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3GPP LTE Downlink Scheduling Strategies in Vehicle-to-Infrastructure Communications for Traffic Safety Applications

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Abstract — Long Term Evolution (LTE) is the new generation of infrastructure-based wireless technologies that can be used for vehicular communications, and already a standard considered as the preliminary version of 4G mobile communications. It provides a cellular networks-based solution, generally called vehicle to infrastructure (V2I), for vehicular safety applications. In this work, we evaluate the performance of different downlink scheduling strategies under various urban and rural scenarios, in which voice, video and safety data traffic coexist. The traffic safety application scenarios we consider are variations of collision avoidance using LTE-based broadcast communication. Our main evaluation criteria are delay and packet loss rate. We present our findings for each scenario and compare the results.

Keywords — 3GPP long term evolution (LTE); traffic safety; broadcast; vehicular communications; downlink scheduler

I. INTRODUCTION

Vehicular safety communications have the potential to increase the range, coverage of location and behavior awareness of vehicles to develop safety systems for active collision avoidance [1]. The basic idea is to communicate information such as speed, position and direction at a regular basis, so critical and life-saving decisions can be made when required. The last years, numerous projects and consortia have worked on the issues of active safety systems with vehicular communication [2], [3]. In [4] a survey on inter-vehicle communication systems is presented. A good overview of recent projects in this field is given in [5].

There are mainly two realistic ways to disseminate data in a vehicular communication system. First, vehicle-to-vehicle (V2V) communication can be used, where the vehicles organize themselves and transmits data either single-hop or multi-hop. Second, vehicle-to-infrastructure (V2I) communication can be used, where vehicles transmit data to each other via a roadside base station (BS). In this case, the vehicles do not need to be aware of each other, since BS will have total control of the network. A summary of some characteristics of standard network access technologies is given in [5].

The majority of the work on radio-based collision warning systems focuses on V2V communications. In [6], for instance, the authors propose a Cooperative Collision Avoidance (CCA) system to enhance driving safety on

highways. In [7], [8], the authors utilize auxiliary devices such as gyroscopes and Bluetooth radios to improve the accuracy of a GPS-based system. Field trials are conducted to evaluate the performance of the proposed approach.

A V2I application requires a connection with the infrastructure located at the roadside. Cellular networks have been proposed for this purpose for many years [5], [9]. In [10], the author presents the concept car based on 4G technology, and describes various applications like infotainment, diagnostics and navigation. It is shown that the system, working at the data rate of 10 Mbps, operates well up to speeds of 140 km/h. In [11], the authors propose radio-based Collision Warning Systems (CWS) employing V2I communications. They show that the proposed CWS can reduce the number of vehicle collisions without degrading the traffic throughput of the network. Considering the V2I patterns, a TDMA-like channel access scheme between the vehicle and the roadside infrastructure based on the IEEE 802.11b ad hoc mode MAC layer is defined. In [1], the authors compare UMTS and Long Term Evolution (LTE) technologies at intersections, and address the non-line-of-sight (NLOS) reception problem. The article analyzes the suitability of UMTS and LTE for cross traffic assistance in terms of latency and capacity. It also discusses performance influence factors as well as operational aspects.

The main advantage of cellular networks is that the infrastructure is already deployed and operational. Also, many vehicles today are equipped with cellular communication equipment, mainly used for infotainment applications. Early customers will benefit from the applications since the data dissemination is independent of the penetration. Cellular networks have a long history of providing robust mechanism for mobility management proven to work with high cell loads, and reducing the need for extensive signaling, whereas similar add-ons have come later to many other of the standards and have not yet proven in systems with high user densities.

3GPP Long Term Evolution, usually referred to as LTE, is a standard for wireless communication of high-speed data for mobile phones and data terminals [12]. It is based on the GSM/EDGE and UMTS/HSPA network technologies, increasing the capacity and speed using new modulation techniques. The progress has been rapid during the last years with improvements in higher data rates, spectral efficiency, and reduced communication latencies [13].

