

LTE/LTE-Advanced for Vehicular Safety Applications

by

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Abstract

IEEE 802.11p, the known standard for Vehicular Adhoc NETWORKS (VANETS), suffers from scalability issues and unbounded delay. In addition, the desire to use networks already in existence has created motivation for using cellular networks for vehicular applications. LTE-Advanced is one of the most promising access technologies in the wireless field, providing high data rate, low latency, and a large coverage area. Thus, LTE/LTE-A can be potential access technologies for supporting vehicular applications. Vehicular safety applications are based on broadcasting messages to neighboring vehicles. The vehicle location precision is crucial for safety applications. Thus, the freshness of the information (i.e. vehicle location) at the neighboring vehicles is very important. As LTE is an infrastructure-based network, all transmissions should pass through it. When the load of the network is high compared to the available resources, large delays may occur.

The focus of this thesis is to propose solutions to make LTE suitable for vehicular safety applications. The first solution is to adapt the vehicular safety application to be suitable in LTE network. For this purpose, we propose an adaptation of the safety message generation rate. This adaptation uses a queueing model to compute the freshness of the information of vehicles at the destination, based on their message generation rates. It then adjusts the generation periods to provide a similar accuracy for all vehicles. The second approach is to modify the LTE and make it suitable for these kinds of applications. Thus, we proposed a scheduler for LTE which is suitable for vehicular safety applications. It considers the speed and location of the vehicles to allocate the resources to them for the transmission of safety messages. We also studied the message dissemination in the downlink, and proposed an efficient way to deliver the safety messages to the neighboring vehicles. Finally, we propose a scheme that uses both LTE-D2D and LTE-cellular communication for the transmission of safety messages. The centralized location information is used for Device-to-Device (D2D) pair discovery and resource allocation.

The proposed scheme provides resource efficiency by enabling the reuse of the resources by vehicles. We also study the effect of the awareness range and period of updating location information at the server on resource usage and accuracy of D2D pair detection.

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Publications

The following publications by the author are relevant to this thesis:

Journals

- Hossein Soleimani, Azzedine Boukerche, Thomas Begin. *Safety message generation rate adaptation in LTE-based vehicular networks*. Computer Networks, Elsevier, vol.128, Pages 186-196, 2017.
- Hossein Soleimani, Azzedine Boukerche. *On Vehicular Safety Message Transmissions Through LTE-Advanced Networks*. Ad-Hoc Networks, Elsevier, vol.79, Pages 133-145, 2018.

Conferences

- Hossein Soleimani, Azzedine Boukerche. *A Comparative study of possible solutions for transmission of vehicular safety messages in LTE-based networks*. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Montreal, Canada, 2017.
- Hossein Soleimani, Azzedine Boukerche. *D2D scheme for vehicular safety applications in LTE advanced network*. IEEE International Conference on Communications (ICC), Paris, France, 2017.
- Hossein Soleimani, Azzedine Boukerche. *SLA: Speed and Location Aware LTE scheduler for vehicular safety applications*. ACM International Symposium on Mobility Management and Wireless Access (MobiWac) Cancun, Mexico, 2015.
- Hossein Soleimani, Azzedine Boukerche. *CAMS transmission rate adaptation for vehicular safety application in LTE*. ACM international symposium on Development and analysis of intelligent vehicular networks and applications (DIVANet) Montreal, Canada, 2014.

Glossary

BET: Blind Equal Throughput

BMSC: Broadcast Multicast Service Centre

CAM: Cooperative Awareness Message

D2D: Device-to-Device

DL: DownLink

eMBMS: evolved Multicast Broadcast Multimedia Service

eNB: eNodeB

EPC: Evolved Packet Core

FDD: Frequency Division Duplex

GPS: Global Position system

GSM: Global System for Mobile communication

ITS: Intelligent Transportation System

LTE: Long Term Evolution

LTE-A: Long Term Evolution Advanced

MAC: Medium Access Control

MCS: Modulation and Coding Scheme

OFDMA: Orthogonal frequency-division multiple access

SC-OFDMA: Single Carrier - Orthogonal frequency-division multiple access

PDCCH: Physical Downlink Control CHannel

PDCCP: Packet Data Convergence Protocol

PDCCP: Packet Data Convergence Protocol

PF: Proportional Fair

PGW: Packet Gate Way

ProSe: Proximity Service

PRB: Physical Resource Block

RB: Resource Block

RLC: Radio Link Control

RR: Round-Robin

SC-OFDMA: Single Carrier - Orthogonal frequency-division multiple access

SGW: Service Gate Way

TB: Transport Block

TBS:Transport Block Size

TMGI:Temporary MBMS Group Identifier

TTI: Transmission Time Interval

QoS: Quality of Service

UE: User Equipment

UL: UpLink

UMTS: Universal Mobile Telecommunications Service

V2V: Vehicular to Vehicular

VANET: Vehicular Ad-hoc NETwork

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Chapter 1

Introduction

1.1 Vehicular Applications

Vehicular applications can be categorized into three application categories [5]: safety, traffic efficiency and infotainment applications. Infotainment applications consist of traditional Internet such as content downloading, file sharing, web browsing, using cloud services, other emerging services, such as audio/video streaming, and information and advertisement services. These applications can be extended to video-related services such as video traffic information services. Infotainment applications usually need constant throughput, and are not very delay-sensitive. The range of required data rate varies from 32 kbit/s (for a low quality audio) to even 6 Mbits/s (for high-definition video). On the other hand, the delay requirement varies from 100 ms to large delays (for non delay-sensitive applications).

Traffic efficiency applications are designed to reduce travel time and mitigate traffic congestion. Although the traffic efficiency applications have fewer delay requirements (similar to infotainment applications), their performance gradually degrades with increasing delay and packet loss. These applications are based on floating car data (FCD) service [6]. These data are collected by vehicles and external sensors, and are periodically

transmitted to remote management servers.

Safety applications are intended to reduce the number of road fatalities. These applications are based on broadcasting messages to neighboring vehicles. There are two types of vehicular safety messages: event-triggered and periodic messages [7]. Event-triggered messages are generated in the case of hazardous events on the road, and report to other vehicles. The periodic safety messages are called Cooperative Awareness Messages (CAMs) and are also known as beacons. These are short messages containing the basic information of the vehicle, such as its location and speed. These messages are generated periodically, and broadcast to neighboring vehicles to increase their awareness of their environment.

There are several vehicular safety application use cases such as pre-crash warning, lane-change warning, emergency electronic brake lights, left turn assistant, traffic-signal violation warning. [8, 9, 10]. These applications rely on the periodic transmission of safety messages to the neighboring vehicles or infrastructure (or vice versa). Safety applications require specific location information accuracy, and are very delay-sensitive. Table 1.1 summarizes the required rate, maximum tolerable latency, range and data that should be included in the messages in each use case.

Table 1.1: Safety applications' use cases and their requirements

Application	Comm. Type	Rate	Max. Latency	Data Transmitted	Range
Pre-crash sensing	V2V	50 Hz	20 ms	Vehicle type, position, heading, velocity, acceleration, yaw rate	50 m
Lane-change warning	V2V	10 Hz	100 ms	Position, heading, velocity, acceleration, turn signal status	150 m
Traffic signal violation	I2V	10 Hz	100 ms	Signal phase, timing, position, direction	250 m
Forward collision	V2V	10 Hz	100 ms	Vehicle type, position, heading, velocity, acceleration, yaw rate	150 m
Stop sign assist	I2V or V2V	10 Hz	100 ms	Position, velocity, heading	300 m

1.2 LTE for Vehicular Applications

IEEE 802.11p is the known standard for VANETs. It suffers from scalability issues and unbounded delay [11], [12]. This has not yet been deployed in the real world, and there are only a few pilot projects [13], [14] in existence. In addition to the drawbacks of IEEE 802.11, the desire to use networks already in existence has created the motivation to use cellular networks for vehicular applications. LTE is one of the most promising access technologies in the wireless field, providing high data rate, low latency, and a large coverage area. Thus, LTE/LTE-Advanced can be potential access technologies for supporting vehicular applications. Automotive companies and researchers have begun to evaluate the possibility of using LTE for vehicular applications [15]. Overall, latter works demonstrated the proof of concept of using LTE to run vehicular networks while discussing potential performance degradation, possibly compromising the behavior of safety applications when the network load is too high.

1.3 Thesis Problem Statement

In this thesis, our focus is on safety applications, which are based on the transmission of periodic messages. The vehicle location precision is crucial for safety applications. It is important to note that the location precision is not only related to the accuracy of locating the vehicle, but also to the freshness of the location information at the neighboring vehicles that receive the information. Using GPS devices, vehicle location can be obtained with a high degree of accuracy. However, this information should be transmitted to other vehicles. Two main factors can affect the location precision. The first is the freshness of the information, which is defined as the difference between the current time and the time when the information was generated at the source vehicle. During this time, the source vehicle moves and its location is changed. The second factor affecting the location precision is the speed of the source vehicle. Faster vehicles move more in

the same amount of time, thus leading to larger errors.

Among the factors affecting the location precision, we focus on the freshness of the information, as the location obtained by the GPS device is assumed to be accurate enough, and the speed of the vehicles is a parameter that we cannot change. The freshness of the information depends on the end-to-end delay between the source vehicle and the destination. Freshness also depends on the generation period of the messages.

In the LTE networks, the access network latency is small. Thus, if there are enough resources for users, they do not need to wait to obtain resources, and send the packet as soon as it is generated. In this case, messages are received with the same period as the generation period. However, if the resources are insufficient, i.e. the number of vehicles is too large, the message generation periods are too short, or the number of vehicles is too high, vehicles should wait to get resources before sending their packets. Thus, some packets may be dropped if they are not sent before the new packet is generated. In this case, messages are received at the neighboring vehicles with a period larger than the generation period. This period depends on the generation period of the vehicle, and also the generation periods of other vehicles, which represent the load of the network and also the available resources. Although the LTE has a large bandwidth and can support high data rates, the amount of resources that can be allocated for the safety applications is limited, because other applications (such as infotainment) consume most of the bandwidth. On the other hand, the cost of using LTE is high; thus, it is better to use as few resources as possible for the safety applications.

When using cellular-only communications, vehicles transmit their safety messages to the server in the backbone of the network. The server extracts the information and forwards it to the neighboring vehicles of the transmitter. The network load on uplink depends on the safety message size, message generation periods, and the number of vehicles. Some level of congestion may occur when the load of the network is greater than the available bandwidth. In this situation, some vehicles have to wait longer to get

resources for transmission. This leads to larger delays for some vehicles, affecting the location information accuracy of vehicles on the server. Another parameter affecting the location accuracy is the speed of vehicles. Faster vehicles travel a longer distance in the same time; thus, they are more vulnerable to the latency. We show that using traditional LTE schedulers and considering fixed message generation periods for all vehicles are not suitable for safety applications.

1.4 Thesis Contributions

This thesis makes the following contributions:

1. A speed- and location-aware scheduler is proposed for LTE that is suitable for vehicular applications. This scheduler considers the speed and location of vehicles in order to assign priorities for resource allocation. Faster vehicles, which suffer more from delays, receive priority for the allocation of Physical Resource Blocks (PRB). Simulation results show that the proposed scheduler outperforms existing algorithms by preventing high delays and large position errors for faster vehicles.
2. An efficient is proposed solution for adapting the generation rate of vehicles' safety messages so that each of them experiences the same level of location precision. This fairness is attained using an analytical model, based on a queueing model that approximates the level of precision for each vehicle given their movement speed and their generation rate of safety messages. The numerical and simulation results show the accuracy of the model and effectiveness of the message generation rate adaptation algorithm.
3. A solution is proposed for dynamically discovering the minimum number of resources, i.e. PRBs, that should be allocated by LTE, so as to meet a certain level of location precision for all vehicles.

