds called Arbitrary InterFrame Space (AIFS). If the channel is not idle for AIFS seconds then the vehicle will wait for the channel to become free and then the vehicle will randomly select the backoff delay value from the given range of integer numbers known as Contention Window (CW), the vehicle decreases the value of backoff counter (set by the given integer numbers) after each idle slot and as the backoff counter decreases to zero the vehicle is allowed to access the channel for transmission [16].

The whole procedure of sensing the channel is done before every transmission. For every retransmission the size of CW will be doubled from its starting value CWmin until the size reaches its maximum value CWmax. For example if the starting size of CWmin is equal to an integer value 16 then in the second attempt of retransmission this value will be doubled to 32 and with every attempt it will continue to double until it reaches to its maximum value CWmax which is equal to 1024. If the CWmax has been achieved but still there is no availability of the channel then the packet will be dropped and then the contention window will be set to its initial value CWmin and in the event of successful transmission also afterwards the contention window will be set to its initial value CWmin [17]. The Quality of Service prioritization is also done in MAC layer, there are in total four different Access Classes (ACs) which ensures that safety messages get higher priority and it is transmitted timely and accurately [5]. The details of the access list with their priorities is given in Table 3 and it is important to note that standard aCWmin value is 16 and aCWmax value is 1024, it is obvious as the priority increases the value of AIFS and CWs decreases.

Table 3. WAVE QoS parameters [5]

AC	***CWmin***	***CWmax***	***AIFS***	***Waiting time(μs)***
0	aCWmin	aCWmax	9	264
1	[(aCWmin+1)/2]-1	aCWmin	6	152
2	[(aCWmin+1)/4]-1	[(aCWmin+1)/2]-1	3	72
3	[(aCWmin+1)/4]-1	[(aCWmin+1)/2]-1	2	56

2.2.2 WAVE Physical Layer

The IEEE 802.11p/WAVE Physical layer can be characterized as the enhancement of the physical layer of IEEE 802.11a to support the vehicular communications. The most important specification of the physical layer is the operating frequency and channeling, WAVE operates in the frequency range of 5.85 to 5.89 GHz which falls under the spectrum of Direct Short Range Communication (DSRC). This operating frequency range is divided in such a way that there is one Control Channel (CCH) reserved for control messages and up-to six Service Channels are reserved for data. The channels are accessed alternatively between CCH and SCH , it is done in a way that channel time is divided into synchronization interval, this interval consists of CCH interval and SCH interval of equal length of 46 ms and they are separated by the guard interval of 4 ms so in total the synchronization interval is 100ms long [16].

The other important physical layer parameters are deduced from [9] which are presented in the tabular form in Table 4.

Table 4. WAVE Physical Layer Specifications

Parameters	***Values***
Operating Frequency	5.9 GHz
Bandwidth	In Europe 30 MHz for traffic safety and 20 MHz for commercial
Multiplexing	OFDM (64 point IFFT, 48 data subcarriers, 4 pilot subcarriers, 11 guard subcarriers)
Modulation	BPSK, QPSK, 16/64 QAM
Data rate	3-27 Mbps
Range	Optimum 300 m

2.3 Long Term Evolution (LTE)

LTE is currently the most advanced technology in the field of wireless telephony; it was developed by the 3rd Generation Partnership Project (3GPP), the LTE technology details were specified in the Release 8 of 3GPP. LTE is the continuation of cellular technologies like GSM and UMTS, it has the performance benchmark better than any other wireless mobile communication right now and its working efficiency is better than the previous technologies, because of all these reasons it is referred as 4th Generation (4G) cellular technology. To understand the concept of generation in cellular technologies, we will take a look at the brief history of cellular communications [18].

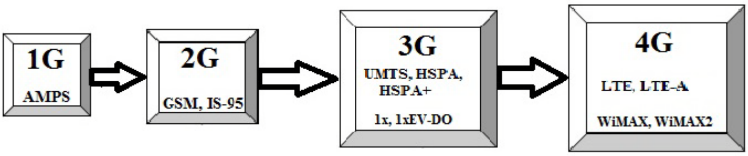

Figure 6. Generations of cellular technologies

As Figure 6 shows, until today, there have been four generations of cellular technologies. The technology which is referred to as 1st Generation (1G) was developed in 1980s and based on analog telephony called Analog Mobile Phone System (AMPS) , it was the first wireless phone system that was deployed on large scale commercially. Then comes the first digital wireless mobile telephony system called Global System for Mobile communications, famously known as GSM in 1990s and the international roaming services was first time introduced in this system, the GSM is referred to as 2G technologies and the access scheme they used was based on time division and frequency division multiple access. In the first half decade of 2000 the third Generation (3G) of mobile communication was developed called Universal Mobile Telecommunication System (UMTS) and it was based on code division multiple access scheme and it has better bandwidth and data rate then GSM. The main difference between the Generations of mobile communication systems are based on data rate, bandwidth and spectral efficiency, so in every new generation these three parameters are mainly improved along with a number of different services. In the second half of 2000s first decade LTE was introduced as the 4G technologies and its access scheme is based on orthogonal frequency division multiple access (OFDMA) and it has a number of new techniques involved like MIMO (multiple input multiple output) antenna arrays and LTE core part is totally based on IP technology. The biggest advantage of LTE is its internationality and globally accepted system which is due to the fact that it is developed by 3GPP [18].

LTE has number of technical attributes both in core and access network, which make it superior to other wireless telephony technologies; some of the major technical aspects of the LTE technology are summarized in Table 5:

Table 5. LTE Specifications

Feature	***Capability***					
Operating Frequency	In Europe 800,900,1800 and 2600 MHz					
Channel Bandwidth(Hz) 1RB=180kHz	1.4M	3M	5M	10M	15M	20M
	6RB	15RB	25RB	50RB	75RB	100RB
Transmission scheme	Downlink: OFDMA Uplink: SC-FDMA					
Modulation	QPSK, 16/64 QAM					
Peak Data rate	Downlink: 300 Mbps Uplink: 75 Mbps					
Cell Range	Upto 5 km					
Mobility support	Upto 350 km/h					
Bearer Service	Packet only					
Transmission time interval (TTI)	1 ms					
Access Mode	FDD and TDD					

2.3.1 3rd Generation Partnership Project (3GPP)

3GPP is the most dominant standardization body for mobile wireless communication systems. It is basically a body that unites various standardization groups working in the field of wireless communication from different regions of the world. It is comprised of different regional organizations, which includes ARIB and TTC from Japan, TTA from Korea, ATIS from North America, CCSA from China and ETSI from Europe as depicted in Figure 7.

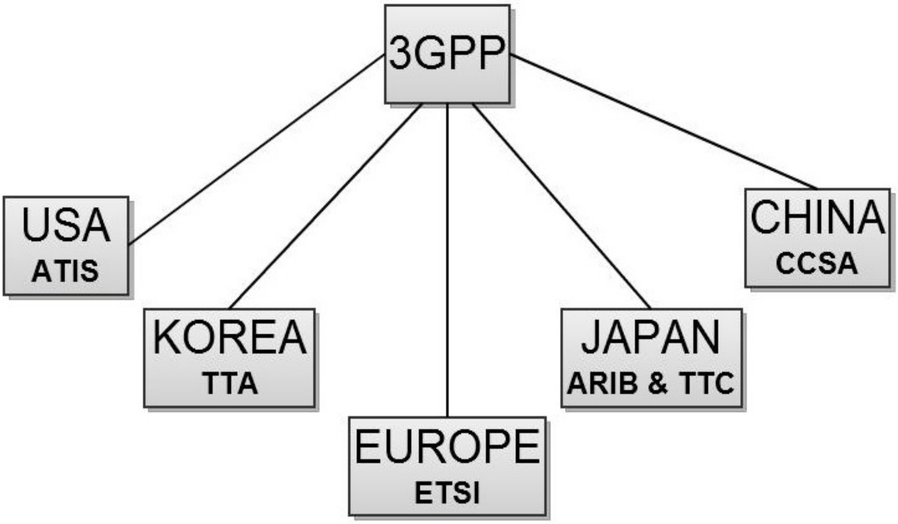

Figure 7. 3GPP body

By 2011, 3GPP had 380 different member companies; it is a very well structured organization as it is divided into four Technical Specification Groups, each of which is comprised of a number of different Working Groups with responsibility of specific aspects of the technology [18].

2.3.2 Technologies for LTE

Since we know that LTE performance is state of the art and cannot be matched right now with any other wireless cellular technology, so to achieve and maintain this performance LTE uses some specific cutting edge technologies. In wireless communication the main degrading factor is radio or air interface, so keeping that in view, LTE has following fundamental technologies which shape the radio interface design [18]:

2.3.2.1 Multicarrier Technology

Multicarrier technology plays a vital role in improving spectral efficiency; it basically allows multiple users to access the frequency band at the same time. In LTE, Orthogonal Frequency Division Multiple Access (OFDMA) has been selected for downlink communication and Single Carrier Frequency Division Multiple Access (SC-FDMA) for the corresponding uplink communication. Both these technologies provide flexibility in using the frequency band. OFDM basically divides the bandwidth into multiple narrowband subcarriers and all those subcarriers are orthogonal to each other to nullify the effect of inter symbol interference and these subcarriers are allocated to different users [18].

2.3.2.2 Multiple-Antenna Technology

It is based on the principle of multiple input multiple output (MIMO), which implies that several antennas are used for transmitting and receiving a signal, that helps in improving the overall gain of the antenna system, which includes diversity, array and spatial multiplexing gain [18]. Diversity gain corresponds to the minimization of multipath fading effect. Array gain corresponds to concentrate the beam forming in a particular direction and finally spatial multiplexing gain correspond to the ability of sending multiple data streams in parallel at a time which can be differentiated at the receiver on the basis of spatial signature.

2.3.2.3 Packet Switched Radio Interface

LTE is completely based on the packet switched connectionless protocol. The packet scheduling over the radio interface allow the transmission of short packets having duration of the same order of magnitude as the coherence time of the channel. This technology was already present in the High Speed Downlink Packet Access (HSDPA) and it requires the tight coupling of MAC and physical layer. The only difference from HSDPA to LTE is to improve the system latency the packet duration has been decreased to 1ms in LTE. The advantage of this technology includes optimized resource allocation, fast channel state feedback, dynamic link adaptation etc. [18].

2.3.3 LTE Network Architecture

The LTE Network architecture is designed keeping in mind that it has to provide seamless internet protocol (IP) connectivity between the User Equipment (UE) and backhand packet data network (PDN). On the radio network LTE uses the Evolved Universal Radio Access Network (E-UTRAN) and then it is connected to the core network called Evolved Packet

Core (EPC). The EPC and E-UTRAN combined together are called Evolved Packet System (EPS) [18].
EPS is responsible to route the IP traffic from the gateway in PDN to the UE. EPS route this traffic by using EPS bearers and bearers are defined as an IP packet flow with a defined QoS. The bearers are setup and released collectively E-UTRAN and EPC depending on the requirements of the applications. Multiple bearers can be assigned to a single user to provide different QoS connectivity to different PDN [18].

The overall architecture of EPS is given in Figure 8, with the details of network elements and interfaces.

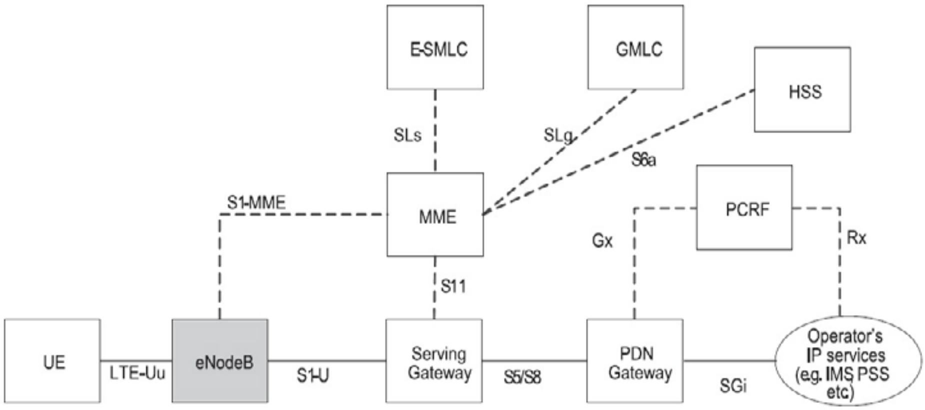

Figure 8. EPS Architecture

We can easily divide the overall network architecture in two categories; Core Network and Access Network. The following section will explain both the networks in detail with their entities.

2.3.3.1 Core Network

EPC is the core network and it basically responsible for the overall control of the UE and the setting up of EPS bearers. All the nodes other than UE and eNB are the part of EPS shown in Figure 8. The main entities of EPC are comprised of:

- PDN Gateway (P-GW)
- Serving Gateway (S-GW)
- Mobility Management Entity (MME)
- Evolved Serving Mobile Location Centre (E-SMLC)
- Gateway Mobile Location Centre (GMLC)
- Policy Control and Changing Rule Function (PCRF)
- Home Subscriber Server (HSS)

The brief detail of all the entities of the EPC is as follows [18]:

P-GW:

The main responsibility is the allocation of IP addresses to all the UEs along with QoS enforcement. It filters the downlink traffic by allotting different QoS bearers to different user IP packets. It also serves as the mobility anchor for internetworking with non 3GPP technologies such as WiMAX [18].