LTE is an OFDM-based system, and can use channel-dependent schedulers in both the time as well as frequency domains, mitigating the traditional fading effects present in every wireless channel. The scheduler's function is to control dynamically which frequency and time resources will be allocated to a specific user at a given time [14]. It analyzes the channel periodically and decides which users are allowed to transmit, on which frequency and at what data rate. Thus, the scheduler has a crucial impact on the overall performance of the LTE system.

In this paper, we evaluate the performance of different downlink scheduling strategies for LTE when used for traffic safety communication. We develop simulation scenarios in LTE-Sim [15], [16], one of the few open source simulators available for performance simulations of LTE systems. The paper is organized as follows. In Section II and Section III, respectively, we summarize LTE and LTE-Sim. In Section IV, we introduce the simulation settings for our evaluation, and present the results we obtained. Finally, our conclusions are summarized in Section V.

II. LTE – LONG TERM EVOLUTION

The first 3GPP meetings in order to analyze and define the requirements for the evolution of the 3G systems were held in 2004 in Toronto. Some of the high level requirements that were identified in this workshop focused on the evolution of the 3GPP radio-access technology towards a high data rate, low latency and a packet based optimized architecture. As a result of a series of workshops, an agreement was formulated indicating the requirements of the new access network called Evolved Universal Terrestrial Radio Access Network (E-UTRAN) [12].

An LTE BS is supposed to support at least 200 users per cell in active state for spectrum ranges of 5 MHz. From the *Control Plane* side, and regarding the transition time, there are two requirements: The first one is to have less than 100 ms transition time from a camped state (idle mode) to active mode, and the second one to be less than 50 ms from dormant to active state. From the *User Plane* side, less than 5 ms are required in an unload condition, this means when one user has a single data stream.

As LTE is intended to address the increasing demand of mobile data services; E-UTRAN should be optimized for low mobile speeds (up to 15 km/h). However, higher user displacement speeds (between 15 and 120 km/h) should be also supported in an optimized way. Mobility across the cellular network (handover) should be maintained, even at high speeds between 120 and 350 km/h. Throughput, bandwidth efficiency and mobility targets need to be fulfilled within 5 km cells.

The LTE architecture, in both the radio and the core network, was defined to enhance the end to end Quality of Service (QoS) and to optimize the backhaul communication protocols; and E-UTRAN should be packet based but able to support real-time and conversational class traffic. Services have to be delivered to users keeping in mind the Quality of Service (QoS). In this regard, scheduling becomes an important component in LTE.

Since the scheduler plays an important role in increasing the overall performance output, the terminal needs to give feedback to BS about the quality of channel (CQI) as often as possible. The scheduling for the downlink is made in the following way: Based on the CQI received from the user equipment (UE) in the up-link shared control channel (UL-SCH), the scheduler at BS knows about the quality of the channel in the frequency domain, which will help to select the best frequency block that the scheduler will choose to use in the downlink transmission. The scheduler takes this kind of decisions every millisecond and then selects the appropriate number of resource blocks (of 180 kHz each), the size of the transport block (TB) that will implicitly point out the size of the code rate used, the modulation scheme and the antenna mapping information.

Depending on the implementation, the scheduler will determine its scheduling method based on the QoS class and the queuing delay of the available data, the instantaneous channel conditions, or fairness indicators. The challenge for the scheduler is to provide a desired QoS on a shared channel [14]. If the UE provides sufficiently detailed channel-quality information to the eNB, the scheduler can perform channel-dependent scheduling in the time and frequency domain and thereby improve the cell and system capacity [17], [18].

III. LTE SIMULATOR

In this paper, we will evaluate the performance of an LTE system used for vehicular communication. We have performed the evaluations in the simulation tool LTE-Sim [16], developed by Piro et al. [15]. It has been developed to simulate downlink and uplink scheduling strategies in multi-user environments, taking into account UE mobility, radio resource optimization, Adaptive Modulation Coding (AMC) as well as other aspects such as E-UTRAN and Evolved Packet System (EPS). It supports single cell as well as multi-cell environments. Three network nodes have been modeled or implemented: UE, eNB, Mobility Management Entity/Gateway (MME/GW).