4. In the downlink, we present three possible approaches for delivering the safety messages to the appropriate vehicles, which can be determined by the server based on the previously received information. We proposed an efficient approach, based on broadcasting which guarantees the delivery of messages to all vehicles.
5. A scheme is proposed that relies on both cellular and D2D communications. Vehicles transmit their safety messages with a longer period to the server, using cellular communications. The location information at the server is used for D2D pair detection and resource allocation. In the following period, vehicles use the established D2D connections and allocated resources to transmit their safety messages to the neighboring vehicles. With our resource allocation algorithm, vehicles are categorized into subsets. The transmission of vehicles in each subset does not produce any interference on other vehicles in that subset. Thus, the same resources can be allocated to all vehicles in a subset, increasing the reusability of the resources.

1.5 Thesis Organization

The structure of this thesis is organized as follows. Related works are studied in Chapter 2. An overview of LTE/LTE-Advanced is provided in Chapter 3. Chapter 4 contains the scenario of safety message transmission through LTE, and proposed solutions for both uplink and downlink directions. Chapter 5 includes the proposed analytical approach to model the safety message transmission, and the proposed safety message generation rate adaptation. In Chapter 6, the proposed D2D scheme and the resource allocation algorithm is presented. Finally, Chapter 7 concludes the thesis, and introduces some future works.

Chapter 2

Related Works

As mentioned in Chapter 1, we propose some solutions to make LTE/LTE-Advanced more suitable for vehicular safety applications. There are two possible approaches to accomplish this. The first approach is to adapt the vehicular safety application so that it is suitable for LTE networks. The second approach is to modify the LTE and make it suitable for this type of application. In the first approach, we will propose a message generation rate adaptation. For the second approach, which focuses on the LTE networks, we propose a scheduler for LTE that is suitable for vehicular safety applications. We also propose a D2D scheme for transmission of safety messages. Thus, in this Chapter, we first survey the works that investigated the suitability of cellular networks for vehicular applications. The beacon rate adaptation algorithms are investigated. Then, different schedulers proposed for LTE networks are introduced. Finally, we explore the studies on D2D communications over LTE networks.

2.1 Investigation of The Suitability of Cellular Networks for Vehicular Applications

A significant amount of research resulted in the development of IEEE 802.11p [16], which is a variant of the IEEE 802.11 standard [17]. Although IEEE 802.11p provides some features such as low overhead, support of high-speed users, and less dependence on infrastructure, it suffers from scalability issues, unbounded delays, and short radio range. Moreover, despite the vast research on the standardization of the IEEE 802.11p, it has not yet been widely deployed in the real world, with only some pilot projects and prototypes in existence [18, 19, 20, 21, 22].

Some drawbacks of IEEE 802.11p, such as scalability issues and unbounded delays [23] on one hand and using already existing networks on the other hand, have motivated researchers and car companies to investigate the possibility of using the cellular networks for vehicular applications. Different cellular networks have been evaluated for different kinds of vehicular applications. Several studies have assessed the performance of different mobile networks to support vehicular applications [24, 25, 26, 27, 28, 29]. Long Term Evolution (LTE) [30] and its enhancement LTE-Advanced are the most outstanding deployed access networks, providing high data rates with low latencies. LTE/LTE-Advanced also support high-speed terminals, and can cover broader areas.

2.1.1 Evaluation of Using Cellular Networks for Vehicular Applications

Many studies have analyzed and evaluated the concept of using the mobile network (e.g. cellular networks) to support vehicular applications [24, 25, 31, 26, 32, 33, 27, 34, 35, 36, 37]. European Telecommunications Standards Institute (ETSI) published a technical report [24] to introduce a framework for public mobile networks in Cooperative Intelligent Transport Systems (ITS). This report evaluated the performance of different

generations of cellular networks (i.e., GSM, UMTS, and LTE) in supporting vehicular safety applications. The obtained results from the CoCarX project [26] proved that using LTE for vehicular safety applications is feasible. However, the results show that increasing the load of the network (e.g., larger number of vehicles) introduces long delays that are not tolerated by safety applications.

3GPP released a technical report on a study of LTE-based V2X services [38, 39]. This report introduced different V2X operation scenarios (i.e., V2I, V2V, V2P) and evaluated the functionalities required for the operation of LTE-based V2X operations. The essential enhancements for LTE interfaces, Physical layer, and RAN protocol are outlined. The performance of PC5-based (D2D link) and Uu-based (Uplink) V2X is evaluated based on a metric known as PRR (Packet Received Ratio) for different distances between vehicles. They concluded that support of V2V based on LTE PC5 interface is feasible, but some essential enhancement for resource allocation and physical layer structure is required. [40] presented an overview of requirements and use cases in V2X communication in LTE networks. Authors in [41] provided an analytical model to evaluate the performance of LTE for vehicle safety services. They used Markov models to determine the number of idle resources required for safety applications. [42] performed an experiment-based study on LTE networks in three different countries to show the possibility of using smartphones for vehicular applications. They also used the NS3 simulator [43] to evaluate the scalability of the smartphone-based solution, and confirmed the potential performance issues (i.e., significant delays) when the total number of vehicles is too large. Hameed et al. [32] compared the performance of IEEE 802.11p standard and LTE for vehicular networks. The authors concluded that LTE is much more suitable than IEEE 802.11p. They also showed that the high levels of the load could increase the transmission latency of safety messages.

2.1.2 Comparative Studies of IEEE 802.11p and LTE

In [44] the authors have performed a comparative study of LTE and IEEE 802.11p for vehicular applications. They evaluated both standards in terms of delay, scalability, reliability and mobility support in different conditions and parameters settings. For the given simulation scenarios and network traffic load, their results show that LTE outperforms network capacity and mobility support as compared with the IEEE 802.11p standard. The authors concluded that the LTE network is suitable for most of the applications and use cases. However, they observed a tendency towards increased latency as the network load increased (in terms of either the increase in cellular traffic load or the number of vehicles). Authors in [25] compared the ability of LTE and IEEE 802.11p for supporting vehicular safety applications using a theoretical framework. They use the probability of successful beacon delivery as the metric. The results show that the ability of the LTE network to support the transmission of periodic safety messages is poor as it becomes overloaded with a larger number of vehicles. In [42], a feasibility study for smartphone-based vehicular networking was completed. The authors conducted the real experiments with the existing LTE networks in three countries. They justified the usability of LTE with measurements of latency and reliability with the experiments. They also evaluated the scalability of the smartphone-based network using NS-3 simulator [43]. The results showed performance degradation for a large number of vehicles. Thus, they suggested decreasing the transmission rate when the number of vehicles increased. Tila et al. [45] proposed a Virtual Drive Test emulation for V2I communications in LTE-A network and compared it against traditional drive tests. Authors in [28] compared the performance of UMTS and LTE for safety communication at intersections. Their study shows that UMTS might suffer from capacity issues, while LTE network can perform reasonably well in these applications. The preliminary study of WiMAX for vehicular networking was conducted in [46], which showed that it can be an alternative for some V2I/I2V communications.

2.1.3 Heterogeneous Network of LTE and other Networks to Support Vehicular Applications

Certain works have proposed a heterogeneous network of LTE and other networks, such as IEEE 802.11p, Wi-Fi [47, 48, 49, 50, 51, 52, 53, 54]. Authors in [55] provide a survey of the Heterogeneous Vehicular NETWORK (HetVNET), that integrates cellular networks with DSRC. The main idea is to divide vehicles into clusters. The intra-cluster communications are based on IEEE 802.11p, and the cluster head collects the messages from cluster members and forwards them to the LTE network. The integration of LTE with IEEE 802.11p for content distribution in vehicular networks is discussed in [56]. A Cluster-based heterogeneous vehicular network (C-HetVNETs) is proposed in [57]. They proposed a framework that employs cluster mechanism and used Markov queuing model to evaluate the performance of inter-cluster and intra-cluster communications. A two-level clustering algorithm is proposed. The cluster head in the first level, reduces the contentions in the MAC layer, while the cluster head in the second level acts as a gateway between V2V and LTE. Although the number of vehicles communicating in the LTE is considerably reduced, the amount of data offered to the LTE is not significantly decreased. Thus, the possible congestion effects might still affect the network performance.

According to the results from the works, which investigated the possibility of using LTE vehicular applications, LTE performs well as long as the network is not overloaded. When the load of the network is high relative to the available resources, large delays occur. This affects the freshness of the information at the server and leads to low location precision for the vehicles (especially the faster ones). These latter studies indicated that the general idea of using LTE for vehicular applications is feasible. However, additional work is required to address the potential performance issues.

Table 2.1: Summary of studies for cellular networks for vehicular applications

Study	Investigated Networks	Method of Evaluation	Summary
[24, 26]	GSM, UMTS, and LTE	Simulation	Evaluated different generations of cellular networks in supporting vehicular safety applications
[38, 39]	LTE/LTE-Advanced	Simulation	Different V2X operation scenarios are introduced and required functionalities are evaluated
[42]	LTE	Experiment/ Simulation	Experiment-based study on LTE networks in three different countries
[25]	LTE, IEEE 802.11p	Analytical model	Compared the ability of LTE and IEEE 802.11p for supporting vehicular safety applications using a theoretical framework
[32, 44]	LTE, IEEE 802.11p	Simulation	Comparative study between LTE and IEEE 802.11p for vehicular applications
[28]	UMTS, LTE	Simulation	Compared the performance of UMTS and LTE for safety communication at intersections
[37]	Cellular mobile network	Simulation/ Analytical	Capacity Analysis for the transmission of Event and Cooperative Awareness Messages in LTE Networks
[36]	LTE	Simulation	A case study of obstacle warning application over cellular mobile networks is investigated
[41]	LTE	Analytical	provided an analytical model to evaluate the performance of LTE for vehicle safety services
[42]	LTE	Experiment-based/ Simulation	experiment-based study on LTE networks in three countries to show the possibility of using smartphones for vehicular applications

2.2 Adaptive Beacons Approaches for Vehicular Applications

Vehicular safety applications are based on broadcasts of periodic safety messages, also known as beacons. These messages contain the basic information about the vehicles, such as location, speed, acceleration, etc. The first approach for making LTE suitable for vehicular safety applications is to adapt the beacon rates. Thus, in this section, we introduce the works that have been done to adapt the vehicular beacon rate. Several adaptive beaconing algorithms have been proposed for vehicular networks [58, 59, 60, 61, 62, 63]. Table 2.2 summarized these algorithms. There are three main approaches for beacon adaptation: beacon rate control, transmission power control, and hybrid approaches.

2.2.1 Beacon Rate Control

The load that beaconing introduces on the wireless channel should be monitored accurately in order to prevent congestion on the wireless channel. If the wireless channel is overloaded and the bandwidth requirement of safety applications is not met, it will result in degradation of vehicular network performance. Thus, the first approach in adaptive beaconing is to control the vehicular beacon rate to prevent network congestion. The beacon rate control can be done based on traffic situation or position prediction.