S-GW:

Every UE IP packet is passed through S-GW and when the UE moves from one eNB to the other it serves as the mobility anchor for data bearers. If the UE is in idle state then it retains the information about bearers and temporarily buffers downlink data while MME pages to the UE to re-establish the bearers [18].

MME:

MME controls the signaling process between the UE and EPC. The protocols running between UE and EPC are called Non-Access Stratum Protocols. The other main functions supported by MME are bearer management, connection management and functions related to interworking with other networks [18].

E-SMLC:

The management of scheduling resources and coordination to find out the geographical location of the UE within the coverage region is done by E-SMLC. The estimation of mobile UE speed is also done by this node [18]

GMLC:

The functionalities GMLC contains are required for the support of location services, it is connected to MME and sends a request for the position of the UE to MME and receives final location estimates [18].

PCRF:

It decides the policy for flow based charging functionalities and gives QoS authorization according to the profile of the user [18].

HSS:

HSS maintains user's data containing EPS subscribed QoS profile and any access restrictions for roaming. It also maintains the information about the PDNs to which user can connect and MME to which user is currently connected [18].

2.3.3.2 Access Network

As mentioned before the access network of LTE is comprised of E-UTRAN which includes UE and eNB. There is no centralized controller in it.

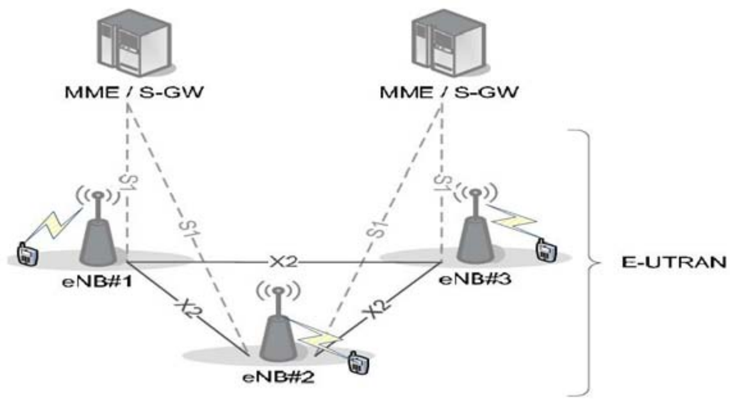

Figure 9. Access Network

As shown in Figure 9 the UE (mobile device) is connected to eNB on the air interface and all eNBs are interconnected with each other through X2 interface. The eNB is then connected to the Mobility Management Entity (MME) or Serving Gateway (S-GW) through the S1 interface, important to note that MME/S-GW is basically part of the core network (EPC) so the S1 interface is connecting an access network to core network. The protocols between UE and eNB are called Access Stratum (AS) protocols.

All the radio related functions are present in eNB, and E-UTRAN is responsible for these [18]:

- The most important function is of radio resource management which covers a number of different functions related to radio bearers.
- It compresses the IP packet header to minimize the overhead which enables the efficient use of the radio interface.
- Data encryption is done on the radio interface for security.
- It enables E-SMLC in finding the UE position by sending required positioning related data to E-SMLC.
- It maintains the backend connectivity to EPC.

2.3.4 LTE Protocol Architecture

The radio protocol architecture of E-UTRAN can easily be divided into two categories; User plane and Control Plane. It is also important to mention that from ITS point of view the very low latency of packet is very crucial requirement and in LTE the packet latency is basically dependent on these two E-UTRAN user and control planes, so it is important to study both planes in detail [18].

2.3.4.1 User Plane

First of all let’s discuss the latency parameter in User plane, latency here is defined as the average time taken between the data packet transmission and reception on the physical layer including the retransmissions. In optimal conditions, ideally one way communication latency should be 5ms on user plane but practically latency is directly related to the system load and radio propagation conditions [18].

User plane covers the communication between the UE to P-GW through eNB. Actually all IP packets belonging to users are tunneled between P-GW and eNB for transmission to UE. All IP packets are encapsulated using EPC-specific protocol before tunneling. Figure 10 gives the detail picture of E-UTRAN user plane protocol stack and how they connect UE to P-GW through eNB and S-GW. The main entities of user plane protocol stack lies in the Layer 2 of the overall LTE protocol stack, it divides the layer 2 in three different sub-layers and together they form E-UTRAN user plane protocol stack and their names are [18]:

1. Packet Data Convergence Protocol (PDCP)
2. Radio Link Control (RLC)
3. Medium Access Control (MAC)

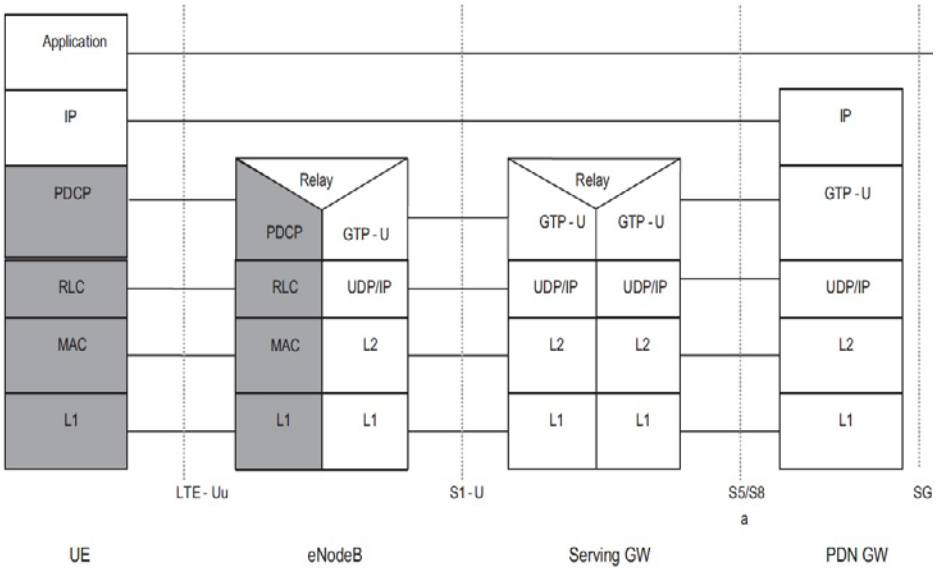

Figure 10. LTE E-UTRAN User plane protocol stack

PDCP:

The main function of PDCP layer is header compression and security of the messages. On the transmission side this layer receives IP packets from above the IP layer and process it and transfer it to lower layer (RLC) while on the receiving side its the total opposite. It also supports retransmission during handovers. Every radio bearer has one PDCP entity [18].

RLC:

The segmentation and reassembly of upper layer data units or packets is done in RLC layer to make packets transmittable on the radio interface. On the transmission side RLC receives packets from PDCP called PDCP PDUs (Packet Data Units) and then process it according to its functionalities and then these processed packets are called RLC SDUs (Service Data Units) and send to the lower layer (MAC) and on the receiving side the total process is reversed. As in PDCP there is also one RLC entity per every radio bearer [18].

MAC:

MAC layer performs multiplexing and de-multiplexing of data between logical channel and transport channel. Logical channel is between MAC and RLC layer while Transport channel is between MAC and physical layer. On the transmission side MAC receives RLC PDUs and call it MAC SDUs (from the MAC point of view) and then construct MAC PDUs which is known as Transport Blocks (TBs) and transmit it to the lower physical layer while on the receiving side the process is reversed. There is always one MAC entity per user [18].

2.3.4.2 Control Plane

Let's first discuss the latency in control plane; the control plane latency is defined as the average time taken from the device to transit from idle state to connected state. Ideally according to 3GPP the control plane latency should be less than 100ms [18].

The control Plane protocol stack is responsible for the communication between UE and MME through eNB. Figure 11shows the complete protocol stack control plane and all the lower layers are same as user plane except instead of IP layer the Layer 3 in control plane is Radio Resource Control (RRC). The functionalities of layers lower than RRC are same except there is no header compression in control plane [18].

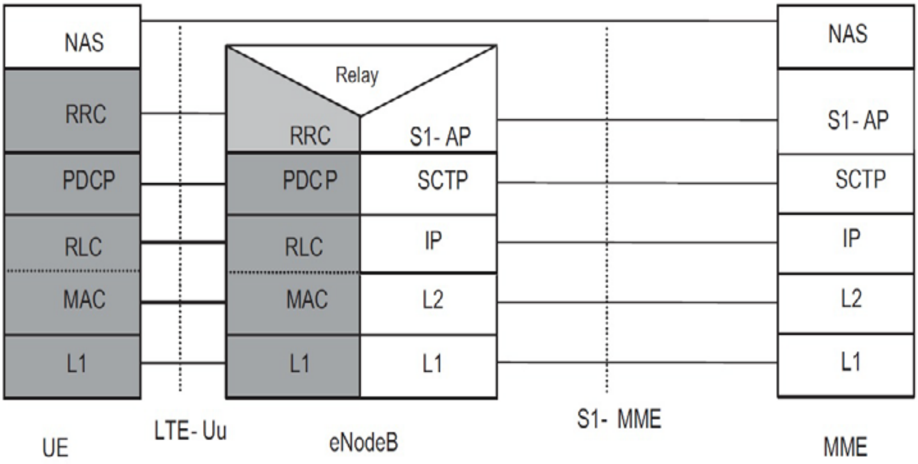

Figure 11. LTE E-UTRAN Control plane protocol stack

RRC:

RRC has the all main controlling functions related to connection establishment, establishing the radio bearers and configuration of lower layers by using RRC signaling between eNB and UE [18].

2.3.4.3 LTE Study Conclusion

The study of protocol architecture of LTE enable us to conclude that latency parameters of User Plane and Control Plane are seems good enough to test the LTE technology for the ITS cooperative safety applications. Since the given latency parameters in ideal condition for LTE are way below the maximum limit of the latency (100 ms) in vehicular safety applications.

CHAPTER 3

3 System Model and Simulation

In order to fulfill the goal of this thesis presented in *section 1.3*, we have to develop a basic common simulation scenario for LTE and WAVE. This chapter will give you the brief overview about the built scenario and about the simulator we have used to model the system.

3.1 Scenario

The basic scenario used in our model covers two vehicular communication environments, V2I (Vehicle to Infrastructure) in case of LTE and V2V (Vehicle to Vehicle) in case of WAVE.

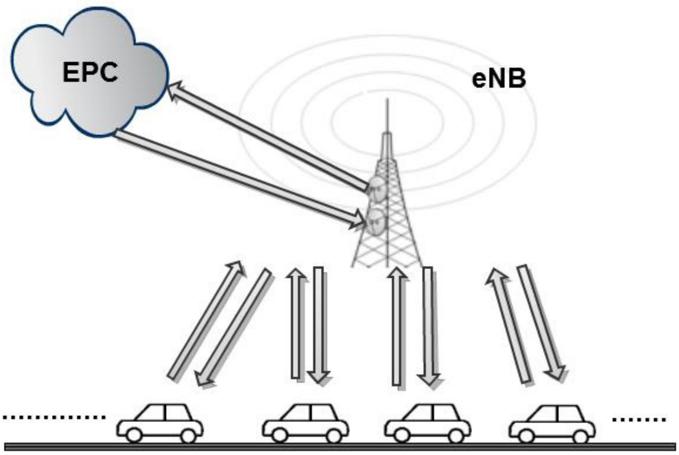

Figure 12. LTE-EPC simulation Scenario

Figure 12 depicts the V2I environment of our simulation. Vehicles communicate with each other through LTE infrastructure. A single lane highway road model is implemented, with one eNB located strategically alongside the road at a height of 10 meters and vehicles moving with different constant velocities. Each vehicle is connected to the eNB and exchanging the periodic messages through the eNB with the other vehicles. These messages have a predefined size and frequency, with which they are being transmitted so; they are referred to as Beacons as defined in section 2.1.2.1. Each transmitted beacon in the uplink has to reach eNB and then EPC. The beacons are processed by EPC to determine the destination node (vehicle) in the cell and the serving eNB to redirect the beacon in downlink.

Figure 13 depicts the V2V WAVE environment simulated in our model. The road model is the same as V2I, single lane highway with vehicles moving with different constant velocities. But as it is V2V we have no infrastructure and communication is vehicle to vehicle. Each vehicle is transmitting and receiving beacons to and from its neighboring vehicle within its communication range.

Figure 13. Wave Simulation Scenario

3.2 About NS-3

To simulate the above explained scenario we have used Network Simulator 3 (NS-3). NS-3 is a discrete-event network simulator, targeted primarily for research and educational use. NS-3 is free software, licensed under the GNU GPLv2 license, and is publicly available for research, development, and use.

The goal of the NS-3 project is to develop a preferred, open simulation environment for networking research: it should be aligned with the simulation needs of modern networking research and should encourage community contribution, peer review, and validation of the software. NS-3 is supported by multiple operating systems e.g. Linux, Mac OS and Microsoft

Windows using Cygwin. The development of realistic simulation models with the help of NS-3 infrastructure allows it to be used as a real-time network emulator by allowing the reuse of many existing protocol implementations within NS-3. It provides the platform for both IP and no-IP based networks. However much research work focuses on wireless/IP simulations involving WiFi, WiMAX or LTE model for layer 1, layer 2 and static or dynamic protocols e.g. OSLR , DSDV and AODV for IP based network [19].