A. Data Traffic Generators

Three different traffic generators are provided by the simulator [15], [16]: constant bit rate (CBR), voice over IP (VOIP) and video. CBR traffic generator is used to generate the vehicular communication data packets for the simulation. The data packet size and the interval of transmission can be set by the user. CBR are characterized with low latency and strict Quality of Service (QoS) requirements and hence they are given the first priority in the simulation. The IP header and UDP header is added to the data packet.

The VOIP traffic generator generates G.729 voice flows modeled with an ON/OFF Markov chain, where the ON period is exponentially distributed with a mean of 3 s and during the OFF period has a truncated exponential probability density function with the upper limit of 6.9 s. During the ON period, the source sends data packets of size 20 bytes every 20 ms. On top of the 20 bytes data packet, a real time protocol (RTP) header of 12 bytes is added.

The video traffic generator is based on the H.264 video standard. The average bit rate is kept at 242 kbps. A video

traffic trace is provided by the simulator to be used as a sample video application in the simulations. Video packets are generated periodically every 40 ms. Packet sizes vary.

B. Downlink Schedulers

Scheduling is a process by which a radio resource is allocated to each user optimally. A flow can be scheduled if the scheduler has data packets to send in the MAC layer and UE is not in the idle state. Every transmission time interval (TTI), the scheduler computes a given Weight W_i where i is the i -th user. The scheduler works as follows.

- In the current subframe, eNB creates a list of downlink flows having packets to transmit.
- The MAC queue length and the CQI feedbacks are stored for each flow. For each flow, the metric W_i is calculated.
- The flow with the highest W_i is given the resource blocks. For each flow, eNB computes the transport block size, the amount of data to be transmitted during each TTI.
- eNB uses AMC to map the CQI feedback with proper modulation and coding scheme (MCS).

The schedulers implemented in LTE-Sim are Proportional Fair (PF) scheduler, Modified Largest Weighted Delay First (MLWDF) scheduler, and Exponential Proportional Fair (EXP-PF) scheduler [15], [16].

1) *PF scheduler*: The assignment of radio resources is done taking in account the channel quality and past user throughput. The objective of the scheduler is to maximize throughput. The metric for PF scheduler is given by [15]:

$$W_i = \frac{r_i}{R_i}. \quad (1)$$

Where r_i is instantaneous data rate and R_i is average data rate. The PF scheduler has no QoS parameter as such.

2) *MLWDF scheduler*: It supports multiple data users with different QoS requirements. For each real time data flow (CBR, Video) the weight is given by [15]:

$$W_i = \frac{r_i}{R_i} D_{HOL,i} \alpha_i. \quad (2)$$

The parameter α_i is given by:

$$\alpha_i = -\frac{\log \delta_i}{\tau_i}. \quad (3)$$

Where $D_{HOL,i}$ is the head-of-line (HOL) delay of user i at time t , δ_i is the maximum probability, i.e. packet drop probability, for HOL packet delay of the i -th user to exceed the delay threshold τ_i of the i -th user. MLDWF prioritizes the user with higher HOL packet delay and better channel conditions relative to its average levels.

3) *EXP-PF scheduler*: It is designed to increase the priority of real time flows with respect to the non-real time when their HOL packet delays approach the delay deadline. The considered metric for such a scheduler is given by [15]:

$$W_i = \exp\left(\frac{\alpha_i D_{HOL,i}^{-X}}{1+\sqrt{X}}\right) \frac{r_i}{R_i}. \quad (4)$$

Where the symbols are the same as defined before, and the parameter X is given by the following equation:

$$X = \frac{1}{N_{rt}} \sum_{i=1}^{N_{rt}} D_{HOL,i} \alpha_i. \quad (5)$$

Where N_{rt} is the number of active real time flows.