A- Beacon rate control based on traffic situation

Schmidt et al. [64] proposed a situation-adaptive beaconing. This adaptation is based on the movements of the vehicle, as well as those of surrounding vehicles. The authors also considered macroscopic aspects such as vehicle density. In [65], authors proposed a beacon rate control that focused on cellular-based vehicular networks. The proposed method was a centralized mechanism designed to find an optimal trade-off between the freshness of the information and network congestion. The transmission rate

adjustment is determined based on a metric that is calculated with the transmission rate of the latest received packet and the delay. Feng et al. [66] proposed an Adaptive Beacon Rate Adjusting (ABRA) mechanism for monitoring the network performance; if performance deterioration exceeded a certain threshold, newly adjusted rates were calculated. Authors in [58] investigated the effect of the beacon rate on the network performance. They formulated finding the optimal beacon rates as an optimization problem based on a utility maximization framework. They formed the message utility in a way that considered the reliability requirements of safety messages.

Drigo et al. [67] proposed a distributed beacon rate control algorithm which estimates channel load. They adopted a Fast Drop approach to drop the rate when an event-driven message was detected. The proposed beacon rate adaptation scheme in [68] depended on channel load and information utility. Their method estimated the channel load by channel busy ratio and local density parameters. It then prioritized the vehicles based on the importance of their information and adjusted their beacon rates. Zemouri et al. [61] proposed a method based on a search algorithm. It set an initial rate between the upper bound and lower bound rates, and determined the collision rate and busy ratio. It then updated the upper and lower bound based on these parameters, set the new rate in the middle of this range, and continued to do this until the acceptable collision rate and the busy ratio was obtained. In [69], authors modeled the channel congestion with a Network Utility Maximization (NUM) problem. The proposed Fair Adaptive Beaconing Rate for Inter-vehicular Communications (FABRIC) algorithm solved the dual of the NUM problem by using a scaled gradient projection algorithm. Chabouni et al. [70] proposed a collision-based approach for beacon rate adaptation. They used the detected collision number as a metric for adapting the beacon generation rates. Authors in [71] proposed a beacon rate control algorithm that is based on non-cooperative game theory. Their algorithm assigns a beacon rate to each vehicle proportional to its requirements, while satisfying fairness between vehicles. Sepulcre et al. [72] proposed INTERN (INTE-

gRatioN of congestion and awareness control), that dynamically adapts the transmission parameters of beacons by considering the channel load and the requirements of each vehicle's application.

All aforementioned beacon rate adaptations were designed for the vehicular beaconing in Vehicular Adhoc Networks (VANETs), and are not intended for use in cellular networks such as LTE. Thus, the beacon rate adaptation is performed in a distributed manner and uses only local information or statistical information about the network load. Moreover, most of the proposed methods are based on observing the performance metrics, such as delay and loss, to determine the congestion and react to it by adjusting the beacon rates. Conversely, our proposed mechanism predicts the behavior of the network based on the available resources, and adapts the rates in order to get the best possible results.

B- Beacon rate control based on position prediction

The primary objective of this approach is to reduce the network congestion by eliminating beacons that are unnecessary. Rezaei et al. [73] proposed beacon rate adaptation which is based on predicted locations differences. In their approach, vehicles are modeled as Kalman filter that provides estimations of current vehicles' locations using previous beacon message. This estimation enhances the location accuracy between two consecutive beacon message. When a vehicle finds a change in its location, it will generate the next beacon message. This helps vehicles to estimate the duration of next beacon message. Authors in [74], proposed a mobility-adaptive beacon (MAB) broadcast scheme. They defined guaranteed tracking degree K (GTD K) which means the position of the transmitter vehicle can be estimated by the neighbor vehicles with at least one of the K beacons. The generation of a new beacon is differed until the tracking condition of GTD K is met.

Boukerche et al. [75] proposed an approach that exploits improved neighbor localization scheme. The sender vehicle stores its position information and determines the error between this value (i.e. actual position) and the predicted position. Once this error is

greater than a predefined threshold, it triggered a new beacon message and broadcast it to its neighbors. Liu et al. [76] proposed an approach based on position prediction to reduce bandwidth consumption by decreasing frequency of beacons. Instead of using periodic beacon broadcasting for neighbor tracking, each vehicle tracks its neighbors by the predicted position and broadcast beacons when the prediction error is higher than a threshold. They categorized the vehicles' motions into two categories: constant speed and maneuvering pattern.

Although these beacon rate control can effectively reduce the number of required beacon messages and reduce the congestion on the network, they might not be able to track the rapid topology changes of vehicles.

2.2.2 Beacon Transmission Power Control

The lifetime of the links is short in VANET as vehicles move fast. One of the methods to increase the link lifetime is to increase the radio coverage range by increasing transmission power. However, the increase of transmission power causes interferences and affects the VANET performance, especially when the density of vehicles is high. On the other hand, reducing the transmission power can help reduce the network load and interference. Thus, an adaptive transmission power is an approach to dynamically adapt the power transmission of beacons to satisfy the beaconing requirements.

Lopez et al. [77] proposed statistical beaconing congestion control (SBCC) for transmission power adaptation to control beaconing congestion. Their approach used local information and some feedbacks. Vehicles compute the required power for a given maximum beacon load as a function of beaconing rate, estimated channel parameters and density of vehicles. Authors in [60] proposed to define multiple transmit power levels, each with a specific beacon rate. They modeled the rate selection a problem of network utility maximization (NUM). They maximized the number of beacons received at each transmit power level while satisfying the maximum beaconing load allowed on the chan-

nel. The parameters of the algorithm are set per vehicle and can be dynamically changed. Lei et al. [78] proposed a power control based congestion control scheme that depends on the channel condition and priority of messages. In their scheme, channel conditions are evaluated based on the current channel load and historical transmission delay. Authors in [79] controlled the transmit power to prevent channel saturation to provide the best use of the channel for safety-related applications. They proposed a distributed fair power adjustment for vehicular environments (D-FPAV). Their algorithm controls the periodic messages' load on the channel.

2.2.3 Hybrid Approach

The last approach is a hybrid one which exploits both beacon rate adaptation and transmission power control for vehicular beacon adaptation. Zemouri et al. [61] proposed to jointly adapt transmission rate and transmission power in a way that provides a good level of awareness in shorter ranges while maintaining a proper level of channel utilization and lowest possible collision rate. First, the beacon rate is adapted to meet the channel load and collision rate conditions; In the second step, the transmission power is adapted to guarantee an acceptable level of awareness for neighbor vehicles that are closer. Authors in [80] proposed a congestion control protocol that is a prediction and adaptation algorithm. It jointly adapts the transmit power and rate, using an altruistic short-term prediction algorithm. This algorithm estimates the density of vehicles near a vehicle within the next near future and adapts the transmit parameters in a way that guarantees the beaconing requirements. Authors in [81] proposed an Energy-Efficient beaconing control strategy based on time-continuous Markov model. They formed six different dynamic functions to control the beaconing frequency.

Table 2.2: Beacon rate adaptation algorithms

Authors	Adaptation Method	Performance metric	Centralized	Simulator
Tielert [82]	Beacon rate control	Channel busy ratio	No	NS 2
Sommer [83],[84]	Beacon rate control	Speed, delay, number of collisions	No	OMNET ++
He [85],[86]	Beacon rate control	Reception number, BRR, delay	No	-
Huang [87]	Joint Tx. power and freq. control	Tracking accuracy	No	OPNET
Drigo [67]	Beacon rate control	Channel load estimation	No	-
Schmidt[64]	Beacon rate control	Delay	No	-
Wang [65]	Beacon rate control	Delay, previous Beacon rate		NS 3
Feng [66]	Beacon rate control	Delay	No	NCTUns6.0
Liu[68]	Beacon rate control	Channel busy ratio, local density	No	NS 3
Zemouri [61]	Joint Tx. power and freq. control	Busy ratio, collision rate	No	NS 3
Lopez[69]	Beacon rate control	Delay	No	OMNET ++
Chabouni [70]	Beacon rate control	Number of detected collisions	No	-

2.3 LTE Scheduling

Schedulers are implemented in the MAC layer of the base station (eNodeB). The responsibility of the scheduler is the allocation of the Physical Resource Blocks (PRBs) to the UEs. They compute a metric for each PRB based on the information they have received from control channels (e.g. buffer status, channel condition, required QoS, past resource allocation history, etc.) and the parameters they intend to optimize (e.g. throughput, fairness, latency, etc.). At each TTI (Transmission Time Interval) the packet scheduler computes the metric for the pair of users and PRBs and selects the UE that has the maximum metric on that PRB, and assigns it to that user. For example, if the metric of j th PRB for i th user is $m_{i,j}$ the scheduler selects the k th UE that has the maximum metric on that PRB:

$$k = \underset{i}{\operatorname{argmax}} \{m_{i,j}\} \quad (2.1)$$

this allocation is valid for the next TTI and the scheduler uses the Physical Downlink Control Channel (PDCCH) to transmit the allocation information to the UEs. Users are informed about allocated PRBs for data transmission on the PUSCH (or PDSCH) in the uplink (or downlink) direction using the DCI messages that are included in the PDCCH payload.

2.3.1 Key Design Features of LTE Schedulers

There are some key design features that differentiate the LTE schedulers. The trade-off between these features leads to different schedulers:

- **Throughput and spectral efficiency:** One of the main objectives is to efficiently use the resources to gain the maximum possible throughput. This goal is achievable by assigning more resources to the users that experience best channel conditions.
- **Fairness:** Although maximization of the throughput increases the spectral efficiency, it can cause unfairness among users. In some situations, which is called

starvation, there might be a user that cannot get any resource as it experienced a bad channel condition. Considering the fairness as a key design parameter can ensure minimum guaranteed performance for all users.

- QoS requirement: Each application and user require a certain level of QoS constraints. It is crucial to design schedulers that can prioritize user in resource allocation to provide different levels of QoS for users.
- Scalability and Complexity: As the resource allocation should be performed every TTI which is 1 Millisecond, it is important that the scheduler is low complexity enough.

2.3.2 LTE Schedulers Classification

Depending on the parameters used to compute the scheduling metric, schedulers can be categorized into three categories: channel unaware, channel-aware/QoS-unaware and channel-aware/QoS-aware scheduling [88, 89].

A- Channel Unaware Schedulers

Channel unaware strategies, such as Round Robin, Largest Weighted Delay First (LWDF) and Blind Equal Throughput (BET), do not consider channel conditions and QoS. The Round-Robin scheduler divides the bandwidth equally to the users that have data to transmit. The BET scheduler uses this metric to allocate PRBs to users [90]:

$$m_{i,j} = \frac{1}{\overline{R_i(t)}} \quad (2.2)$$

where $\overline{R_i(t)}$ is the past average throughput of the user i and calculates as:

$$\overline{R_i(t-1)} = \beta \overline{R_i(t-1)} + (1 - \beta)r_t(t) \quad (2.3)$$

The schedulers in this category provide the same level of throughput for all users, regardless of their channel condition. Thus, these schedulers are suitable for situations in

which there is no prioritization between users. They also do not consider the channel condition, either because of simplicity or just due to unavailability of channel condition information. Thus, the performance of these schedulers is not resource-efficient, and also cannot guarantee QoS for users.

B- Channel-aware/QoS-unaware Schedulers

The second category of schedulers is Channel-aware/QoS-unaware. These schedulers consider the situation of the channel and the achievable rates for each user in the resource allocation. There are several proposed schedulers in this category [91, 92, 93, 94]. The scheduler such as Proportional Fair (PF) and its extensions [95, 96, 97, 98, 99] are in the channel-aware/QoS-unaware category. The general metric used by PF scheduler to allocate PRBs is:

$$m_{i,k} = \frac{d_{i,k}(t)}{\overline{R_i(t-1)}} \quad (2.4)$$

where $d_{i,k}(t)$ is the achievable throughput of i th UE in k th PRB and $\overline{R_i(t-1)}$ is the past average throughput of i th UE. The PF metric is a trade-off between fairness and spectral efficiency.