The scripting in NS-3 is mainly done in C++ and Python. Most of the API is available in Python, but the models are written in C++. We have used C++ as a programming language in our simulation. It includes rich environment allowing users at several levels to customize the kind of information that can be extracted from the simulations [20].

3.2.1 Mobility and Positioning

In our simulation we have considered a single road highway with the length of 1000 meters and width of 3.3 meters. To make our system model realistic we have assigned the mobility to our nodes by using mobility models in NS-3. NS-3 mobility module supports the sets of mobility models which are used to track the and maintain the current cartesian positions and speed of an object. The design includes mobility models, position allocators, and helper functions. The initial position of the nodes is set with *PositionAllocator*. Most users interact with the mobility system using mobility helper classes. The *MobilityHelper* combines a mobility model and position allocator, and can be used with a node container to install mobility capability on a set of nodes [21].

We have used two mobility models in NS-3 named as *ConstantPostionMobilityModel,* used to give a constant position to eNB with respect to the UE/vehicles. With the assignment of mobility to eNB, *PositionAllocator* was used to place it in the middle of the highway at 500 meters on X axis, at a height of 10 meters in case of LTE.

The second mobility model *ConstantVelocityMobilityModel* was used to give a constant velocity to all UEs in both LTE and WAVE scenario, but this time we have used *RandomRectanglePositionAllocator* to assign the initial position to all UEs uniformly and to randomize the initial positions of each UE at every run. Mobility of UEs is bound to the minimum and maximum of X (0-1000 m) and Y coordinates (3.3 m). Individual car speeds were randomly assigned according to a normal (Gaussian) distribution with the parameters of, Mean Speed = 25 m/s, Speed Bound = 9 m/s and Speed Variance = 6.0 m/s.

3.2.2 Beaconing

Beaconing in our model for both LTE and WAVE has been implemented with the help of *Application* module in NS-3. As according to our requirement each UE should have the capability to generate beacons and receive them, in this context we have utilized two application models named *OnOff* application and *PacketSink* application from NS-3 for generation of beacons and to sink them respectively.

Here we want to discuss an issue related to the installation of *OnOff* application that's due to the simultaneous installation of the application on UEs it was limiting the number of UEs to 50 in our case as we are using 20 MHz bandwidth which is mentioned in terms of 100 RBs in uplink and downlink in NS-3. The UEs more than 50 were not able to transmit and receive. To overcome this problem we have installed the *OnOff* application on each UE at different instant of time. As current LTE module in NS-3 does not support the broadcast traffic so, for the sake of comparison with LTE in WAVE the UE to UE communication is based on Unicast.

3.2.3 Randomness

In NS-3 user can script the program in such a way that he can have deterministic results on every execution or can have random results by using the Seed or Run value in the simulator. To have independent trials of simulation one can change the global seed and rerun the simulation, or can advance the substream state of the RNG, which is referred to as incrementing the *run number* as described in [22]. In our simulation we are incrementing the run number 1 to 10 to simulate the same scenario 10 times .This randomness is applied in the state of all the random variables used in the script, e.g. in our simulation the assignment of the initial position of vehicles is different for every run value so a vehicle gets a different initial position for every run.

3.2.4 Simulation Time

The biggest hurdle during our simulations that we faced was the extraordinary time taken by NS-3 to process the simulations. To give an idea of how much time the simulations were taking for processing, the basic scenario with maximum 10 UEs in LTE will take up to 1 hour and this processing time increases with the number of UEs in the scenario, for 100 UEs LTE scenario the time taken by the simulator for single run is 20 hours, which implies after running the code we have to wait 20 hours for single run result and on the basis of those results the troubleshooting in the code is done and then ran it again and wait for another 20 hours to get new results. The reason for this extra ordinary delay in simulation processing is the detailed implementation of LTE model and according to the NS-3 developers the performance optimization of the simulator is still in process.

3.3 LTE

In this section we will explain the system architecture of LTE model implemented in NS-3. The LTE Radio Protocol stack entities (RRC, PDCP, RLC, MAC, PHY) resides entirely within the UE and the eNB nodes and the core network interfaces, protocol entities resides within the SGW, PGW, MME and partially within the eNB nodes [23]. The overall architecture of the LTE simulation model is depicted in the Figure 14.

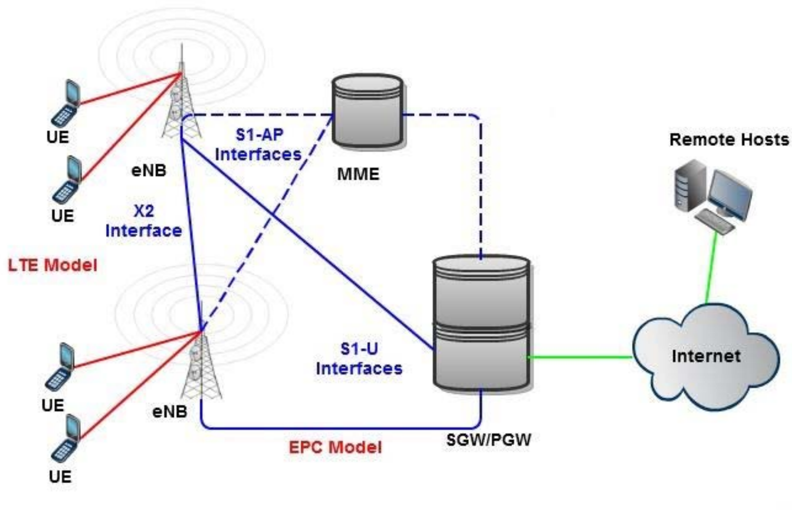

Figure 14. Overall architecture of the LTE-EPC simulation model

3.3.1 LTE-EPC Data Flow

The EPC model supports the end-to-end IP connectivity over LTE model. In particular, it supports for the interconnection of multiple UEs to the internet, via a radio access network of multiple eNBs connected to a single *SGW/PGW* node. Figure 15 shows the end-to-end LTE-EPC protocol stack implemented in NS-3. Simplification made in the EPC model for the data plane is the inclusion of the SGW and PGW functionality within a single *SGW/PGW* node, which removes the need for the S5 or S8 interfaces specified by 3GPP. On the other hand, for both the S1-U protocol stack and the LTE radio protocol stack all the protocol layers specified by 3GPP are present.

As shown in the Figure 15, there are two different layers of IP networking. The first one is the end-to-end layer, which provides end-to-end connectivity to the users; this layer involves the UEs, the *PGW* and the remote host (including eventual internet routers and hosts in between), but does not involve the eNB. By default, UEs were assigned a public IPv4 address in the 7.0.0.0 /8 network, and the *PGW* gets the address 7.0.0.1, which is used by all UEs as the gateway to reach the internet.

The second layer of IP networking is the EPC local area network.This involves all eNB nodes and *SGW/PGW* nodes. This network is implemented as set of point-to-point links which connect each eNB with SGW/PGW node; thus, the SGW/PGW has a set of point-to-point devices; each providing connectivity to a different eNB. By default, a 10.x.y.z/30 subnet is assigned to each point-to-point link (a /30 subnet is the smallest that allows for two distinct host addresses) [23].

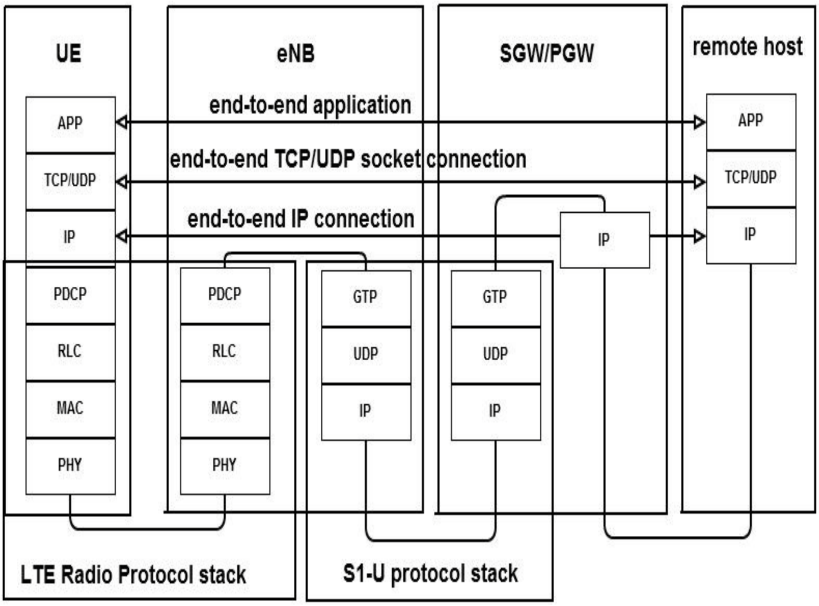

Figure 15. LTE-EPC data plan protocol stack

In the following we will explain how end-to-end IP communications is tunneled over the local EPC IP network using GTP/UDP/IP in NS-3. For this explanation we will explain end-to-end data flow in downlink and uplink respectively.

3.3.1.1 Downlink Data Flow

Figure 16 is the representation of the downlink data flow in our simulation among UEs by using LTE-EPC data plan. Downlink Ipv4 packets are generated from a UE in our simulation, and addressed to one of the UE devices. The IP stack of the *SGW/PGW* will redirect the packet again to the *VirtualNetDevice* rather forwarding it to a remote host. The *SGW/PGW* has a *VirtualNetDevice* which is assigned the gateway IP address of the UE subnet; hence, static routing rules will cause the incoming packet from another UE to be routed through this VirtualNetDevice. Such device starts the GTP/UDP/IP tunneling procedure, by forwarding the packet to a dedicated application in the SGW/PGW node which is called *EpcSgwPgwApplication*. This application does the following operations [23].

1. It determines the eNB node to which the UE is attached, by looking at the IP destination address (which is the address of the UE);
2. It classifies the packet using Traffic Flow Templates (TFTs) to identify to which EPS Bearer it belongs. EPS bearers have a one-to-one mapping to S1-U Bearers, so this operation returns the GTP-U Tunnel Endpoint Identifier (TEID) to which the packet belongs;
3. It adds the corresponding GTP-U protocol header to the packet;
4. Finally, it sends the packet over a UDP socket to the S1-U point-to-point NetDevice, addressed to the eNB to which the UE is attached.

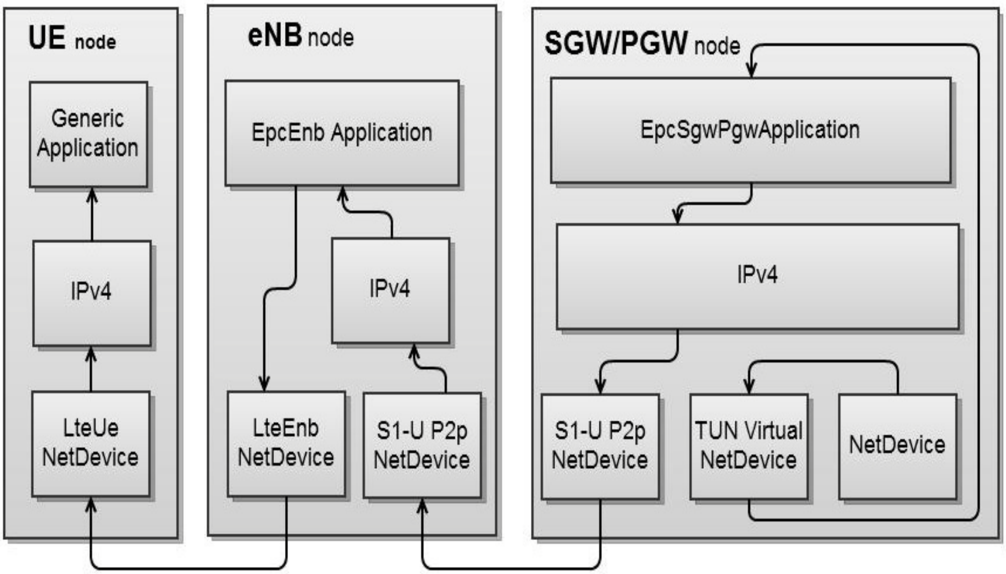

Figure 16. Downlink Data Flow in LTE-EPC

As a consequence, the end-to-end IP packet with newly added IP, UDP and GTP headers is sent through one of the S1 links to the eNB, where it is received and delivered locally (as the destination address of the outmost IP header matches the eNB IP address). The local delivery process will forward the packet, via a UDP socket, to a dedicated application called *EpcEnbApplication*. This application then performs the following operations:

1. It removes the GTP header and retrieves the Tunnel Endpoint Identifier (TEID) which is contained in it;
2. Leveraging on the one-to-one mapping between S1-U bearers and Radio Bearers (which is a 3GPP requirement), it determines the Radio Bearer ID (RBID) to which the packet belongs;
3. It records the RBID in a dedicated tag called *LteRadioBearerTag*, which is added to the packet;
4. It forwards the packet to the *LteEnbNetDevice* of the eNB node via a raw packet socket.