Both MLDWF and EXP-PF are QoS-restricted and real time schedulers; the main objective of these schedulers is to allocate radio resources as per the QoS requirements. They can be used to set higher priority to vehicular data (CBR). The parameters *packet drop probability* and *delay threshold* are set to the same value for all the applications. The way the scheduler prioritizes resource blocks is, thus, by using HOL with these two parameters.

MLDWF and EXP-PF have previously been compared in [19], but only for a cell radius of 150 m and users moving in random directions with a random speed between 1 and 100 km/h. The schedulers' performance is evaluated under real-time (video streaming) and non-real-time (web browsing) traffic. The authors determine QoS parameters like HOL delay and packet loss ratio (PLR) as their performance criteria. They state that MLDWF prioritizes users with higher HOL and better channel conditions relative to the average, while EXP-PF prioritizes real-time users over non-real-time when their HOL approaches the delay threshold. The throughput and PLR of both schedulers are analyzed; the result is that EXP-PF performs much better than MLDWF as the number of user's increases, which is due to the failure of MLWF to dynamically adjust priorities for real-time traffic according to strict delay requirements.

IV. PERFORMANCE EVALUATION

In our simulations, we lay emphasis on the downlink broadcast transmission of the safety messages from BS to the vehicles. Broadcast is more favorable in emergencies as it is more efficient than multiple unicast and does not put a huge load on the network traffic. (Multimedia Broadcast Multicast Service (MBMS) is already standardized in LTE [12].) The schedulers' delay threshold, packet drop probability, and other simulation parameters we set are listed in Table I.

TABLE I. SIMULATION PARAMETERS AND SETTINGS

Parameter Description	Scenario	
	S1 and S3	S2
Speed (km/h)	30	120
BS distance (m)	500	1500
Payload size (B)	50	50
Packet interval (s)	0.1	0.1
Number of vehicles	5 .. 50 300 .. 600 in S3	5 .. 50
Macrocell radius (km)	3	3
Channel realization model	Urban area	Rural area
Application flow time (s)	10	10
Packet drop probability	0.005 MLDWF 0.010 EXP-PF	0.005 MLDWF 0.010 EXP-PF
Delay threshold (s)	0.1	0.1
Bandwidth (MHz)	10	10
Resource blocks	50	50
Intervehicle distance (m)	10	50

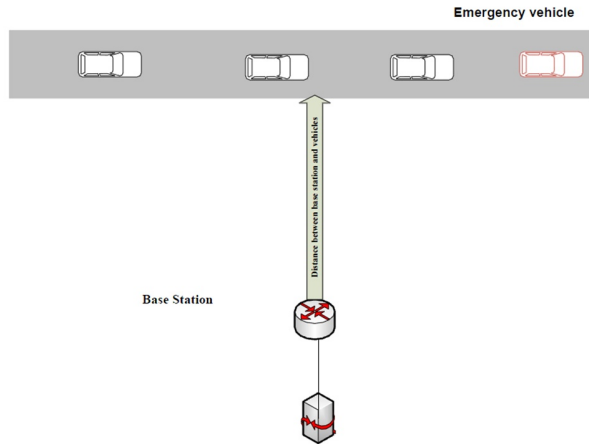


Figure 1. Emergency situation description.

We simulate a generic collision avoidance situation, as depicted in Fig. 1, under three scenarios. The number of cars is our simulation variable. In each scenario, we place the cars on a straight line (representing the road) with an intervehicle distance and speed that we set accordingly. We place a single BS at a certain distance from the midpoint of the platoon of cars, and we set the cell radius accordingly. When simulation starts, the vehicle in the front transmits the initial emergency message to BS (uplink). Upon receiving the message, BS broadcasts it to all the vehicles in the cell range (downlink). BS is assumed to be broadcasting periodically during the entire simulation period. Under each scenario, the vehicles generate all three types of data traffic in parallel. The traffic generators are provided by LTE-Sim as explained above.

The evaluation criteria in our simulations are delay and PLR. The delay is the time interval between the instant the packet is generated at BS and the instant it is received by UE. This value depends on how radio resources are distributed among the users. For this reason, the scheduling strategies and channel quality affect this value. The delay takes into account HOL, defined as the delay accumulated by the first packet in queue, for each MAC queue. HOL is used by the scheduler in order to schedule packets the best possible way.