The fair throughput guarantees scheduler (FTG) [100, 101] is a channel-aware scheduler that is designed to provide equal throughput in long-term for all UEs. FTG exploit the temporal variability of the channel to enhance the cell throughput. The FTG uses this metric to choose a user for resource allocation:

$$m_{i,k} = \frac{r_{i,k}(t)}{\alpha_i} \quad (2.5)$$

where α_i is a weighting factor of the i th user and intended to maximize the guaranteed throughput of all UEs in a long time. These factors are computed based on the SINR of the users. The user with a lower average SINR (i.e. poor channel conditions) has smaller weighting factor which means higher priority compared with users with better channel

conditions. Authors in [97] plugged geometric average into the metric of Proportional Fair scheduler to increase the cell's throughput while providing better fairness.

The schedulers in this category can improve the network performance regarding the throughput as they consider the channel condition and SINR in resource allocation.

C- Channel-aware/QoS-aware Schedulers

Approaches that consider both channel conditions and QoS parameters are categorized into the channel-aware/QoS-aware category [102, 103, 104]. Some examples of the schedulers in this category are Modified LWDF (M-LWDF) and Exponential/PF (EXP-PF) and [105, 106, 107, 108, 107, 109, 110, 111, 112, 113]. M-LWDF is a modification of LWDF scheduler, which considers the channel condition and provides bounded packet delay. The M-LWDF uses this metric to assign PRB to the UEs:

$$m_{i,j} = \alpha_i * D_{HOL,i} * \frac{d_{i,k}(t)}{R_i(t-1)} \quad (2.6)$$

where $D_{HOL,i}$ is the head of the line packet delay and α_i is a metric that is calculated based on the QoS requirements of i th UE.

EXP-PF is another channel-aware/QoS-aware scheduler that has the characteristics of PF, and is also an exponential function of the end-to-end delay parameter. The metric used by EXP-Pf is:

$$\exp\left(\frac{\alpha_i D_{HOL,i} - \chi}{1 + \sqrt{\chi}}\right) \cdot \frac{d_{i,k}(t)}{R_i(t-1)} \quad (2.7)$$

where χ is the average of $\alpha_i D_{HOL,i}$ on all active UEs. Authors in [114] proposed an uplink scheduling algorithm for SC-FDMA-based heterogeneous traffic. They considered both individual user QoS requirements and standard specific constraints. They used a utility function that is already used for the downlink to capture the QoS requirements of different types of traffic. Ergul et al. [115] proposed to take Discontinuous reception (DRX) states into account in the design of the packet scheduler. They designed a DRX

and QoS-aware uplink packet scheduler (DQEPS) and form metrics using DRX states, channel conditions, QoS parameters. QoS guaranteed channel-aware (QGCA) scheduler is proposed in [116]. They also considered the buffer status to improve system capacity.

Although the schedulers in this category take the QoS of users into account for prioritizing them in resource allocation, they consider these parameters to be constant in time. However, in vehicular safety applications, users' priority can change over time. For example, in one instance, vehicle A is slower than vehicle B; therefore, it has lower priority. However, in another instance their respective speeds might change, with A moving at a greater speed; thus, it should have higher priority.

Table 2.3: LTE Schedulers

Name	Category	Input parameter					
		Requested bit rate	Instantaneous data rate	Average data rate	Queue size	HOL delay	Max. delay
RR	CH.Unaware				X		
EDF [117]	CH.Unaware				X		
BET [118]	CH.Unaware				X		
PF [119]	CH.-aware/ QoS-unaware		X	X	X		
BATD [120]	CH.-aware/ QoS-unaware		X	X	X		
GPF [121]	CH.-aware/ QoS-unaware		X	X	X		
M-LWDF [122]	CH.-aware/ QoS-aware		X	X		X	X
EXP-PF [123]	CH.-aware/ QoS-aware		X	X		X	X
PSS [124]	CH.-aware/ QoS-aware	X	X	X			
VPM [125]	Semi-persistent				X		

2.4 D2D Communication in LTE-Advanced

Direct Device-to-Device communication is introduced in 3rd Generation Partnership Project (3GPP) release 12 [3], also known as LTE-Advanced. This feature allows devices in proximity to one another to establish a direct connection and transfer data without passing through the infrastructure. D2D communications consist of two main phases: device discovery and data transmission.

2.4.1 D2D Device Discovery

The device discovery phase can be done with or without network assistance [126, 127]. In the latter approach, devices transmit beacons to discover the possible D2D pair in their proximity [128, 129, 130]. Doppler et al. [131] proposed a scheme that relied on device beaconing for device discovery. They divided the devices into groups, each of which used different patterns for beacon transmission. Zhang et al. [132] proposed a direct discovery scheme based on random backoff procedure. The D2D UEs randomly selected a backoff time, and retransmitted their beacons. FlashLinQ [133], a prototype for direct D2D discovery, became the base for the LTE direct technology introduced by Qualcomm [134]. The direct discovery schemes suffer from energy efficiency, and that scanning for devices could lead to battery draining [135]. Moreover, device discovery can fail due to collisions [136].

On the other hand, some network-assisted device discovery methods will exploit the information of EPC for device discovery [137, 138, 139]. Doppler et al. [131] proposed a network-assisted beacon-based algorithm for D2D device discovery, wherein UEs transmit beacons using OFDMA resources. The network-assisted discovery is suitable for cases in which UEs do not have high mobility, and the limited EPC knowledge about the UEs' location is sufficient.

2.4.2 D2D Resource Allocation for Data Transmission

The resource allocation mechanism is the most important part of the D2D communications. The goal of D2D resource allocation for data transmission is to optimally allocate resources to the D2D pairs to optimize a performance metric of interest. D2D UEs can use licensed or unlicensed bands for communications [140, 137]. When the licensed band is selected for D2D communications, it is preferable to use the Uplink band, as it is usually less utilized [141, 142]. There are two modes for D2D communications using the licensed band [143, 144]. The first, underlay mode, refers to the scenario wherein cellular and D2D UEs share the spectrum. The second mode is overlay, where some resources are dedicated exclusively for D2D communications [145]. The majority of the works in D2D resource allocation belong to the underlay mode, and schemes are proposed to maximize the sum-rate of cellular users while satisfying some constraints such as energy limitation [146], spectral efficiency limitation [143], and average CSI [147]. Meshgi et al. [148] proposed a resource allocation for multicast D2D communications. They maximized the sum-rate of cellular users and D2D users under certain SINR constraints. A power-aware scheme is proposed in [149] which formulated the power-aware resource allocation as a MINLP problem, which was divided into four linear programs and optimally solved. Authors in [150] proposed a distributed resource allocation algorithm that also controlled power consumption to increase the network capacity. They used the Stackelberg game model to solve the resource allocation problem. A time division resource allocation was proposed in [151] using the downlink band of the LTE. Here, the base station divides its scheduling period into sets of time-slots. Each time-slot is assigned to a D2D pair to serve more D2D users in the network. Table 2.4 shows the summary of the D2D resource allocation algorithm.

Table 2.4: Summary of D2D resource allocation algorithms in LTE networks

Study	Objective	D2D reuse direction	Overlay/ Underlay	Solution
[152]	Minimize the D2D interference on cellular users	DL and UL	Underlay	Greedy heuristic algorithm
[153]	Maximize the sum-rate	UL	Underlay	Linear optimization
[148]	Maximize the sum-rate of cellular users and D2D users	UL	Underlay	Mixed Integer Nonlinear Programming (MINLP) problem
[154]	Increasing spectrum efficiency	UL	Underlay	Graph-coloring algorithm
[155]	Minimize the D2D transmission time	DL and UL	Underlay	Column generation method
[149]	Increasing spectrum efficiency	DL and UL	Underlay	Mixed Integer Nonlinear Programming (MINLP) problem
[156]	Energy efficiency	DL and UL	Overlay	Optimization problem
[157]	Maximize sum-rate	UL	Underlay	Stackelberg game based

2.4.3 D2D for Vehicular Communications

Cheng et al. [158] performed a feasibility study of D2D for ITS applications. They showed the effectiveness of D2D for ITS applications and proposed a predictive resource allocation, an interference control algorithm, and RSU cooperative scheduling approach for improving network performance. In the proposed resource allocation, they used the vehicles location, speed, and acceleration to predict the location of the vehicle at the time of scheduling. This predicted location information is used for resource allocation. Authors in [159] compared the scalability of IEEE 802.11p and LTE-V2V for beacon transmission. They used an analytical model for this comparison, and showed that LTE-V2V is able to support beaconing transmission. However, there is a trade-off between resource usage and the maximum range in which beacons can be received, which is determined by the definition of the awareness range. Bazzi et al. [160] used an analytical model to do the same comparison between these two technologies. Their results showed that IEEE 802.11p performs well in short ranges, while LTE-V2V is more suitable for longer distances. Authors in [161] investigated the possibility of using LTE-D2D for transmission of data in a platoon of vehicles. They used a pool of LTE resources for resource allocations, in which the foremost vehicle is responsible for coordinating the resource allocations. Their solution reduces the capacity demand by reusing the resources inside and between platoons. [162] evaluated the number of neighboring vehicles that can be managed by LTE-V2V in the awareness range of the vehicles in Half Duplex and Full Duplex radio modes. Their results showed that LTE-V2V can handle tens of neighboring vehicles in Half Duplex mode, and this number is significantly increased in Full Duplex mode. However, the Full Duplex radio needs more complexity.

Prio et al. [163] proposed a methodology to characterize the upper bound performance of D2D in vehicular networking. They assessed the number of required radio resources for the broadcasting of vehicles' CAM. Authors in [164] studied the performance of underlay D2D for vehicular communications. The authors proposed a joint mode selection and

power control for Vehicular D2D communications in order to increase the throughput of the network. The D2D mode is selected when the D2D link is better than the uplink channel quality.

Ren et al. [165] used D2D technique for V2V communication in underlay mode. They used local geographic knowledge about vehicles and cellular users for resource selection to maximize the sum rate of users. [166] compared the CSI-based and location-based radio resource allocation schemes to evaluate the required measurement overhead. Authors in [167] applied a cooperative scheme to overcome the Carrier Frequency Offset (CFO). As both vehicles move, the CFO is twice that of a normal scenario. The cooperative communication can make D2D more suitable for V2V by providing diverse values of CFO.

Ashraf et al. [168] proposed a dynamic clustering algorithm to categorize vehicles into zones. They then proposed a matching game for resource allocation to each V2V pair. A similar cluster-based resource allocation is proposed in [169]; however, (as in [168]), the method for clustering is not properly addressed. Xiguang et al. [170] proposed Location-based Centralized Scheduling Algorithm (LB-CSA). This algorithm allocates random resources to a user. It then selected another user, and if there is a user in its broadcast range that has been allocated RBs, this user cannot get the resources. Otherwise, users that have been allocated RBs in the resource reuse range are checked, and any unused RBs are allocated to this user. A resource allocation scheme is proposed in [171] to maximize the number of simultaneous V2V transmissions. The authors defined resource allocation and resource reuse matrix for each PRB, and computed the mutual interference matrix. They formulated the Rb allocation to maximize the number of concurrent V2V transmissions. As the problem is NP-hard, they proposed a MISR algorithm to solve the problem. Finally, [172] proposed a resource allocation algorithm for V2V underlying a LTE network. They divided the vehicles into clusters, and found the optimal clustering solution based on dynamic programming techniques. Table 2.5 summarized the works

that have been done in D2D for vehicular applications.