Note that, at this point, the outmost header of the packet is the end-to-end IP header, since the IP/UDP/GTP headers of the S1 protocol stack have already been stripped. Upon reception of the packet from the EpcEnbApplication, the LteEnbNetDevice will retrieve the RBID from the LteRadioBearerTag, and based on the RBID will determine the Radio Bearer instance (and the corresponding PDCP and RLC protocol instances) which are then used to forward the packet to the UE over the LTE radio interface. Finally, the LteUeNetDevice of the UE will receive the packet and deliver it locally to the IP protocol stack, which will in turn deliver it to the application of the UE, which is the end point of the downlink communication [23].

3.3.1.2 Uplink Data Flow

The case of the uplink is depicted in Figure 17. Data flow in the uplink between the UEs. Uplink IP packets are generated by a generic application inside the UE, and forwarded by the local TCP/IP stack to the *LteUeNetDevice* of the UE. The *LteUeNetDevice* then perfo
rms the following operations:

1. It classifies the packet using TFTs and determines the Radio Bearer to which the packet belongs (and the corresponding RBID);
2. It identifies the corresponding PDCP protocol instance, which is the entry point of the LTE Radio Protocol stack for this packet;
3. It sends the packet to the eNB over the LTE Radio Protocol stack.

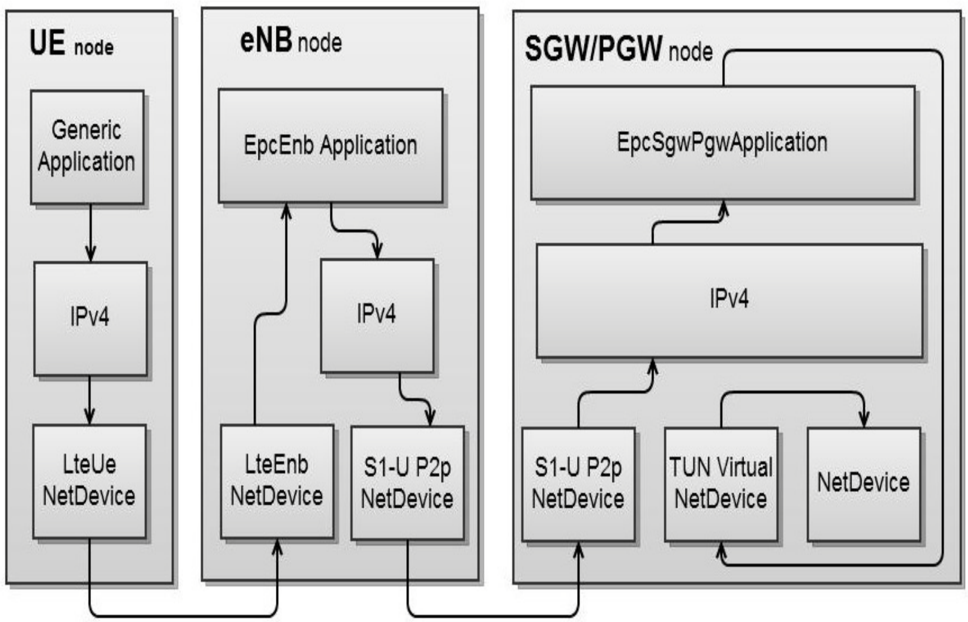

Figure 17. Uplink Data Flow in LTE-EPC

At this point, the packet contains the S1-U IP, UDP and GTP headers in addition to the original end-to-end IP header. When the packet is received by the corresponding S1-U point-to-point *NetDevice* of the *SGW/PGW* node, it is delivered locally (as the destination address of the outmost IP header matches the address of the point-to-point net device). The local delivery process will forward the packet to the *EpcSgwPgwApplication* via the corresponding UDP socket. The *EpcSgwPgwApplication* then removes the GTP header and forwards the packet to the *VirtualNetDevice*. At this point, the outmost header of the packet is the end-to-end IP header. As the packet is addressed to one of the UE, IP stack of the *SGW/PGW* will redirect the packet again to the *VirtualNetDevice*, and the packet will go through the downlink delivery process in order to reach its destination UE [23].

3.3.2 LTE Layers Implementation

In this section we will explain how LTE layers have been implemented in NS-3 and what parameters we have chosen related to our simulation for each layer.

3.3.2.1 Physical Layer

To implement the time and frequency varying aspects in LTE communication NS-3 utilizes the *Ns3::Spectrum* model. Because it provides the framework for the spectrum-aware channel and PHY simulation i.e. is the base for modeling of the OFDMA and SC-FDMA technologies. Two separate instances of *SpectrumModel* have been considered in NS-3, one for uplink (UL) and one for downlink (DL) in accordance with paired spectrum in Frequency Division Duplex (FDD) mode for LTE. At the moment LTE model in NS-3 supports FDD mode only. So FDD access mode defines a different set of sub-channels for uplink and downlink [23]. The physical model also includes the inter cell interference calculation and the simulation of uplink traffic, including packet transmission and Channel Quality Indication (CQI) generation. Table 6 below summarized the physical layer attributes we have used in our simulation

Table 6. Physical Layer Attributes

Attribute Name	***Attribute Value***
E-UTRA Band	1 (FDD)
DlBandwidth (in terms of resource block)	100 RB
UlBandwidth (in terms of resource block)	100 RB
DlEarfcn	100
UlEarfcn	18100
PathlossModel	FriisPropagationLossModel
eNB Antenna Model	IsotropicAntennaModel
eNB TXPower	30 dBm
eNB NoiseFigure	5 dB
UE Antenna Model	IsotropicAntennaModel
UE TXPower	10 dBm
UE NoiseFigure	9 dB
Transmission Mode	SISO

3.3.2.2 MAC Layer

In LTE resource allocation is done at MAC layer by the scheduler. Scheduler generates the Data control indication (DCI) which is transmitted by the physical layer of eNB to the connected UEs, in order to update them about the resource allocation on subframe basis. In downlink scheduler informs each UE about the allocation bitmap which identify that which RBs transmitted by eNB contains data, by filling the information such as Modulation and Coding Scheme (MCS) and MAC Transport Block (TB) size [23].

There are different types of scheduling algorithms now implemented in new version of NS-3 but at the time of our simulation, there were two main scheduling algorithms were there, Round Robin (RR) scheduler and Proportional Fair (PF) scheduler. We have used PF scheduler for our simulation so here we will explain the implementation of the PF scheduler in NS-3. The Proportional Fair (PF) scheduler schedules the user when its instantaneous channel quality is high relative to its own average channel condition over time.

3.3.2.3 Radio Link Control (RLC) Layer

According to 3GPP technical specification RLC layer comprises of three different types of RLC;

1. Transparent mode (TM)
2. Unacknowledge Mode (UM)
3. Acknowledge Mode (AM)

All the three types have been implemented in NS-3. In NS-3 RLC entities provide the RLC service interface to the upper PDCP layer and the MAC service interface to the lower MAC layer. The RLC entities use the PDCP service interface from the upper PDCP layer and the MAC service interface from the lower MAC layer [24]. In our simulation we have used UM mode of RLC layer. It differs from the AM mode in the context that there is no retransmission in downlink in UM mode and from TM mode in the context that TM mode is much simpler than UM as it does not add any header and packets received with error are just dropped or forwarded to higher layers.

3.3.2.4 Packet Data Convergence Protocol (PDCP)

PDCP layer in NS-3 is implemented according to the 3GPP standard with the following functionalities;

- Transfer of data (user plan or control plan)
- Maintenance of PDCP Sequence Number (SNs)

In our simulation we have used the default attributes of a PDCP layer in NS-3 without any modification.

3.3.2.5 Radio Resource Control (RRC) Layer

RRC layer implemented in NS-3 implements the procedures for managing the connection of the UEs to the eNBs, and to setup and release the Radio Bearers. The RRC entity also takes care of multiplexing data packets coming from the upper layers into the appropriate radio bearer. In the UE, this is performed in the uplink by using the Traffic Flow Template classifier (*TftClassifier*). In the eNB, this is done for downlink traffic, by leveraging on the one-to-one mapping between S1-U bearers and Radio Bearers, which is required by the 3GPP specifications [24]. In NS-3 at RRC layer once UE goes into the connected state it will never switch back to any of the IDLE state, hence the UE will remain in connected state throughout the simulation.

3.4 WAVE

WiFi module in NS-3 is a detail implementation of IEEE 802.11 standard. It provides the following aspects of 802.11 as described in [25];

- Basic 802.11 Distributed Coordination Function (DCF) infrastructure and adhoc modes.
- 802.11 a/b/g physical layers
- QoS-based EDCA and queueing extensions of 802.11e
- various propagation loss models including Nakagami, Rayleigh, Friis, LogDistance, FixedRss, Random
- two propagation delay models, a distance-based and random model
- various rate control algorithms including Aarf, Arf, Cara, Onoe, Rraa, ConstantRate, and Minstrel
- 802.11s (mesh), described in another chapter.

3.4.1 WiFi

Nodes in NS-3 can contain multiple *NetDevice* objects, a simple example can be a computer with different interface cards, e.g. for Ethernet, Wifi, Bluetooth. When we add a *WifiNetDevice* to a node that create models of 802.11 based infrastructure and adhoc network [25]. As depicted in Figure 18 at the time of transmission *WifiNetDevice* converts the IP address to MAC address and add Logical Link Control (LLC) header to the packet and pass it to *AdhocWifiMac* which add WiFi Mac header and estimate the physical mode i.g. the data rate supported by the destination node.

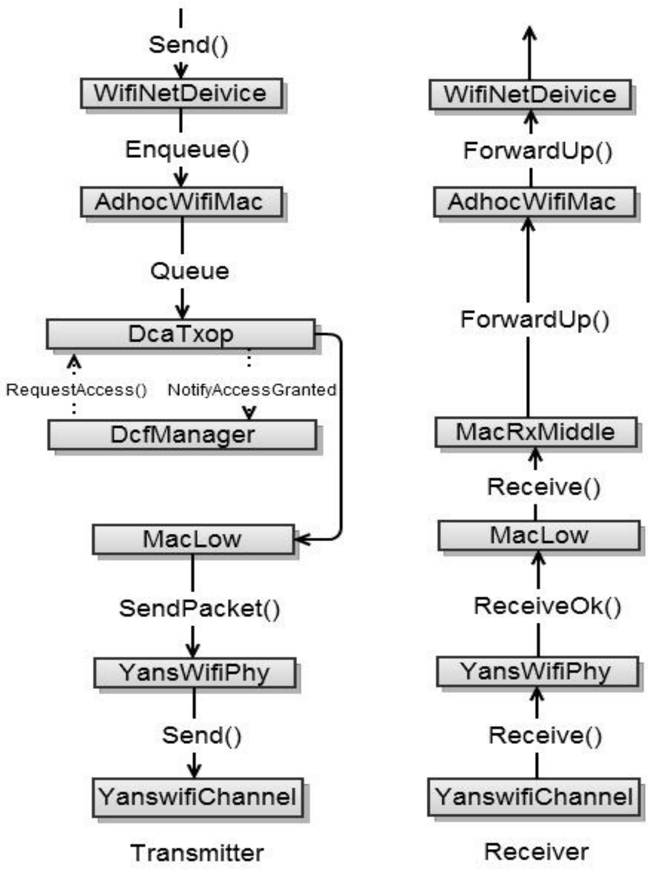

Figure 18. Wifi Data Flow in NS-3

After that Dynamic Channel Assignment (DCA) DcaTxop class insert the new packet in the queue and check for another packet transmission or reception along with a Distributed Coordination Function (DCF) class. If there is no packet pending, the packet is handed over to the MacLow class. In case of a pending packet, DcfManager acknowledges the collision and starts the backoff procedure by selecting a random number and wait to access again. DcaTxop also checks whether the packet is multicast or it requires fragmentation or retransmission. When it reaches to the MacLow class of NS-3 it checks if the retransmission was required; it's called the procedure for retransmission of the packet, if not it sends the packet to the physical layer of NS-3 named as *YansWifiPhy*. Which informs the DCF about the start of transmission, after that the packet is handed over to the channel class named as *YansWifiChannel* which estimate the receive power and set the propagation delay.

At the receiver side YansWifiChannel hand over the packet to the YansWifiPhy which calculates the interference level, it drops the packet if the state of PHY is not idle or the receive power is below the threshold. It also estimates the packet error rate (PER) from signal to noise ratio. Then the packet is handed over to the MacLow which check its destination and send the acknowledgement if the destination is reached. MacRxMiddle checks whether the received packets is duplicated one with the correct sequence and passes the packet to the AdhocWifiMac and then to the WifiNetDevice.

To implement WAVE we have used the following specifications in our simulation.

Table 7. Wifi Specificatons

Attribute Name	***Attribute Value***
Operating Frequency	5 GHz
Bandwidth	10 MHz
Data Rate	6 Mbps
Propagation Delay	Constant Speed Propagation Model
PathlossModel	FriisPropagationLossModel
MAC Service Specifiaction	QoS, Channel Access Priority: AC_BE(best effort access)

CHAPTER 4

4 Performance Evaluation Results

This chapter focuses on all the simulations findings. There were number of simulations run to find the answer of our thesis research questions. The simulations were set up in such a way that, three different cases were defined for a comparative analysis between LTE and WAVE. As the whole simulation scenario has already been defined in detail in Chapter 3, now the focus will be on its organization and how the simulations were executed. Before going into the details of simulation organization, it is important to mention the performance metrics on the basis of which both LTE and WAVE performances will be evaluated in vehicular communication scenario.