The delay threshold is one of the QoS parameters of the simulations; it is set to 100 ms. Packets not conforming this threshold are dropped, which, in its turn, affects PLR.

A. Scenario 1: Urban area, 30 km/h

This scenario analyzes collision avoidance for a set of 5 to 50 cars situated around 500 m from BS. The delay for different traffic types and schedulers are shown in Fig. 2. We can see that the MLDWF and EXP-PF scheduler work far better than the PF scheduler considering all the three traffic types. The reason for the better performance is that these two schedulers have drop probability and HOL restrictions. So, the scheduler in BS allocates the best radio resource to the vehicle data. On the other hand, the PF scheduler aims only to maximize the throughput. The target delay is set to 100 ms for vehicular data. With this target delay, the PF scheduler supports up to 30-35 cars, whereas both MLDWF and EXP-PF can support more than 50 without problem. In MLDWF

and EXP-PF, the minimum delay is above 15 ms, which is actually the uplink delay from the emergency car to BS [6].

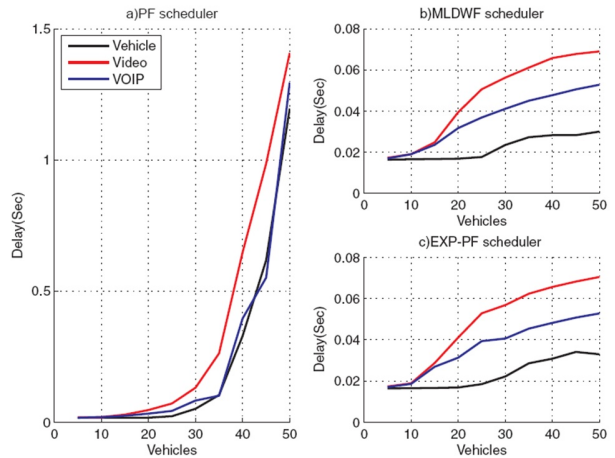


Figure 2. Delay experienced by different traffic types in Scenario 1.

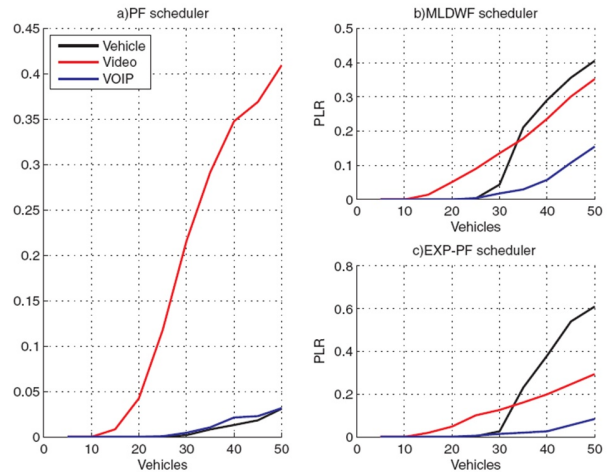


Figure 3. Packet loss experienced by different traffic types in Scenario 1.

The other parameter under analysis is PLR, which lets us know at what rate the packets are correctly received. It also helps to know how the system behaves with the various QoS parameters. The simulated PLR results are shown in Fig. 3. The PF scheduler performs better than MLDWF and EXP-PF. This is due to the fact that the PF scheduler does not take into account the drop probability and HOL as the other two schedulers do. Due to the set drop probability value, MLDWF and EXP-PF experiences more packet losses. With a target PLR of 0.1, the PF scheduler supports all the 50 cars, whereas MLDWF and EXP-PF can support up to 30 cars.