Table 2.5: Summary of related works in D2D for vehicular applications

Study	Objective	Summary/Results
[158]	Feasibility study of D2D for vehicular applications	Showed effectiveness of D2D, proposed predictive resource allocation
[159]	Comparison of IEEE 802.11p and LTE-V2V	LTE-V2V can support beacon transmission. Trade-off between resource usage and max. range
[160]	Comparison of IEEE 802.11p and LTE-V2V	IEEE 802.11p has good performance in short range. LTE-V2V is suitable for longer range
[161]	Investigation of the use of LTE-D2D for vehicular platoon	Reduce the capacity demand by reusing resources inside and between platoons
[162]	Evaluation of the number of vehicles that can be handled by LTE-V2V	LTE-V2V can handle tens of vehicles in HD and more in FD mode
[163]	Characterize the upper bound performance of Vehicular D2D	The number of required resources for broadcasting CAMs are assessed
[165]	Resource allocation	Used local geographic knowledge for resource allocation to maximize the sum-rate
[168]	Resource allocation	Clustering algorithm into zones. Matching game for resource allocation
[170]	Resource allocation	Location-based Centralized Scheduling Algorithm for resource allocation
[171]	Resource allocation	Maximize the number of simultaneous V2V transmissions
[172]	Resource allocation	Divide vehicles in clusters. Find the optimal clustering solution using dynamic programming

2.5 Discussion and Summary

In this Chapter, we first presented the studies investigating the suitability of LTE networks for supporting vehicular applications. Overall, these works demonstrated the proof of concept of using LTE to run vehicular networks while discussing potential performance degradation, possibly compromising the behavior of safety applications when the network load is too high.

In Section 2.2, we introduced the proposed vehicular safety messages (beacon) rate adaptation algorithms. Despite the vast number of aforementioned works dealing with adapting the rate of safety messages, they were all designed for the case of vehicular beaconing in Vehicular Adhoc Networks. Their applicability for handling the case of cellular networks such as LTE, which is the matter of interest of our paper, is not clear. Moreover, the overwhelming majority of existing solutions, if not all, rely on the measurement of some network performance metrics, such as loss ratio, delay, latency, and channel busy ratio. These measurements are then used to assess the current level of performance experienced by the network.

Section 2.3 summarized the currently proposed LTE schedulers which play an essential role in improving the performance of the network. Current schedulers aimed to maximize throughput, increase fairness, and providing QoS requirements. However, for vehicular safety messages, the speed and location of vehicles determine their priority. For example, as faster vehicles are more vulnerable to latency and cause large position errors, they should have higher priority in getting resources for safety message transmission.

Finally, Section 2.4 provides the recent works that consider LTE Device-to-Device communications for vehicular applications. We present some studies investigating the possibility of using D2D for V2V. Additional works focused on resource allocation or device discovery. However, we believe there is no comprehensive solution that considers both device discovery and resource allocation for vehicular applications.

Chapter 3

LTE/LTE-A Overview

3.1 Introduction

Long-Term Evolution (LTE) is a standard that is introduced by 3GPP in Release 8-9 document series. It followed by Release 10 that is called LTE-Advanced. In this Chapter, we briefly overview the architecture and specifications of LTE and also present the new features that has been available in LTE-Advanced.

3.2 LTE Architecture

A simplified LTE architecture is shown in Figure 3.1. The LTE network consists of two parts: the access network and the core network. The access network includes User Equipment (UE) and base stations which are called evolved NodeBs (eNBs).

On the other hand, the core network consists of some components such as:

- Home Subscriber Server (HSS) that is a database in the core network and contains information about network subscribers.
- Packet Data Network Gateway (PGW) acts as a gateway to the outside data net-

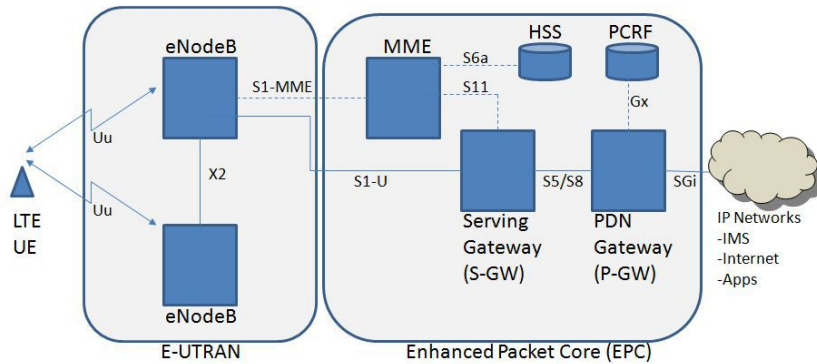


Figure 3.1: LTE architecture [1]

works (e.g. Internet).

- Serving Gateway (SGW) that is a router and transfer data between eNBs and the PGW.
- Policy Control and Charging Rules Function (PCRF) that is responsible for charging and decisions about policy.
- Mobility Management Entity (MME) that controls the mobility of users in high-level using Home Subscriber Server (HSS) and signalling messages.

Our focus in this Thesis is on the access network part, because after the packets are received at the eNodeBs, they will pass through the core network toward the destination. The core network is much less prone to delay, thus it can be neglected for the purpose of estimating the freshness of information.

3.3 LTE Protocol Stack Overview

As shown in Figure 3.2, each IP packet passes through these protocol stack and each layer add its header to the packet. The protocol stack between the UE and eNodeB comprised of four layers:

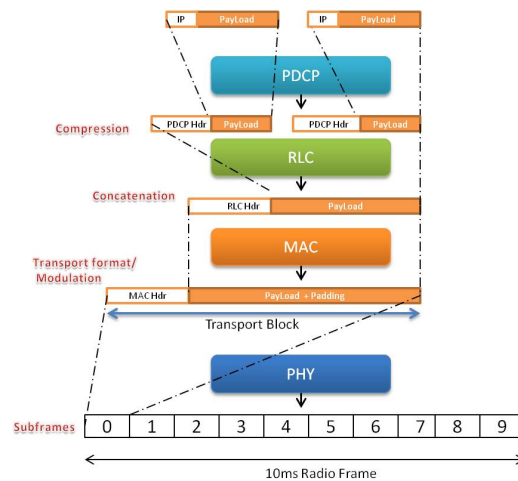


Figure 3.2: LTE protocol stack [2]

- Packet Data Convergence Protocol (PDCP) which is responsible to compress/decompress the header of IP data, Transfer of data (user plane or control plane), ciphering/deciphering of the user plane and control plane data.
- Radio Link Control (RLC) Layer that is responsible for error correction through ARQ and transfers upper layer PDUs. The RLC can operate in three modes: Acknowledged Mode (AM), Unacknowledged Mode (UM) and Transparent Mode (TM).
- Medium Access Layer (MAC) is responsible for Error correction through HARQ, resource allocation between UEs by dynamic scheduling. Data exchange between MAC layer and PHY layer is done in units which are called Transport Blocks (TB). So at MAC layer, the packet is fitted into the TB and is transmitted in one subframe. TB size is a function of Modulation and Coding Scheme (MCS) and the number of available PRBs and can be found in Table 7.1.7.2.1 in [173].
- Physical (PHY) transfer all data from the MAC transport channels through the air interface. It is responsible for power control, link adaptation using Adaptive Modulation and Coding (AMC) and synchronization.

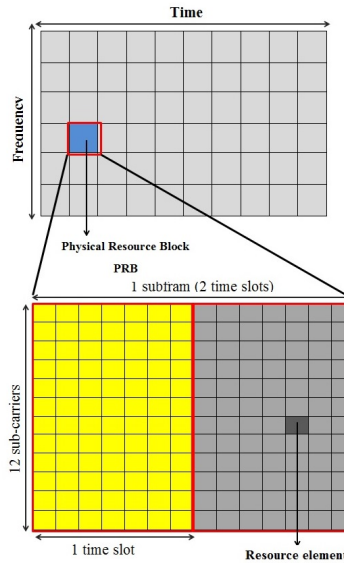


Figure 3.3: LTE Physical Resource Block (PRB)

3.3.1 LTE Physical Layer

LTE physical layer is designed to support multiple channel bandwidths (1.4-20 MHz) and spectral efficiency. LTE uses Orthogonal Frequency Division Multiplex (OFDM) for its physical layer (PHY). It is based on the transmission of data on multiple narrowband carriers over a channel with wideband bandwidth. So each sub-carrier has a flat fading and therefore the frequency equalization would be simpler. LTE uses different technologies for its download and uplink. It uses OFDMA for downlink and Single Carrier OFDMA (SC-OFDMA) for uplink.

LTE frame has a duration of 10 milliseconds. Each frame is divided into 10 sub-frames which is 1 ms. Finally, each subframe comprises two slots with 0.5 ms duration. 6 or 7 OFDM symbol can be transmitted in each slot, depending on the usage of normal or extended cyclic prefix (CP).

In the frequency domain, the bandwidth is divided to sub-carriers. Each sub-carrier is 15 KHz. In LTE, the smallest element that can be allocated to a user by eNodeB is called Physical Resource Block (PRB). Each PRB as shown in Figure 3.3 comprises of

12 consecutive sub-carriers which are grouped and will be allocated to a user for one millisecond.

The number of PRBs depends on total available bandwidth of the LTE network. As LTE supports flexible bandwidth (1.25-20 MHz), the number of PRBs is different for each bandwidth and is shown in Table 3.1.

Table 3.1: Number of PRBs for different bandwidth.

Bandwidth (MHz)	1.4	2.5	5	10	20
PRB Bandwidth	180KHz				
Number of PRBs	6	12	25	50	100

Modulation and Coding Scheme (MCS)

Channel condition impacts the bit rates that users can transmit and receive. LTE can support different bit rates by adapting the modulation and coding. eNB selects the proper Modulation and Coding Scheme (MCS) based on channel condition that each user experiences. The MCS index is selected based on Channel Quality Indicator (CQI) that each UE measures and transmits to eNB. Then eNB maps the received CQI to the MCS based on table. The better channel condition resulted in higher CQI which provides higher data rates.

3.4 LTE-Advanced Features

In this Section we present some new features of LTE-Advanced since 3GPP release 10 was introduced.

3.4.1 Proximity Service (ProSe)

Direct D2D communication using LTE was initially introduced in release 12 of 3GPP. This feature will be included in the LTE networks called Proximity-based Service (ProSe). LTE is natively an infrastructure-based network. Thus, all communications between users should pass through the infrastructure, even if the users are just beside each other. The primary motivation behind D2D communication is to allow UEs that are in close enough proximity to communicate directly, without the base station being involved.

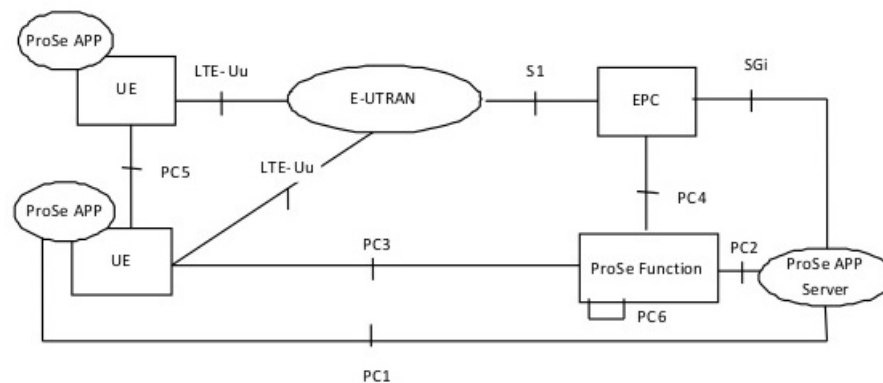


Figure 3.4: ProSe architecture [3].