4.1 Performance Criteria

The main performance metrics are defined as follows;

1. ***Average Delay per Packet (ADPP)***: It can be defined as the average time taken by each packet during its transmission from source to destination. Since ITS had defined a strict latency requirement for cooperative safety applications, it makes this parameter as the most important one in judging the capability of technology for cooperative safety applications in vehicular communication. Hence average delay per packet is basically the total end-to-end delay of beacon (packet) from its source UE to destination UE.

2. ***Average Packet Loss Ratio (APLR)***: It is the ratio between the total number of packets lost to the total number of packets transmitted between source and destination UE.

4.2 Simulation Setup

The performance of LTE and WAVE for vehicular communication is evaluated on the basis of the metrics average packet loss ratio and average packet delay time. The simulations are divided in three different cases. In the first case of simulation, the beacon frequency, beacon size, mean speed of vehicles and propagation loss model remain constant and the number of UEs is variable. Then in the second case the beaconing frequency is changed and the whole simulation process is repeated again and in the third case the beacon size is changed and the whole set of simulation is performed again. The outcome of all the phases of simulations is presented and discussed in the form of average packet loss ratio and average packet delay time. All the three cases of simulations were executed in WAVE and LTE in the same order. In every case of simulation the results of both LTE and WAVE under the same given conditions and environment are analyzed.

As mentioned there are total three cases of simulations and the main parameters that define the difference between the cases are shown in the following Table 8.

Table 8. Simulation Cases Specifications

Parameters	***Values***		
	Case I	***Case II***	***Case III***
Beacon Frequency	10 Hz	20 Hz	10Hz
Beacon Size	300 bytes	300 bytes	100 bytes
Number of UEs	10 to 100	10 to 50	10 to 50

The simulations are organized in a way that for every case the comparative analysis is done between the two technologies LTE and WAVE and also the impact of change in network parameters (as every case has different network parameter from other case) is also evaluated. The summary of parameters that have been set for the comparative analysis between LTE and WAVE is mentioned in Table 9.

Table 9. (LTE vs WAVE) Simulation Specifications

Parameters	***Values***
Beacon Frequency	10 Hz and 20 Hz
Beacon Size	300 bytes and 100 bytes
Length of Road	1 km
Mean Speed of vehicles (UEs)	25 m/s
WAVE Operating Frequency	5 GHz
WAVE Contention Window	512
WAVE Data Rate	6 Mbps
Height of eNB	10 m
LTE Operating frequency	2.1 GHz
LTE Access Mode	FDD
Propagation Loss Model	Friis
LTE Bandwidth	20 MHz
Number of UEs	10UEs to 100 UEs

It is very important to highlight that all the simulations have been executed ten times with ten different random number seeds (each run has its own random seed, as explained in Chapter 4) and the final result is basically the mean of the ten runs. To confirm the integrity of our results the 95% confidence interval was calculated for every run with mean and standard deviation. The integrity of all the presented results is confirmed as for all the results the margin of error for 95% confidence interval was less than the 1% of final mean value used as result for every performance criterion.

4.3 Comparison between LTE and WAVE

For a fair and realistic comparative analysis of LTE and WAVE the test bed or the simulation environment of the test must be exactly the same. In our scenario, as mentioned before, both technologies are simulated on the same simulator, NS-3. The application for the packet transmission and reception on the UE (vehicle) is kept same and the vehicle mean speed and also its random allocation for both technologies scenarios, which implies that vehicle, the road and overall traffic environment is kept same for the simulations of both LTE and WAVE technologies. The other parameter that has been kept same is the Friis propagation loss model on the radio link between the sender and receiver.

4.3.1 LTE vs WAVE Comparison Case I

In this case the packet (beacon) size is been set to 300 bytes and the beaconing frequency is set to 10 Hz, which is required for the vehicular safety applications. The total number of UEs (vehicles) that has been tested for this scenario is ranges from 10 UEs to 100 UEs. As mentioned before, the comparative analysis results are also based on the packet delay and packet loss ratio, these are the two performance criteria which indicates the technology performance for the vehicular communications and especially for the vehicular safety applications.

Before discussing the comparative results between LTE and WAVE, it is important to mention that WAVE with CW of size 512 is considered (**See Appendix 1**) to represent WAVE in comparison with LTE.

4.3.1.1 Beacon Delays in Case I

For cooperative road safety applications, the biggest hurdle for any technology is strict latency requirement. In LTE the latency is dependent on the load of the network and in our case all the other parameters are constant and only load is varied. The network load is basically the number of users in the network and in our simulation the network load is represented by the number of UEs and we analyze the beacon delay by increasing the number of UEs.

As mentioned before the latency in LTE is dependent on control plane and user plane. In control plane, latency is based on the time taken in the transition from idle state to connected state, so it is important to mention that in our simulation the UEs throughout the simulation are in connected state. Therefore our Beacon delay finding is mostly dependent on user plane latency; as user plane latency is average time taken in packet transmission from source UE to destination UE, this delay is totally dependent on network load.

The comparative results between LTE and WAVE of ADPP for Case I are presented in the Figure 19. As the number of vehicles (UEs) is increasing in the network the average delay is also increasing which is as expected. We can easily say that for LTE till 90 UEs the average delay is within 100ms so that means LTE can support at a time 90 UEs for vehicular cooperative safety applications but as the number of vehicles (UEs) goes to 100 the average delay is now more than 100ms but it stills supports the traffic efficiency applications but not safety applications.

WAVE being infrastructureless technology has smaller packet delay than LTE in initial conditions i.e. with smaller number of UEs (up to 10 UEs) but as the number of UEs increases, the WAVE technology suffers with congestion and packet delay started to increase exponentially after 40 UE, while on the contrary the LTE ADPP performance is much better as till 90 UEs LTE technology has served the strict requirement for vehicular safety applications.

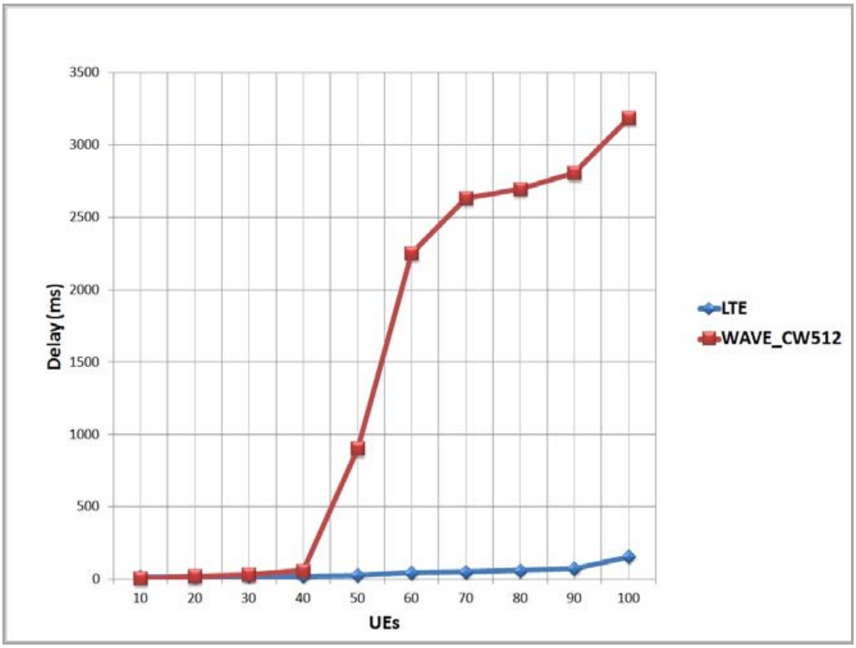

Figure 19. LTE vs WAVE Case I ADPP Results

The result graph of ADPP again confirms that till 40 UEs the LTE and WAVE are almost have the same performance but after 40 UEs WAVE totally failed to support safety applications while LTE has no such issues till 90 UEs. This call for the fact that in WAVE all the vehicles has to adjust itself with the increase number of vehicles within its communication range and there is no central communication processing node who coordinates with the vehicles during transmission so all the vehicles have to coordinate themselves with each other and in congested scenario it becomes a great hindrance factor.

The ADPP as defined by its name is the average delay per packet, which means there is a possibility that some of the packets have delays more than the average delay and some may even have delays more than 100 ms which is not acceptable for vehicular safety applications. Therefore it is important to analyze and find out the percentage of beacons whose delay is more than 100 ms in every scenario of 10 UEs to 100 UEs. The findings of this issue are presented in the graphical format in Figure 20:

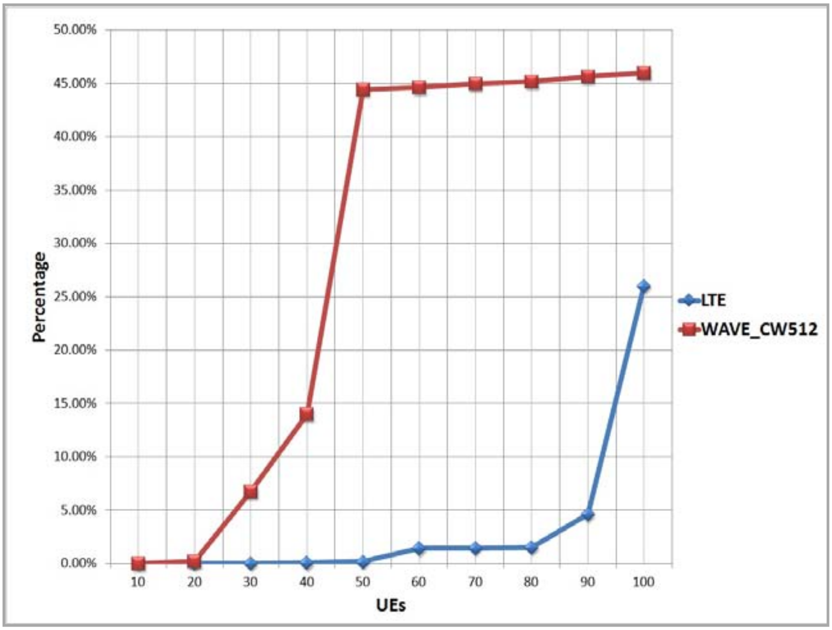

Figure 20. LTE vs WAVE Percentage of Beacons whose delay > 100ms

This again proves the better performance of LTE as till 90 UEs the percentage of beacons (whose delay is more than 100 ms) is below 5% while in WAVE the 5% mark has already been crossed at 30 UEs and after 40 UEs the percentage has jumped above 40%, one more confirmed example of the congestion issue in WAVE.

4.3.1.2 Beacon Loss Ratio in Case I

Along with the latency, it is also important that packet (beacon) transmitted must reach its destination properly. The reliability of communication is very important requirement for vehicular safety applications and this reliability is evaluated by testing the packet loss ratio of the network. The lesser the loss ratio the greater the reliability is, keeping in view the vehicular safety requirement the QoS has been implemented that defines the beacon with a delay of more than 100 ms is considered as a lost packet (beacon). The APLR results of both LTE and WAVE are presented in the Figure 21.

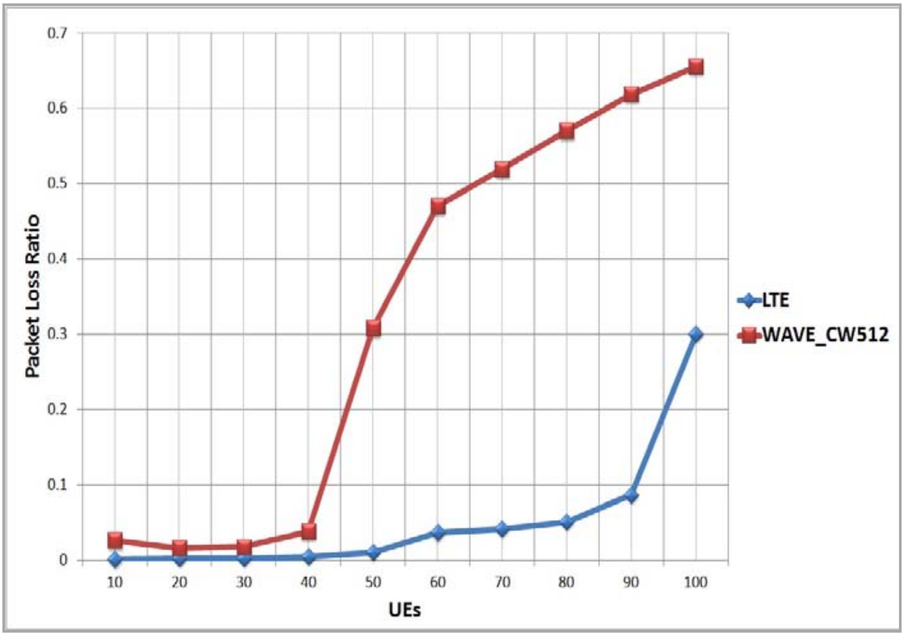

Figure 21. LTE vs WAVE Case I APLR Results

The results clearly suggest that LTE has better performance outcomes as compare to WAVE in terms of APLR. Since it is known that in both the technologies the maximum packet loss occurs at physical layer which is the result of air interface noise issues in LTE or packet collision in WAVE. In LTE the adaptive modulation is done which corresponds to better performance even in the noisy channel, the eNB sets the modulation coding scheme according to the SNR (signal to noise ratio). Because of this factor loss ratio in LTE is very low as compare to WAVE. The other main reason is, LTE has large capacity and there is a very small chance that packet is lost during scheduling queue buffer overflow.