B. Scenario 2: Rural area, 120 km/h

This scenario analyzes collision avoidance for a set of 5 to 50 cars situated around 1500 m from BS. The delay for different traffic types and schedulers are shown in Fig. 4. The delay for the PF scheduler is higher as compared to the MLDWF and EXP-PF scheduler. This is because the PF

scheduler does not have any QoS restrictions while MLDWF and EXP-PF scheduler are QoS aware. Once again, the uplink delay from the emergency vehicle to BS is included in the total delay. With a delay target of 100 ms, the number of vehicles supported by the PF scheduler is 25 compared to 50 in both MLDWF as well as EXP-PF schedulers. As mentioned before, the reason for this is the QoS awareness.

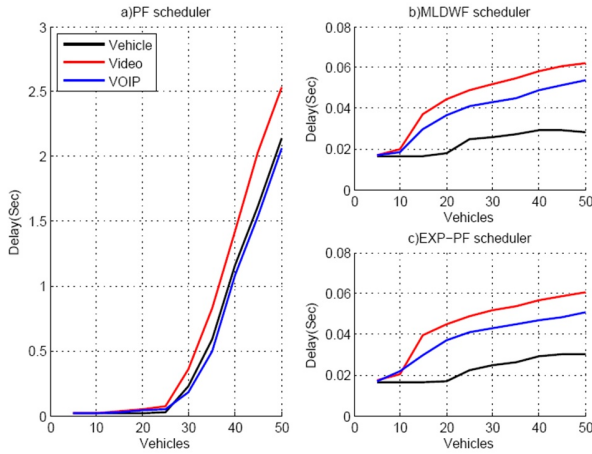


Figure 4. Delay experienced by different traffic types in Scenario 2.

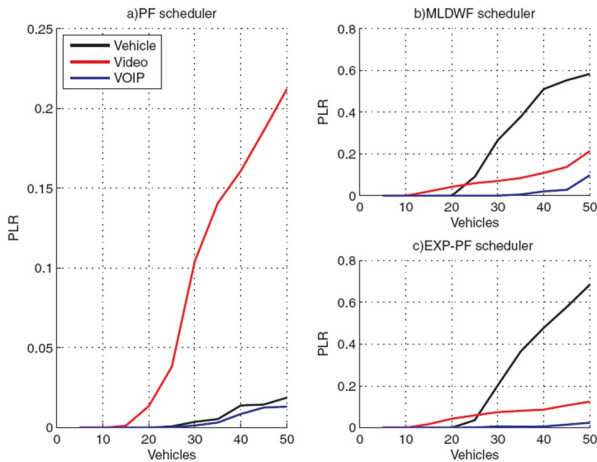


Figure 5. Packet loss experienced by different traffic types in Scenario 2.

The simulated PLR results are shown in Fig. 5. For the same reason mentioned above, the PF scheduler performs better than MLDWF and EXP-PF scheduler. Due to the set drop probability value MLDWF and EXP-PF both experience more packet losses. The target PLR is set to 0.1. With this target PLR, the PF scheduler can support all the 50 cars, whereas MLDWF and EXP-PF both are limited to 25.

C. Scenario 3: Maximum LTE cell capacity

In this scenario, we try to understand the capacity of a LTE macrocell in an urban area with an average speed of 30km/h. As a reference for our settings, we use [14], which assumes 10 intersections with 50 vehicles each. Based on this, the total number of vehicles in a LTE macrocell should

be around 500. We thus simulate the scenario for 300-600 vehicles. The main objective of this simulation set is to analyze how the vehicular traffic data behaves for the given large number of vehicles with the QoS based schedulers (MLDWF and EXP-PF). The background applications, VOIP and video, are thus switched off. From previous simulations, we have observed that both QoS-based schedulers perform in a similar way. Hence, in this section, we focus on EXP-PF.

The results for delay in this scenario are shown in Fig. 6. Logically, the delay increases with the number of vehicles. Nevertheless, the maximum delay never exceeds 100 ms. The EXP-PF scheduler allocates the radio resources successfully below this target delay.