Figure 3.4 shows a general architecture for ProSe communications. The ProSe function is a logical entity that is responsible for discovery and communications. The ProSe application server stores Prose IDs of users and ProSe functions IDs. It also maps application layer user IDs and ProSe user IDs.

3.4.2 Carrier Aggregation (CA)

The Carrier Aggregation is introduced to increase network capacity by adding more bandwidth. LTE-Advanced provides this increase by aggregating the Release 8/9 (LTE) carriers to maintain backward compatibility. The carriers can have a bandwidth of 1.4, 3, 5, 10, 15 or 20 MHz. Moreover, maximum number of carriers that can be aggregated

is five which provides bandwidth is 100 MHz.

As shown in 3.5, there are three ways to arrange aggregation:

- intra-band contiguous that use contiguous carriers within the same operating frequency band.
- intra-band non-contiguous
- inter-band non-contiguous where carriers belong to different frequency band

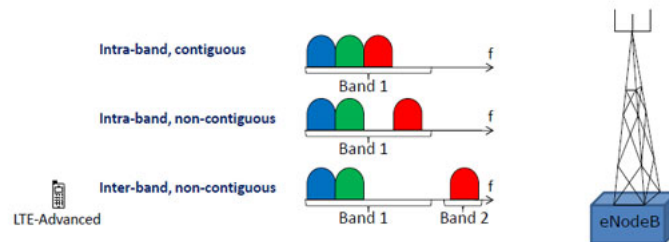
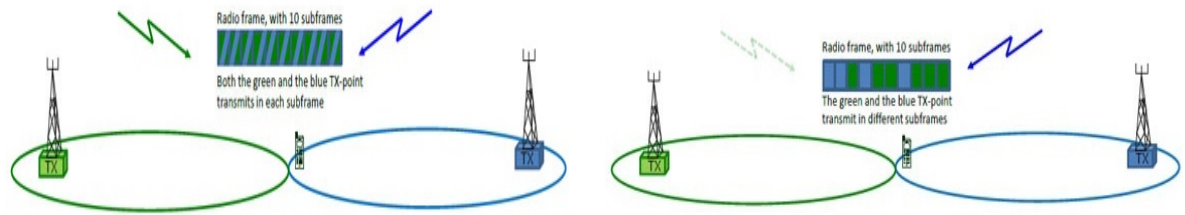


Figure 3.5: Different Carrier Aggregations [4].

3.4.3 Coordinated Multi Point operation (CoMP)

The Coordinated Multi Point operation feature is introduced in Release 11. CoMP improves the cell edge user's performance. In CoMP multiple transmitters perform a coordinated transmission in downlink, and multiple receivers perform a coordinated reception in uplink direction. As shown in Figure 3.6, there are different ways for CoMP:

- Joint Transmission where multiple TX-points transmit in a same subframe and frequency.
- Dynamic Point Selection when only one TX-point is scheduled in each subframe.



(a) Joint Transmission

(b) Dynamic Point Selection

Figure 3.6: Downlink Coordinated Multi Point operation [4].

3.5 Summary

In this Chapter we provide an overview of the LTE architecture, LTE protocol stacks including details of Physical layer. We also presented some features of LTE-Advanced such as ProSe that enables direct D2D communication between UEs, Carrier Aggregation and CoMP.

Chapter 4

Solutions for Vehicular Safety

Message Transmissions Through

LTE

4.1 Introduction

The scheme that we describe in this Chapter is to use only cellular communications for transmission of vehicle safety messages. Every communication is performed through the LTE network infrastructure. Thus, this approach contains two parts: transmission of safety messages toward a central server in uplink direction and delivering the received safety messages to vehicles in the awareness area of that transmitter in the downlink direction. In this Chapter, we first describe the procedure of safety message transmission using cellular connections, i.e., in the uplink direction, and possible ways in the downlink direction. Then we propose some solutions to improve the performance of this scheme and make it more suitable for safety applications.

4.2 Transmission of Safety Messages Through LTE Networks

In this Section, we first describe the procedure of transmission of safety messages using only cellular connections, i.e., the uplink direction toward the server. We then present the possible modes for delivering the messages to the relevant vehicles in the downlink.

4.2.1 Transmitting the Safety Messages in Uplink

In the first step, each vehicle generates a safety message with a period of T_{safety} . These messages consist of information such as position, velocity, acceleration, direction, etc. Each message is fit into an IP packet and will be ready to transmit. Vehicles need to wait for Physical Resource Blocks (PRBs) to send the messages. The MAC scheduler, that is implemented at the eNodeB, is responsible for assigning PRBs to the users. The scheduler can choose from different scheduling algorithms.

Schedulers use specific information of users such as the Buffer Status Report (BSR), channel condition, QoS requirements, past resource usage, etc. to compute a metric for each PRB. The method of metric calculation depends on the parameter to be optimized, e.g., fairness, throughput, latency, etc.. The scheduler assigns each PRB to the UE with the maximum value of the metric. Thus, schedulers play an essential role to improve the performance of the network. After the resource allocation is completed, eNodeB informs vehicles about the assigned resources. Vehicles use these allocated resources to transmit packets to the eNodeB. The eNodeB forwards the packet to the gateways (S-GW/P-GW), and then passes through the Internet, and are received by the server that is located in the core network of the mobile operator or Internet.

4.2.2 Delivering the Safety Messages in Downlink

The server extracts the safety message's information by processing the packet and updates the related information of the vehicle that the packet belongs to. Finally, the server sends the vehicle information to other vehicles in the neighboring area to raise awareness about their environment. The delivery of the safety messages to the appropriate vehicles can be done in three different ways in the downlink: unicast, multicast and broadcast. In the following subsections, we explain these methods in detail and finally propose a mechanism that can efficiently deliver the messages to all concerned vehicles.

Unicast in Downlink

The server can determine the vehicles residing in the awareness area of each vehicle. It then sends the information of each vehicle to its neighboring vehicles separately. The advantage of this method is that the server does not need to wait for packets from other vehicles to be received. It transmits each received packet to the affected vehicles as soon as it receives the message. This method helps to reduce possible latency that occurs by using other methods (multicast/broadcast which we will discuss later). On the other hand, each packet leads to generating n_i packets in the downlink, where n_i is the number of vehicles in the awareness area of the transmitting vehicle, V_i . This number can be more than ten vehicles in dense areas which can impose massive downlink traffic. This high traffic can cause congestion in the network, if the available resources are not enough to handle it and leads to substantial delays that are not suitable for safety applications. Moreover, there might be some errors in the determination of the vehicles in the awareness area of the transmitter vehicle. The server determines the vehicles in the awareness area based on previous received information. The location information is generated at times when vehicles transmit safety messages. Thus, the actual location of vehicles at the time that the server wants to locate the neighboring vehicles might be different than the information on the server, as vehicles move during this time. This difference between

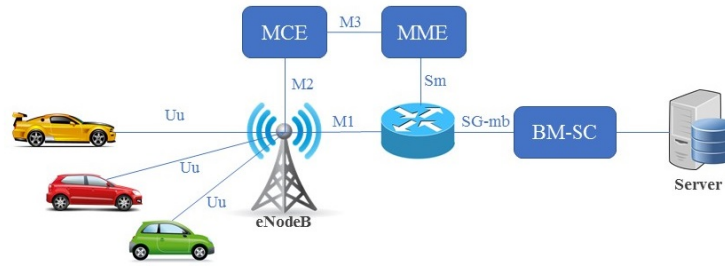


Figure 4.1: MBMS architecture.

the actual vehicle locations and the information on the server can cause an error in neighboring vehicle determination. This can be a false positive error meaning that a vehicle receives the information of another vehicle that is no longer in the awareness area of that vehicle. Another error, which refers to false negative, is the situation when a vehicle is in the awareness area of another vehicle but does not receive its information, as the server could not determine that they are in each others' awareness area.

Multicast/Broadcast in Downlink

The 3GPP, 3rd Generation Partnership Project, initially introduced evolved Multicast Broadcast Multimedia Service (eMBMS) [174], in release 9. The eMBMS is a point to multiple point service that allows LTE networks to transmit data to multiple UEs at the same time. The eMBMS service supports two modes: Multicast Mode and Broadcast Mode. Figure 4.1 shows the architecture that is used for Multicast/Broadcast delivery of the safety messages in the downlink.

The server provides the data that has to be Multicast/Broadcast to the Broadcast-Multicast Service Centre (BM-SC) to schedule and deliver the MBMS data. The BM-SC initiates and authorizes the MBMS bearers. It is also responsible for functions such as membership, service announcement, security, and synchronization for MBMS. The BM-SC labels each MBMS session with a Temporary MBMS Group Identifier (TMGI) that allows UEs to determine different MBMS bearers. The Mobility Management Entity

(MME) provides the MBMS control plane using some functions such as MBMS bearers' session control (e.g., session start/stop), session control message transmissions, etc.

Multicast in Downlink

The multicast service in a general form comprises of eight phases:

1. **Subscription:** Users might subscribe to the services that are provided by the server. The BM-SC stores the information about subscriptions.
2. **Service announcement:** The users are informed about the available service information
3. **Joining:** Each subscriber informs the network that it wants to receive the Multicast data by joining the multicast group of particular service.
4. **Session start:** time when BM-SC is ready to transmit the data. This start time is independent of users' activations.
5. **MBMS notification:** The UEs are informed about the upcoming data.
6. **Data transfer:** The MBMS data are transmitted to the users.
7. **Session stop:** The resources used for the MBMS bearer are released.
8. **Leaving:** Users that do not wish to receive the data anymore leave the multicast group.

In the vehicular scenario, all vehicles are subscribed to the service by default as every vehicle wants to receive safety messages of neighboring vehicles related to them. Thus, this phase can be skipped, or to be more precise is a one-time subscription that vehicles do when they join the network.

A. Server-based single vehicle transmission: In this method, the server determines the vehicles in the awareness area of the transmitting vehicle based on the location information of the vehicles that was last received at the server. For each vehicle, one service is created, and the received information from that vehicle is transmitted to the neighboring vehicles using that service. The MB-SC provides a list of available services that contains N services, where N is the total number of vehicles in the cell. The service announcement data includes information of these services such as IP multicast address, Temporary Mobile Group Identifier (TMGI), and start/stop time of the service. In addition to this information, it contains the list of vehicles which were determined as neighbors of this vehicle. The service announcement is broadcasted in the cell, and each vehicle can determine the multicast services belonging to it. It then joins these services and waits to receive the data from each MBMS service. As vehicles move fast and their locations change, the service announcement should frequently be updated. If a vehicle leaves the current cell, its service will be terminated (another service related to this vehicle will then be started in the next cell). Additionally, the neighboring vehicles of each vehicle are recalculated and will be included in the updated service information. Thus, each vehicle joins the new services that belongs to it and also leaves the services that it is no longer interested in.

B. Vehicle-based single vehicle transmission: This method is similar to the previous one. However, instead of including a list of the vehicles in the awareness area of the transmitting vehicle, the current location of the vehicle is included in the service announcement data. Each vehicle receive the service announcement and, based on the location information of each service, it determines whether it belongs to the awareness area of that vehicle or not. It then joins the related services. Similarly, the service announcement is frequently updated, and vehicles decide to leave or join the new services.