As it can be seen above in the graph that WAVE performs quite well till 40 UEs as its loss ratio is way below 0.1 but after 40 UEs it's just degrades exponentially due to the congestion issue. In WAVE the main reasons of packet loss is packet collision and packet expiry time (in our case 100 ms), the packet collision is because the different UEs are trying to seize the channel at the same time, one more reason of packet collision is when two or more than two nodes tries to send the packet to the same node at the same time the packet will collide at destination. The phenomenon of packet collision increases with the increase in the number of UEs. The loss due to packet expiration is mainly due to the fact in dense scenario (e.g. above 40 UEs) the UEs has lesser time to seize the channel and packet has to wait a lot before being given access to the channel which sometimes results in packet expiration.

4.3.2 LTE vs WAVE Comparison Case II

In case II the beaconing frequency has been increased to 20 Hz and there will be 10 to 50 UEs tested in this scenario while all the other parameters are same as Case I. The increase in beaconing frequency will cause more packets to be transmitted and the network load will increase. This will implies in tremendous increase in load, therefore the latency performance should degrade, as the latency is totally dependent on the network load and as the load increases the delay also increases. The effect of increasing the beaconing frequency will be evaluated for both the technologies and it will be interesting to find out which gets more affected due to this factor.

4.3.2.1 Comparison of Beacon Delay in Case II

The increase in packet generation frequency will affect the packet delay; the results of ADPP for LTE and WAVE are presented in Figure 22.

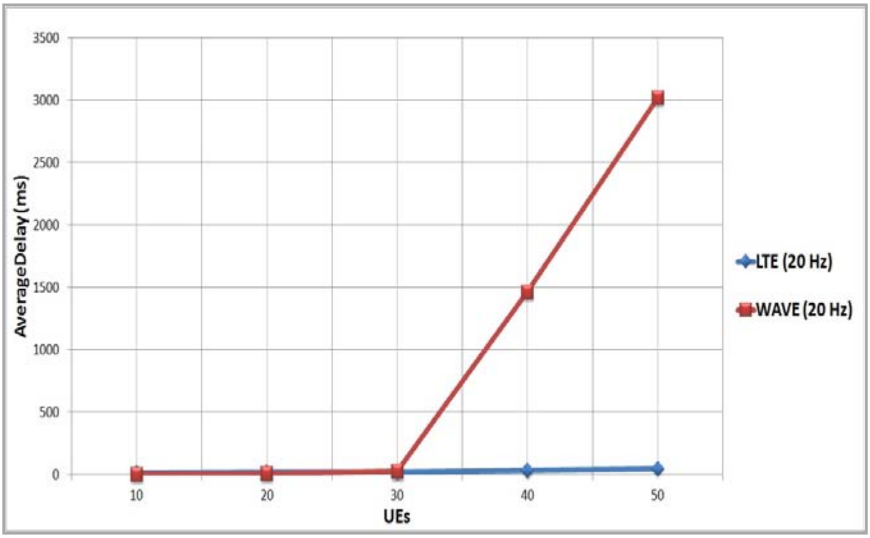

Figure 22. LTE vs WAVE Case II ADPP Results

The results have proved that increase in beacon frequency results in increase in ADPP, but we can see from the results graph above that LTE is still working within the limits of vehicular safety applications requirement for all the 50 UEs but WAVE is affected more severely. Therefore LTE due to its large capacity and infrastructure based architecture has been able to cope with the increase in generation and transmission of packets as compare to WAVE. But it should be noted that before the congestion in network which in this case is till 30 UEs the WAVE performance is perfectly fine with delays fulfilling the safety applications requirements but its only as the network get congested the performance deteriorates exponentially.

The effect of increase in beacon frequency in WAVE is depicted in Figure 23. In WAVE the increase in packet transmissions have caused an increase in network load, which implies that more beacons are in a queue to access the wireless channel, since all the vehicles are transmitting so the wait increases in the queue to access the channel, therefore it affects the overall beacon delay due to which in Case II the WAVE has met congestion at more than 30 UEs, since in case I WAVE was supporting 40 UEs for safety applications but now it’s been reduced to 30 UEs and in congestion the performance of WAVE degrades exponentially.

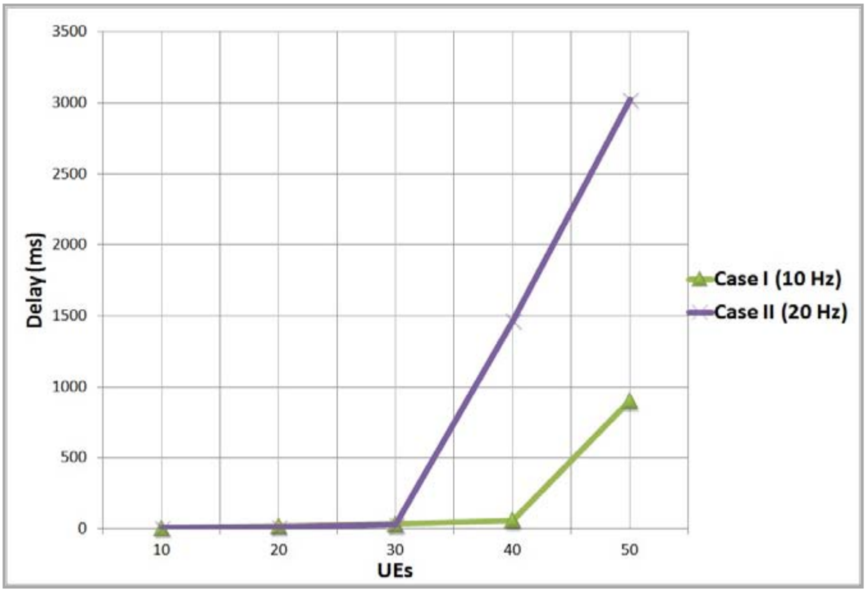

Figure 23. WAVE (CW=512) Case II ADPP with Case I Comparison

The effect of increased beacon frequency in LTE is also evident from the result graph of Figure 24, but as mentioned before it still fulfills the delay requirements of vehicular safety applications. At 50 UEs the significant increase in average delay can be seen in Case II as compare to Case I.

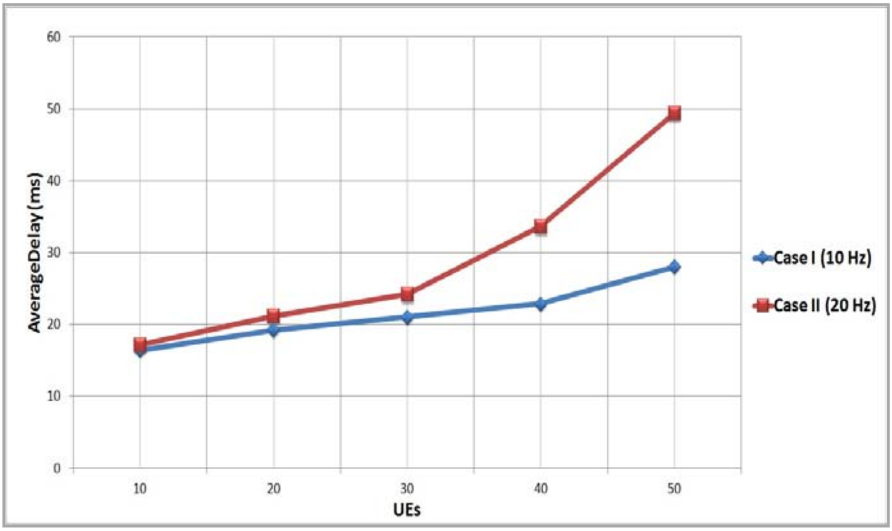

Figure 24. LTE Case II ADPP Results with Case I Comparison

4.3.2.2 Comparison of Beacon Loss Ratio in Case II

The packets transmitted at higher frequency results in more number of packets on the air interface which directly relates to more number of packet losses. The results of APLR with QoS implementation for vehicular safety applications are given in Figure 25.

The results clearly show that LTE supports all 50 UEs but WAVE supports only 30 UEs as after 30 UEs the loss ratio jumps up for WAVE technology, so it's confirmed that this increase in lost ratio is not only because of increased packet collisions but mainly because of packet delay time expiration after 30 UEs, as evident from the Case II ADPP results the delay time also increases after 30 UEs.

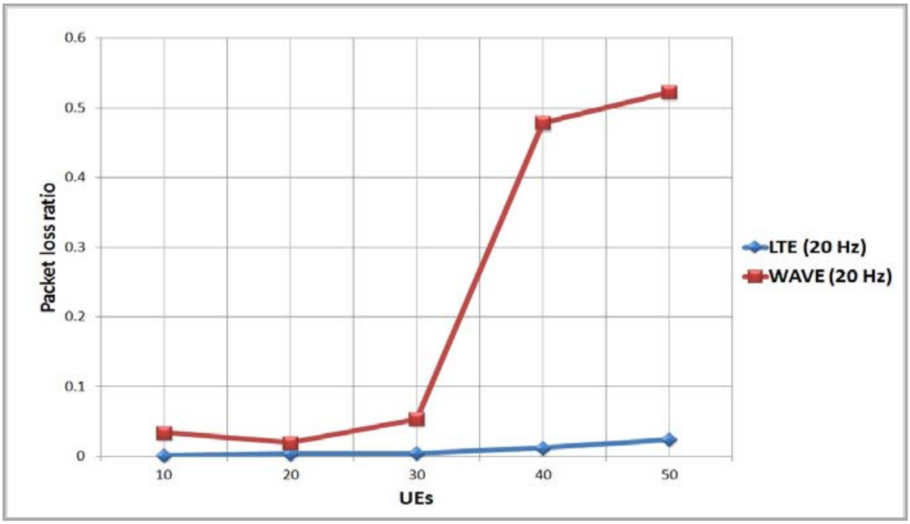

Figure 25. LTE vs WAVE Case II APLR Results

The effect of increasing the beaconing frequency in both technologies can be highlighted by presenting the results in comparison to the Case I. Figure 26 shows the effect on WAVE and Figure 27shows the effect on LTE.

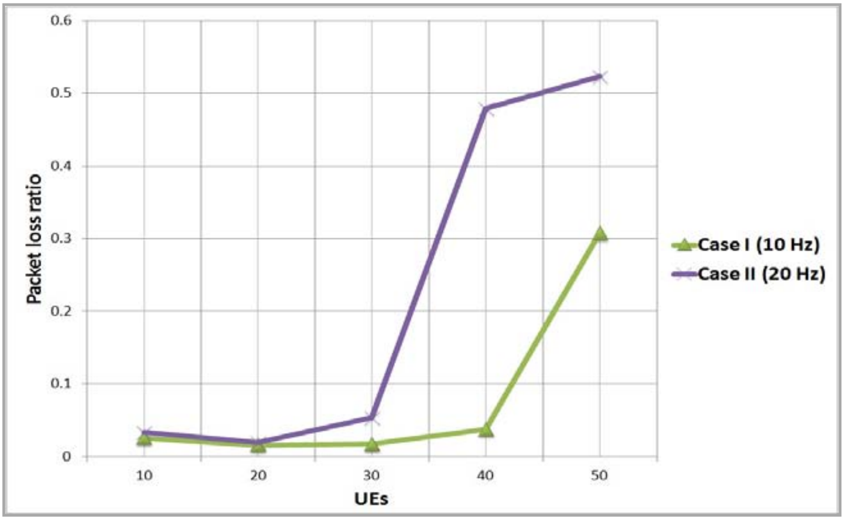

Figure 26. WAVE (CW=512) Case II APLR Results with Case I Comparison

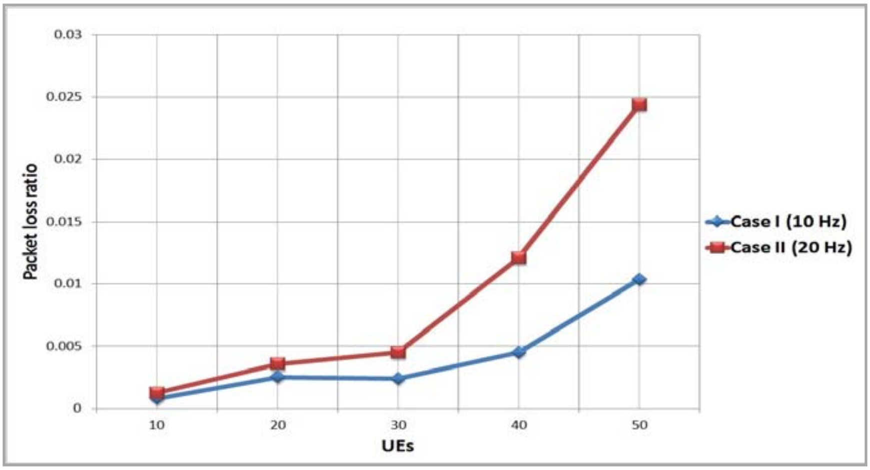

Figure 27. LTE Case II APLR Results with Case I Comparison

It is evident from the graph of Figure 30 that WAVE was supporting 40 UEs in Case I while in Case II it is supporting 30 UEs for vehicular safety applications. Even LTE is also affected by the increased beacon frequency as packet loss ratio almost doubled at 50 UEs but it is still under the bench mark of loss ratio of 0.1 essential for vehicular safety applications. Hence it is confirmed that increase in beacon frequency has degraded the performance of both technologies LTE and WAVE for vehicular safety applications.