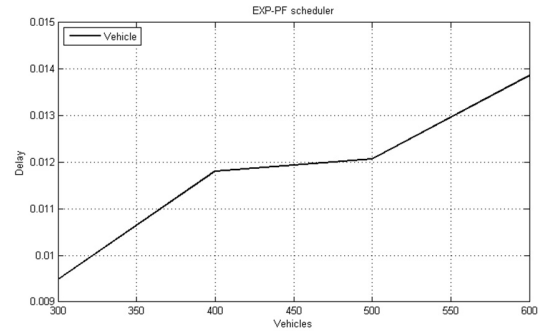


Figure 6. Delay experienced in Scenario 3.

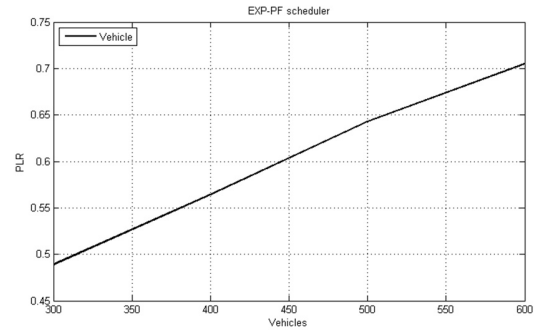


Figure 7. Packet loss experienced in Scenario 3.

As shown in Fig. 7, PLR also increases with the increase in the number of vehicles, the reason being that the probability of dropping packets increases in order to satisfy the QoS parameters. It can be noted that PLR is quite high even if only the vehicular data application is running.

In order to see how many cars one LTE BS can support, one must take into account the tradeoff between delay and PLR. According to our analysis, an LTE BS can serve up to 300 vehicles under the QoS restrictions where the delay is below 100 ms and PLR is around 0.5.

D. Summary

The simulations, with their sufficiently low delay results, suggest that vehicular communication with LTE is a viable option. Although the PLR values are quite high, it should be noted that emergency messages are usually repeated many times, making it possible for the receiver to receive at least a

few messages even under heavy packet loss. Vehicular data can be transmitted in parallel with other services like Video and VOIP. The advantage of using LTE as seen from the simulations that it can serve a certain number of vehicles with given target delays. Nevertheless, we have also seen in our simulations that, although we used broadcasting (point to multipoint) in the downlink transmission, the delay still increased with the number of vehicles. This is, to our understanding, due to the following three reasons: (i) The node receiving the safety message has to be activated first. This activation occurs in a sequential way. As a result, the more the number of vehicles, the greater is the delay. (ii) Since BS uses adaptive modulation coding (AMC), it needs to get the CQI feedback from the different vehicles first, in order to schedule the resources. As the number of vehicles increases, the time to get all the CQI feedback also increases. Hence a higher number of vehicles lead to a larger delay. (iii) As there are more vehicles, the probability of CQI feedback retransmission increases, which, in turn, increases the delay.

V. CONCLUSIONS

LTE is the next generation in mobile communications, and it is feasible to integrate vehicular communications alongside with the standard services provided by LTE technology. LTE is advantageous for broadcasting messages over a large area. As shown by the simulations, the emergency messages can even be broadcast alongside with other services like video and VOIP. In a small coverage area, however, this technology is not as efficient as it could be. The other problem is that LTE based technology works only in licensed spectrum and hence it would be costlier.

Vehicular communications using LTE is well-suited for rural scenarios, where the vehicles are far away from each other and moving at high speeds. In urban scenarios (high node density), on the other hand, where there is a large number of vehicles and the distance between the vehicles is relatively smaller, LTE may suffer from the delays caused mainly by resource scheduling and other, sequential activities. Taking the related research on V2V as a starting point, we can have a discussion on the following alternatives: (i) an LTE-only system; (ii) a combination of V2V and LTE.

In the case of using both V2V and LTE, the motivation is to use the best of both. A hybrid technology using ad hoc and LTE networks together is principally possible, because they operate at different frequencies. The idea is to use LTE to warn vehicles when these are far away from the emergency. As soon as a certain threshold distance is reached, one can switch over to the ad hoc network to send and receive emergency messages. The main challenge that one can face here is the hardware implementation of such a hybrid system.

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