C. Server-based cluster vehicle transmissions: One of the potential problems associate with previous methods is that there should be an MBMS service and bearer for

each vehicle. Thus, the number of services can be large. On the other hand, each service is responsible for transmitting information to only a single vehicle which is typically a small amount of data. Transmission of this data is not efficient. ultimately, the server can create clusters based on the vehicles' location information. Each cluster is assigned to one MBMS service. The messages from vehicles in each cluster are aggregated and multicasted to vehicles in that cluster using the established MBMS service. In this case, the service announcement contains a list of available services where each service represents a cluster and contains a list of the vehicles in that cluster. Each vehicle uses the information in the service announcement to join the service that is related to it. It is worth mentioning that the clusters should have some overlaps; otherwise, the vehicles that are at the edge of a cluster will not receive the information from their neighbors that reside in another cluster.

In the session start phase, the sender (server in this case) requests the MB-SC to establish the MBMS data bearers for the previously discussed MBMS services. Then, the required resource blocks for transmission of each MBMS data block is allocated. In the MBMS notification phase, the vehicles are informed about upcoming MBMS transmissions. Finally, in the data transfer phase, vehicles receive the data from the established MBMS bearers.

Broadcast in Downlink

The broadcast service in general form comprises of five phases:

1. Service announcement: The users are informed about the available service information
2. Session start: time when BM-SC is ready to transmit the data. This start time is independent of users' activations.
3. MBMS notification: the UEs are informed about the upcoming data.

4. Data transfer: the MBMS data are transmitted to the users.
5. Session stop: The resources used for the MBMS bearer are released.

In the broadcast mode, the BM-SC dedicates one MBMS service to the cell and establishes the MBMS bearer. The information about this service is announced, and all vehicles in the cell are informed. The server aggregates the safety messages that it received and broadcasts it to the cell using the established MBMS bearer. Each vehicle receives this data which includes information about all vehicles residing in the cells and then determines which information is relevant (i.e., the vehicles that are in its awareness area) and uses these data, where ignoring the rest.

4.3 Solutions to Improve the Cellular-based Scheme

The transmission of safety messages in the uplink can suffer from congestion problems, which lead to substantial delays that are not suitable for safety applications. In fact, the freshness of information at the server is a key factor that relies on safety messages generation rate and network latencies. Higher message generation rates mean more fresh information which provides more accurate location information. On the other hand, larger latencies mean less fresh information and less accurate location information. It is clear that with a the same generation periods and latencies, faster vehicles suffer more from location information inaccuracy on the server as they move more during the same time, which leads to high position estimation error. We consider this factor and propose two solutions that aim at reducing the location information error of faster vehicles while keeping the average position error the same. We have two approaches to these solutions: modification of the LTE network and modification of the safety application. In the first solution, we introduce a scheduler that takes vehicle speed into account for resource allocation. In the second solution, we propose an algorithm that adapts the generation rate of safety messages based on vehicles speed.

4.3.1 Solution 1: Scheduler for Vehicular Safety Messages

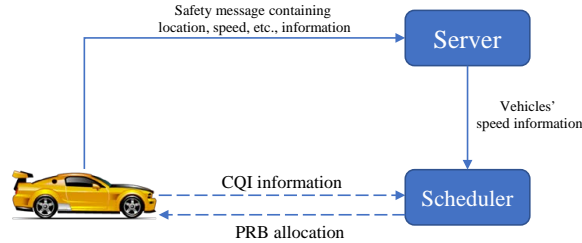


Figure 4.2: Scheduler architecture.

Schedulers play a major role in improving the performance of LTE networks. Several schedulers have been proposed for LTE networks [101]. However, these schedulers cannot meet the requirements for vehicular safety applications.

Channel unaware schedulers such as Round-Robin or Blind Equal Throughput (BET) are not proper for vehicular safety applications, as they assign resources to users equally without considering their priority. Schedulers such as Proportional Fair (PF) [175] and its extensions only consider channel conditions for resource allocation while meeting some levels of fairness among users. Thus, users with good channel conditions have priority to transmit data to maximize the total network's throughput. However, in vehicular safety applications, the delay is more crucial than network throughput. Moreover, faster vehicles are more crucial in safety applications, but due to fast fading, they may experience worse channel conditions. A scheduler, therefore, considers faster vehicles to be lower priority, leading to greater delays for faster vehicles, which is not suitable for vehicular safety applications.

The channel aware/QoS aware schedulers such as Modified Largest Weighted Delay First (M-LWDF) and Exponential/PF (EXP-PF) [88] are also not proper for vehicular safety applications. Although they take into account QoS for prioritizing users in resource allocation, they consider these parameters to be constant in time. However, in vehicular safety applications, user priority can change rapidly over time. For example, at one

instant, vehicle A can be slower than vehicle B; therefore it has lower priority. However, at another instant, their respective speeds might change, with A moving at greater speed; thus it should have higher priority.

We propose a scheduler for vehicular safety applications [176], that takes into account the vehicle information (i.e., speed) for resource allocation. The following presents details of the proposed scheduler, including two phases: providing information to the scheduler computation of the metric used by the scheduler and resource allocation.

A- Providing Required Information to the Scheduler

Schedulers need some information channel quality, buffer status, required QoS, etc., for allocating resources. as shown in 4.2 The UEs, transmit this information to the eNodeB using the Physical Uplink Control Channel (PUCCH)[177]. The primary parameters needed for the proposed scheduler are vehicle speed and channel condition (i.e., Channel Quality Indicator, CQI). The former is needed to compute the scheduling metric that is used for prioritization of vehicles, while the latter is used to determine the proper Modulation and Coding Scheme (MCS) to determine the number of required PRBs for each vehicle. The PUCCH has insufficient capacity, and is intended to carry only crucial information. Therefore, users can only use it for reporting CQI; however, they cannot use this control channel to provide vehicle speed information to the scheduler.

Alternatively, the central server can provide speed information of vehicles to the scheduler. It extracts the speed information from the received safety messages. However, in some circumstances, the server might not have information about a vehicle, e.g., when a vehicle wants to transmit its first safety message or the information of a vehicle is not up-to-date due to the time elapsed since the last message was received at the server. In case, the scheduler can use V_{Avg} , which is the average speed of vehicles in the cell, for that particular vehicle speed. The scheduler uses \widehat{V}_i as the estimated value of i th vehicle

speed:

$$\hat{V}_i = \begin{cases} \left(\frac{\tau_i}{T}\right) V_{Avg} + \left(1 - \frac{\tau_i}{T}\right) V_i & \tau_i < T \\ V_{Avg} & \tau_i > T \end{cases} \quad (4.1)$$

where τ_i is the time elapsed since the last receive message from vehicle i at the server. T is the maximum time that the information of a vehicle is considered to be valid and V_i is the last reported speed of i th vehicle.

B- Calculation of Scheduling Metric:

We introduce two metrics for resource allocation: 1- scheduling based on vehicles' speed, 2- scheduling based on vehicles' speed and region.

B.1- Scheduling Based on Vehicles' Speed

The vehicles with higher speed are more vulnerable to latencies, as their position changes more during the same time compared to slower vehicles. therefore, our proposed scheduler takes into account the vehicle speed as the main parameter to calculate the scheduling metric. However, considering only vehicle speed is not enough; if the scheduler does so, it would always allocate resources to the faster vehicle, and slower vehicle would potentially be excluded from the scheduling. Thus, we consider the time since the last scheduling:

$$T_i = T_{now} - T_i^{last} \quad (4.2)$$

where T_{last} is the last scheduling time of the i th vehicle. Finally, the scheduler metric can then be calculated as:

$$m_i = \theta_i T_i V_i = \theta_i (T_{now} - T_i^{last}) V_i \quad (4.3)$$

where θ_i is 0 if $T_i < T_{safety}$ (T_{safety} is the generation period of safety messages) as the vehicle does not have any message to transmit, and $T_i V_i$ presents an estimate of the maximum distance that the i th vehicle can move during T_i . This distance is equivalent

to the maximum position error if the vehicle transmits the safety message at this time. The scheduler prioritizes the vehicles based on the value of their m value and selects the vehicle with the highest metric for resource allocation. Thus, it is guaranteed that the vehicle that can have largest position error (either due to its high speed or the long time since the last transmitted message) gets resources before other vehicles to prevent larger latencies and errors. After the vehicle with highest metric value is selected, the MCS of that vehicle is selected based on the reported CQI. Thus, the Transport Block Size (TBS) and the required number of PRBs to transmit the safety message of the selected vehicle is determined and will be allocated to it.

B.2- Scheduling Based on Vehicles' Speed and Their Region

As some regions (such as intersections) are more important than other regions, vehicles which are near these regions should have better location accuracy than others. Therefore, the scheduler gives higher priority to the vehicles residing in these regions to send their information.

We define $D_{i,j}$ (see Figure 4.3) as the normalized distance of i th vehicle to center j th important region (e.g. intersection):

$$D_{i,j} = \begin{cases} \frac{|\chi_j - \chi_i|}{D} & |\chi_j - \chi_i| < D \\ 1 & |\chi_j - \chi_i| > D \end{cases} \quad (4.4)$$

where χ_j is the center position of the j th important region, χ_i is the position of i th vehicle, and D is the radius of the important region. Then the normalized distance to the nearest important region is:

$$D_i = \min_j D_{i,j} \quad (4.5)$$

The scheduling metric in eq. 4.3 can be revised as:

$$m_{i,j} = \alpha(D_i)\theta_i T_i V_i = \alpha(D_i)\theta_i (T_{now} - T_i^{last})V_i \quad (4.6)$$

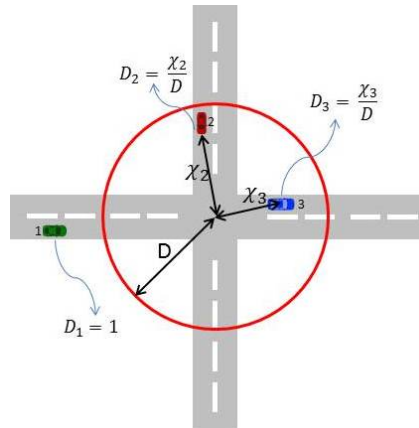


Figure 4.3: Normalized distance of vehicles to the center of an important region

where α is a descending function which has higher value for smaller D_i (i.e. vehicle closer to the important region) and is defined based on the desired safety application.

4.3.2 Solution 2: Safety Message Generation Adaptation

The second solution we propose is to adapt the generation rate of vehicle safety messages based on their speeds. The maximum location error is proportional to vehicle speed and the maximum time between generation of a safety message and the time just before reception of the next message, as shown in Figure 4.4: First message is generated at

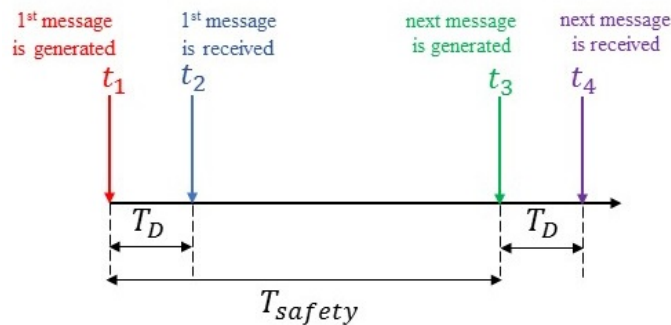


Figure 4.4: Message generation and reception time-line.

t_1 . The server receive this message with a delay T_D and update the vehicle information

based on this message. The next message is generated at t_3 and is received by the server at t_4 . At a time just before reception of this message (i.e. $t_4 - \varepsilon$) the vehicle information on the server belongs to t_1 . However, the vehicle has moved during this time. Thus the maximum location error is the difference between the actual location of the vehicle (at t_4) and the location information on the server (which has been generated at t_1):

$$e_i = v_i(T_{safety} + T_D) \quad (4.7)$$

where, v_i is the speed of vehicle i .