4.3.3 LTE vs WAVE Comparison Case III

In this case, the effect of packet size will be analyzed with reference to average delay per packet and average packet loss ratio. The packet size has been reduced to 100 bytes while the beaconing frequency is been set back to 10 Hz, so this implies the less packets with smaller packet size will be transmitted now as compare to Case II. The simulations will be run for 10 to 50 UEs. The comparative results for LTE and WAVE will be presented for this Case III, as well as to fully understand the effect of decrease in packet size the results in comparison with Case I for both the technologies LTE and WAVE will also be presented.

4.3.3.1 Comparison of Beacon Delay in Case III

Since the packet size has been cut down in this case from 300 bytes to 100 bytes that means the load of the network is reduced. The decrease in the load of network always results in better packet delay performances. The results of ADPP for both LTE and WAVE technology are presented in Figure 28.

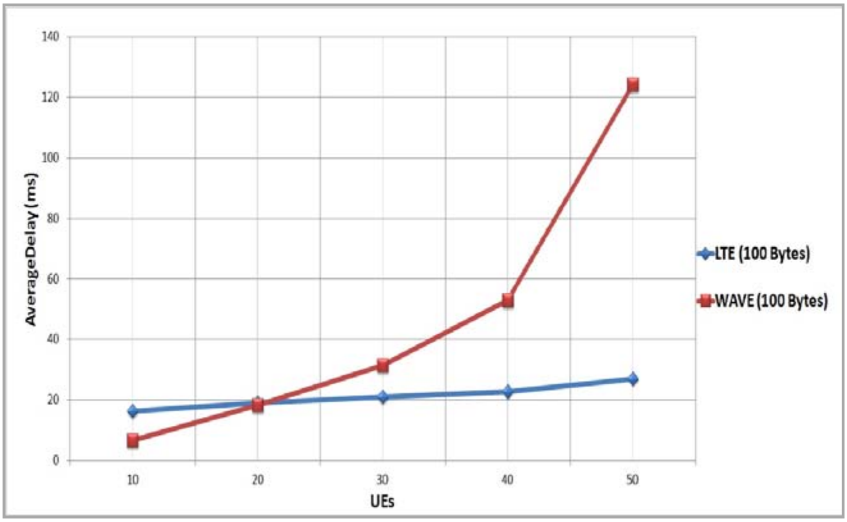

Figure 28. LTE vs WAVE Case III ADPP Results

The ADPP results confirm the better performance of both LTE and WAVE in terms of packet delay. The WAVE result curve in the Figure 28 clearly suggests that with smaller packet size WAVE is now supporting safety applications till 46 UEs as the packet delay till 46 UEs is under 100 ms. As shown in Figure 29, in the previous scenario of packet size 300 bytes (Case I) the WAVE supported till 40 UEs only for safety applications and after 40 UEs there is severe degradation in the ADPP performance but in this case there is no severe degradation after 40 UEs. The LTE on the other hand is supporting all 50 UEs in this scenario also.

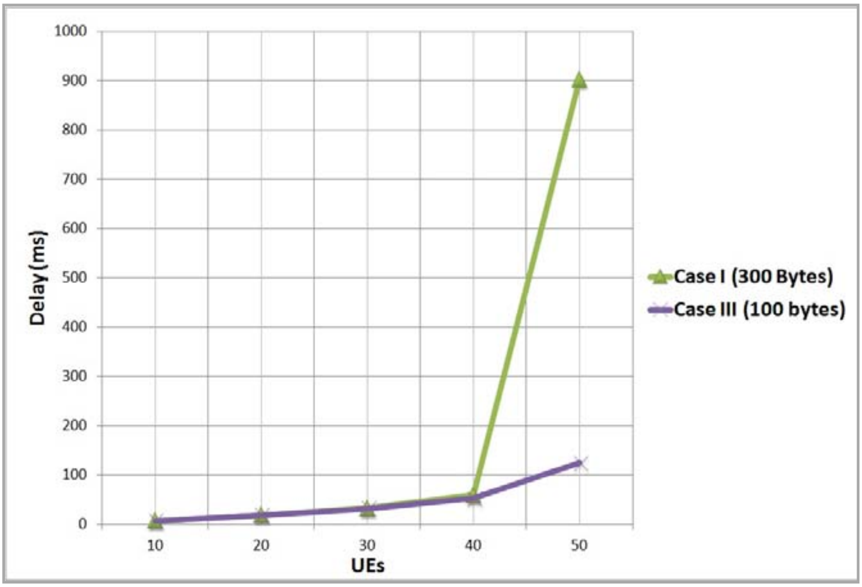

Figure 29. WAVE (CW=512) Case III ADPP with Case I Comparison

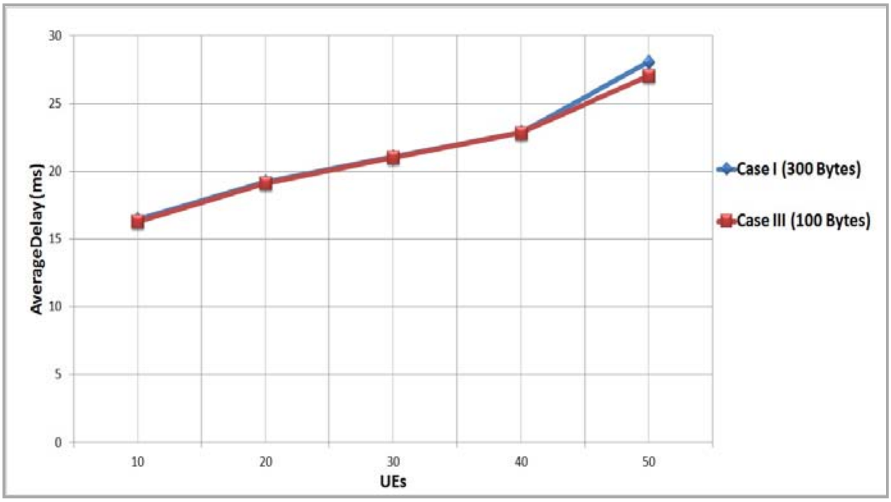

Figure 30. LTE Case III ADPP Results with Case I Comparison

The effect of decreased packet size on the performance of LTE is depicted in the Figure 30. The results show that average delay has reduced as compared to Case I but the reduction is very minute, the reason is because only 50 UEs were tested and the network load did not reach its peak till 50 UEs but as the network load in terms of UEs will increase the delay will become more significant, as we can see that below 50 UEs the difference in average delay of Case I and Case III is smaller than 1ms but at 50 UEs the difference has reached to 1.3 ms so that clearly shows as the UEs will increase this delay difference becomes more significant.

4.3.3.2 Comparison of Beacon Loss Ratio in Case III

With the reduction in packet size, which implies that there will be less bits transmitting, we expect that the packet loss performance of both LTE and WAVE network will improve. The packet (Beacon) loss ratio result with QoS implementation (packet with delay of more than 100 ms will be considered as loss packet) is presented here because this QoS implementation is done to test the network according to the requirement of vehicular safety applications. The APLR results of both LTE and WAVE technology with QoS implementation are presented in the Figure 31.

The LTE result represented by the blue curve in the Figure 31 clearly suggests that LTE has constant better performance throughout the simulations in Case III APLR results, while as compare to LTE the WAVE has a varied performance but still till 40 UEs the WAVE is also perfect as the loss ratio is within the range of 0.05.

Figure 32, clearly shows the effect of decreased packet size on the WAVE. The results have confirmed that with smaller packet size the APLR performance has improved as APLR of Case III is lower than the APLR of Case I. Again in congested scenario i.e. above 40 UEs the impact becomes more visible of lesser packet size.

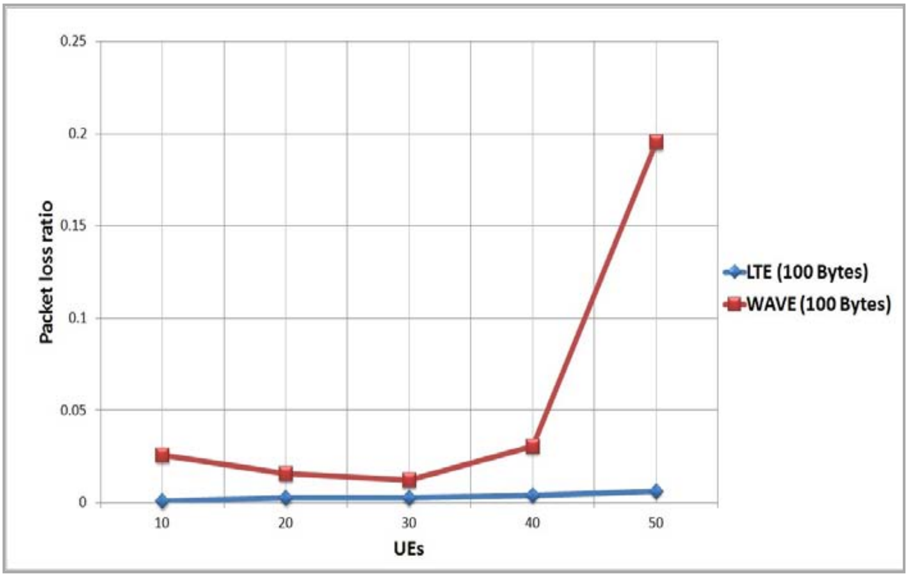

Figure 31. LTE vs WAVE Case III APLR Results

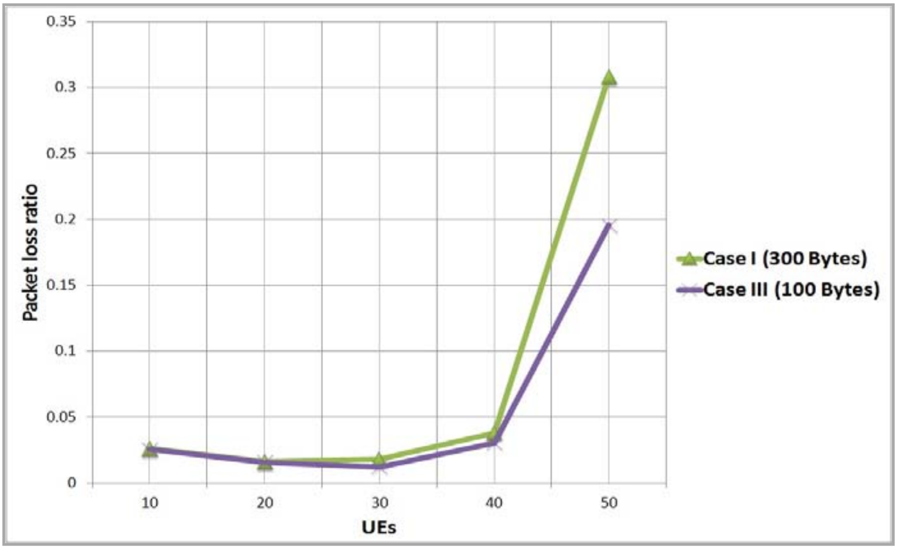

Figure 32. WAVE (CW=512) Case III APLR Results with Case I Comparison

The effect of decreased packet size on LTE is depicted in the graphical format in the Figure 33. The results clearly show that APLR has decreased with decreased packet size and it’s a confirmation that on wireless channel the lesser the bits transmitted the lesser the losses.

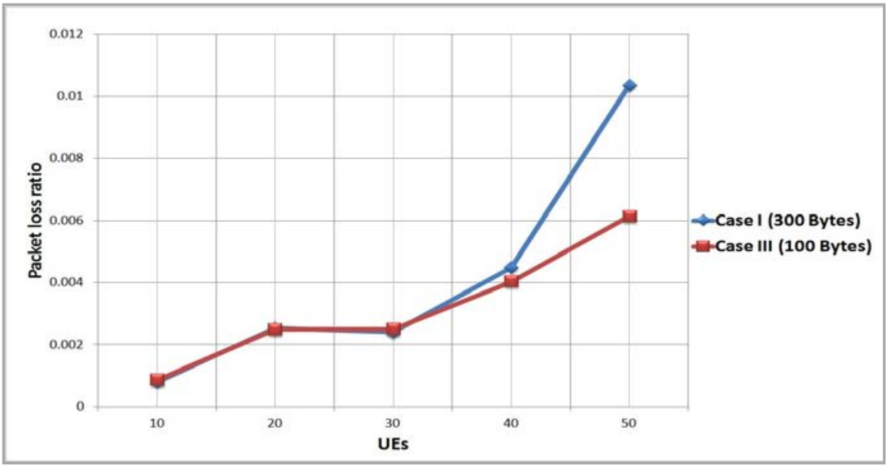

Figure 33. LTE Case III APLR Results with Case I Comparison

Therefore it can be easily seen by our simulation results that in all three cases the LTE has outclassed the WAVE performance especially in the congested scenario i.e. number of vehicles (UEs) in the scenario is greater than 40 UEs. Even below 40 UEs LTE performance is better but WAVE is also supporting the requirements of vehicular safety applications below 40 UEs.

CHAPTER 5

5 Conclusions and Future Work

In this thesis we have come forward with conclusions about the use of 3GPP LTE and IEEE 802.11p/WAVE for vehicular communications. Our conclusions are solely based on the results of the simulations done in NS-3, on the basis of the simulation results presented in the Chapter 4 we try to answer our research question. It is also the highlight of our thesis that LTE has been first time tested for vehicular communications in NS-3.

The main task of this thesis was to find out which technology LTE or WAVE has the better performance results for the vehicular cooperative safety applications. This was the main reason that throughout our different set of simulations the focus was on the fulfillment of requirements for the cooperative safety applications and the accomplishment of these requirements is the benchmark which answered our main task.

By analyzing the results in Chapter 4, we came to the conclusion that for every case discussed in our simulation scenario design the LTE has better performance in terms of packet delay and packet loss ratio, while WAVE performance is severely affected by congestion i.e. when the number of vehicles within the communication region has increased more than 40 UEs. The LTE results have confirmed that it can support on average 90 UEs for vehicular safety applications; after 90 UEs the network started to get overload and performance starts degrading.

The two main parameters for any ITS communication is packet (beacon) size and beaconing frequency. The effect of these two parameters on the network was also analyzed during the simulations. The results suggested that the effect of increase in beacon frequency (from10 Hz to 20 H) has the same impact on both technologies as the network becomes overloaded with the lesser number of UEs in 20 Hz scenario as compare to 10 Hz scenario. Regarding packet size the simulation results analysis shows that when packet size was decreased (from 300 bytes to 100 bytes) the performance of both LTE and WAVE improved as there was a lesser load on the network.

LTE has greater advantage over WAVE as a technology because of its architecture, as there is always a central coordinating node in the form of eNB in the LTE which allows it to overcome the limiting factors of WAVE which are packet delay due to contention window, packet losses due to packet collision and co-channel interface especially in the congestion.

Since all in all the LTE has proved to be better choice for vehicular safety applications as compare to WAVE but there is one limiting factor and that is its normal voice traffic, as our simulation results shows performance of LTE when all the resources are dedicated to ITS communications, so the increase in the amount of voice traffic will increase the overall network load and that results in the degradation in performance of LTE for vehicular safety applications, so this phenomenon of increase in network load on LTE opens the gate of Coexistence for the both the technologies LTE and WAVE, as WAVE is specifically designed for ITS communications and the coexistence can easily be achieved by only using the LTE technology in congested scenario while normal scenario with no congestion the WAVE can be used, in this manner the coexistence of both the technologies can be achieved.

Therefore, it can be finally concluded that LTE does have better performance results in our simulations but due to its primary responsibility of wireless telephony the future is in the coexistence of both LTE and WAVE technologies for supporting cooperative safety applications.

5.1 Future Work

According to IEEE the future of vehicular communication is the concept of autonomous car which will drive by itself and it has also been predicted that by 2040 the driving license would be void [26]. These cars will operate through V2V and V2I communications and to ensure the safety travelling, the technologies which offers V2V communication (IEEE 802.11p/WAVE) and V2I communications (3GPP LTE) must be researched and tested under every extreme scenario.

The future work directly related to simulations done in our thesis could be the implementation of radio bearer supporting the broadcast in LTE model of NS-3. The real life results measurements for the same sets of scenarios defined in our thesis would be interesting to match with the simulation results. This would help in improving the shortcomings, if there are any, of the simulator.

One interesting future work could be the creation of the model in NS-3 that supports the combined application of LTE and WAVE, in simpler words the model in which UE can use both technologies at the same time. The inspiration for this model UE functionality could be taken from smart phones which connects internet through the infrastructure of cellular company and it can also work as the adhoc Wifi node for other local Wifi enable communication devices.

Since, as already mentioned, the future is an autonomous car which will operate through both V2V and V2I communications, the combination of both LTE and WAVE simultaneously implemented will be the most appealing future work.

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Appendix 1

A.1 Beacon Delay in Case I WAVE

The performance of WAVE is evaluated under the four CWs and then it will be determined which CW performs better for vehicular communications and specifically for vehicular safety applications. As the CW increases the beacon delay will also increase and the latency is the most important aspect of vehicular safety applications as it has very strict latency parameter requirement. The results of ADPP for all the four CWs are presented in the graphical format in the Figure A1.

As the CW is increasing the ADPP is also increasing which is absolutely logical as larger the CW is, more the packet has to wait before been transmitted to the destination. In WAVE there is no infrastructure through which packet has to pass to reach its destination; it is direct point to point communication on the wireless link between source and destination. The packet delay parameter in WAVE is mostly dependent on the waiting time during CW size; therefore as the number of UEs increases in the network the average delay time would also increase as there will be more packets in the queue to be transmitted during CW.

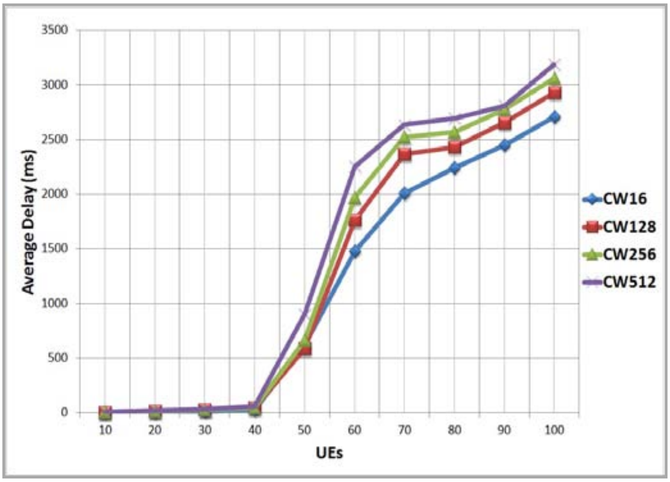

Figure A1. WAVE Case I (ADPP) Average Delay per Packet (Beacon) Results

It can be easily noted in the result of Case I ADPP that WAVE can only support 40 UEs at a time for vehicular safety applications, as after 40 UEs the ADPP has crossed the boundary of 100 ms delay time for safety applications. At 50 UEs the ADPP has even crossed 500 ms delay time bench mark for cooperative traffic efficiency applications. Therefore after 40 UEs the WAVE technology only supports the cooperative local and global internet services. This sever degradation in latency performance after 40 UEs has confirmed the scalability issue in WAVE, since with the increase in the number of UEs there will be increase in number of packets to be transmitted and wireless channel become congested and packet has to wait more and more in the queue of CW before being transmitted which results in overall larger packet delay.

The ADPP results shows the average packet delay which means there is a possibility that some packet delay would have acceded the required safety applications latency boundary of 100 ms, so it is important to know the percentage of packets whose delay is more than 100 ms in every simulation scenario of Case I from 10 UEs to 100 UEs, the results of percentage of packets with delay more than 100 ms is presented in the following
Figure A2.

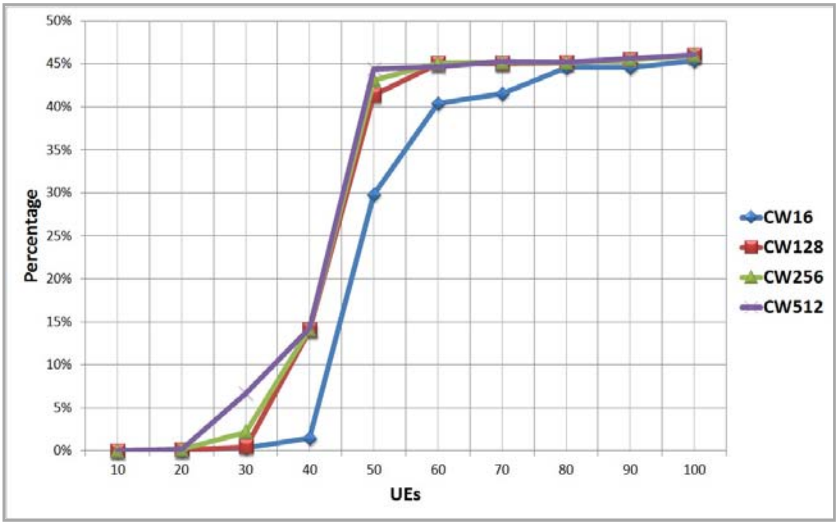

Figure A2. WAVE Case I Percentage of Beacons with Delay > 100 ms

Since from the results of packet delay, it is already confirmed that WAVE with all the four CWs will only support maximum 40 UEs for vehicular safety applications, therefore the result of percentage of beacons with delay more than 100 ms is required for analysis till 40 UEs as after 40 UEs the network in not supporting safety applications. We can see that till 40 UEs for all four CWs the maximum percentage of beacons (delay > 100 ms) is only around 14% of the total transmitted beacons, which means the 86% of the transmitted beacons are qualifying for the latency parameters of vehicular safety applications.

A.2 Beacon Loss Ratio in Case I WAVE

The packet loss ratio is an important parameter to confirm the reliability of network for communication. Again for the packet loss ratio simulations the WAVE technology is simulated with all the four CWs. The greater the CW the lower the packets losses should be. The average packet loss ratio (APLR) results are presented in two conditions, one with QoS implementation and other without QoS implementation. The QoS specification is the packet delay deadline is 100 ms i.e. if the packet delay crosses the limit of 100 ms the packet will be considered as the lost packet, this QoS specification is in accordance to the requirement of vehicular safety applications. The APLR results without QoS and with QoS are presented in the following Figure A3 and Figure A4 respectively.

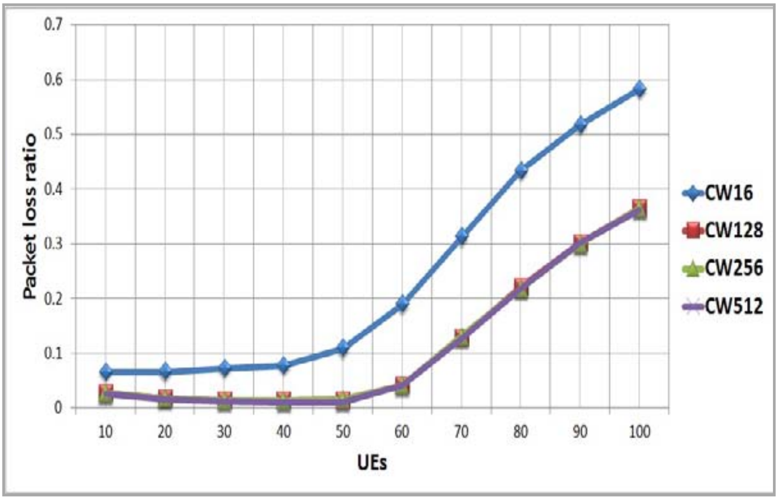

Figure A3. WAVE Case I Average Packet (Beacon) Lost Ratio without QoS

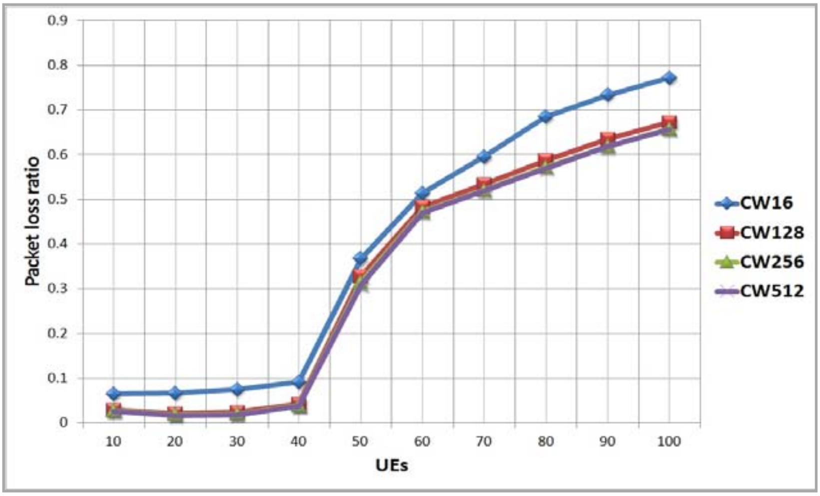

Figure A4. WAVE Case I Average Packet (Beacon) Lost Ratio with QoS

The main reason of packet loss in WAVE is the packet collision on the air interface, this happened because of the possibility that two or more UEs transmitting packet at the same time to the same destination UE the packet will collide and as the number of UEs increases within the network then these collisions will also increase as proved by our simulation results. As we can see the result in Figure A4 that till 40 UEs the packet loss ratio of all CWs is less than 0.1 while the loss ratio of CW of size 512 is smaller than all other CWs throughout.

This can be easily concluded from results of Case I that CW of size 512 is giving the best performance for vehicular safety applications. Since by the performance matrix of ADPP all CWs are supporting safety applications (packet delay less than 100 ms) till 40 UEs but when we see the result of APLR the CW of size 512 is supporting safety applications better than others. It has the lowest packet loss ratio at 40 UEs and after 40 UEs all loss ratio have increased exponentially; this is also due to the fact that packet delay also increased after 40 UEs so with QoS implementation the loss ratio was also bound to increase after 40 UEs. Since CW of 512 has given best performance, therefore for further result comparisons WAVE with CW of size 512 will be considered.