In the previous solution we focused on the network latency (i.e., T_D) by introducing an scheduler that can decrease the network latency for faster vehicles. In this solution we focus on message generation periods (i.e., T_{safety}). The main idea is to increase message generation rates (i.e., decrease the generation period) of the faster vehicles. This helps faster vehicles with higher location errors to send their information more frequently and thereby improve their location precision. However, increasing the generation rate of some vehicles requires more resources. If the required resources are not enough, vehicles should wait to get resources for message transmission. However this increases the network delay, T_D , which is not desirable. Therefore, the message generation rates should be carefully chosen that the total number of required resources is not greater than the total number of available resources:

$$N_{Avg}^{PRB} = \sum_{i=1}^N \frac{N_i^{PRB}}{T_i} < N_{total}^{PRB} \quad (4.8)$$

where N_{Avg}^{PRB} and N_{total}^{PRB} are the average number of required PRBs and total number of available PRBs, respectively, in each sub-frame N_i^{PRB} is the required PRBs for a safety message of vehicle i and is determined based on the message size (which is the same for all vehicles) and the MCS of the vehicles and T_i is the adapted safety message generation period of vehicle i .

As mentioned above, the goal of message generation rate adaptation is to provide the same level of location error. Thus, for vehicles i and j , their location error should be

equal, i.e.: $e_i = e_j$. By substituting into (4.7), we have:

$$v_i(T_i + T_D) = v_j(T_j + T_D) \quad (4.9)$$

Thus, T_j can be obtained in term of T_i :

$$T_j = \left(\frac{v_i}{v_j}(T_i + T_D) \right) - T_D = \frac{v_i}{v_j}T_i + \left(\frac{v_i}{v_j} - 1 \right)T_D \quad (4.10)$$

By substituting T_j in (4.8), an inequality is obtained that is only based on T_i :

$$\sum_{j=1}^N \frac{N_j^{PRB}}{\frac{v_i}{v_j}T_i + \left(\frac{v_i}{v_j} - 1 \right)T_D} < N_{total}^{PRB} \quad (4.11)$$

In this inequality, T_i^{safety} is the only variable that has to be found. Other parameters, i.e. v_i , v_j , N_j^{PRB} , and T_D are constant values. Finding a closed-form solution for T_i in (4.11) is not easy (if not impossible).

If we assume that T_D is too small compare to T_i , then (4.11) can be revised and T_i can be easily found:

$$T_i > \frac{\sum_{j=1}^N \frac{v_j N_j^{PRB}}{v_i}}{N_{total}^{PRB}} \quad (4.12)$$

If T_D is not small compare to T_i , a simple algorithm can be used to estimate the value of T_i . It is initialized with the lowest possible time unit, i.e., one TTI which is $1ms$. At each step, the left side of (4.11) is computed and if it is not satisfied, one time unit will be added to T_i . This loop is continued until the proper value of T_i that satisfies the (4.11) is found. Then, other message generation periods ($T_j, j = 1 \dots N, j \neq i$) are calculated using (4.10).

The message generation periods of vehicles are adapted periodically by the server and it announce the new message generation period to the vehicles.

4.4 Simulation Results

In this Section, we present our simulation results to evaluate the performance of the proposed scheduler for vehicular safety applications as well as the safety message generation

Table 4.1: Simulation parameters

Carrier frequency	2 GHz
Bandwidth	5, 10, 20 MHz
Duplexing mode	FDD
Scheduling algorithm	PF, RR, WFQ and Proposed scheduler
Maximum transmission power of vehicle UE	23 dbm
Number of Vehicles	100 - 1000
Vehicles' speed	50 - 120 Km/h
Safety message size	100 - 500 Bytes
Safety message period	100 ms
Road length	1 Km
Simulation time	100 s

rate adaptation. The simulation parameters are summarized in Table 4.1.

We consider a highway with four lanes. Each lane has a width of 4 meters, and its length is 1Km. The position of N vehicles is determined randomly at the beginning of the simulation. The speed of each vehicle is also selected randomly between 50 and 120 Km/h and is updated every 500ms. We use two values for the size of each safety message, 100 and 500 bytes. The safety message generation period is 100 ms unless we mention another value for a scenario. The operating band of the LTE network is 2 GHz, and we use three different bandwidth, in the simulations: 5, 10 and 20 MHz which provides 25, 50 and 100 PRBs respectively. We also used the well-known WINNER-II (C2) [178] model, to calculate the path loss.

4.4.1 Performance Metrics

We used several metrics to compare the performance of different solutions for the transmission of safety messages in the LTE networks. The first metric is the maximum time between message generation and its reception on the server. This time is proportional

to the safety message generation period and the network latency between the transmission of safety message and its reception at the server. During this time, the server does not have updated information about a vehicle while it moves, as location information is changing. Thus, it is crucial to minimize this time to increase the freshness of vehicles' information on the server.

The second metric that we consider is the maximum distance between the actual position of a vehicle and the location information of the vehicle on the server. This distance is the maximum distance that the vehicle travels while the server has not received updated information. This distance, which can be inferred as the location accuracy of the vehicle on the server, is proportional to the vehicle speed and the maximum time between message generation and its reception on the server. Ideally, it is better to have similar location accuracy for all vehicles instead of having a high accuracy for some vehicles while other vehicles suffer from low accuracy.

In the following, we will evaluate the performance of the proposed solutions based on the introduced metrics.

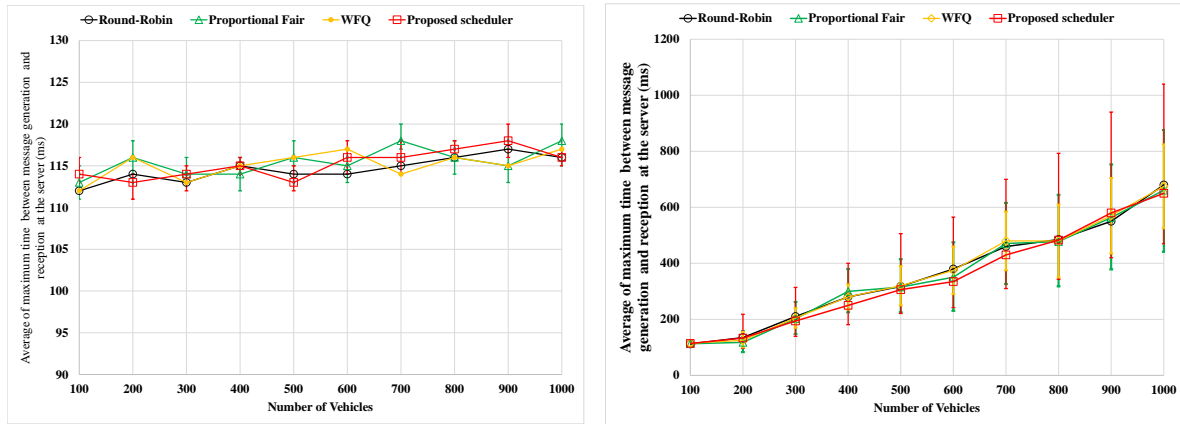
4.4.2 Performance Evaluation of Proposed Scheduler

We compare the performance of our proposed scheduler with the three well-known schedulers, i.e., Round-Robin and Proportional Fair and Weighed fair Queueing. We present the results for two scenarios with different values for safety message transmission period (T), safety messages' size (B) and available bandwidth in terms of number of PRBs (N_{PRB}). These scenarios represent different levels of load on the network. In the first scenario, we choose transmission period of $100ms$, each message size is $100bytes$, and there are 100 PRBs available. As the number of PRBs is enough for transmission of these safety messages, there is no contention for acquiring resources. Thus, on average, the performance of all schedulers is similar and as shown in Figure 4.5a the maximum time between message generation and its reception at the server is basically around $T + T_D$.

Consequently, the accuracy of location information, which is shown in Figure 4.6a is similar for all schedulers.

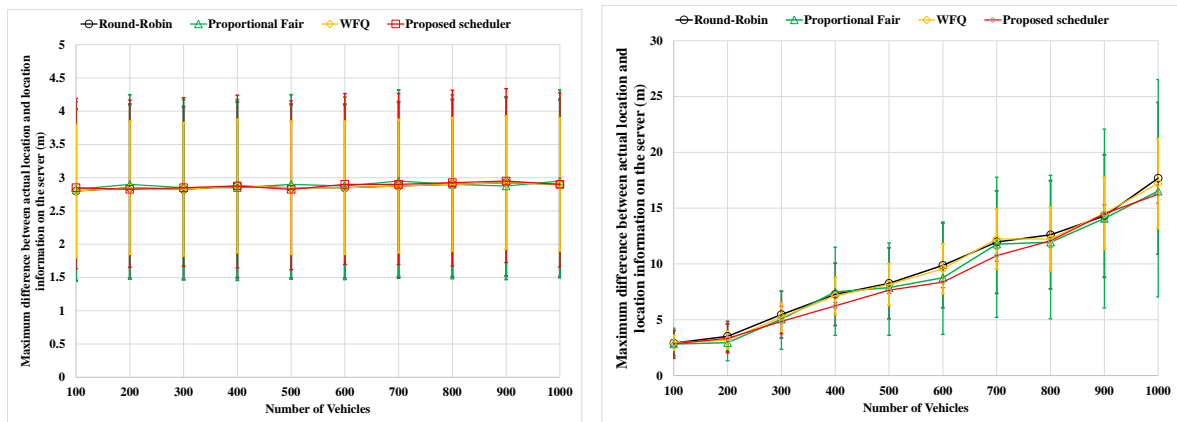
In the second scenario, by increasing the size of messages to 500Bytes and reducing the available number of PRBs to 25, the load on the network increases. When the number of vehicles is less than 200, the number of PRBs are still sufficient. However, by increasing the number of vehicles, the role of the schedulers starts to expose difference. Schedulers prioritize the vehicles based on their criteria and allocate resources to the users with higher priority before others. For the Round-Robin scheduler, the latency of all vehicles increases at the same time, as there is no prioritization implemented in this scheduler. On the other hand, by using PF, WFQ or the proposed scheduler, the experienced latency of vehicles is different. As the PF and WFQ schedulers consider the channel quality in resource allocation, the users with better channel quality get resources before other users. As faster vehicles usually have worse channel condition, they get resources less frequently. Thus it takes more time to update their location information on the server. This effect is less in WFQ compared to PF as it considers the time packet spends in the queue. In contrast, our proposed scheduler gives priority to the faster vehicle to get resources for their message transmissions. Thus it can provide a similar level of location accuracy for all vehicles which is shown in Figure 4.6b, RR, PF and WFQ schedulers lead to lower location accuracy (high position error) for fast vehicles, which is not suitable for safety applications.

We also provide the results based on vehicles' speed in one scenario to better show how the proposed scheduler works. The size and generation period of safety messages are 500Bytes and 100ms respectively. There is also 25 PRBs available. We assumed that the total number of vehicles is 700. Vehicles are categorized into 9 groups. The number of vehicles in each group is the same and vehicles in each group have a speed of $\{50, 60, \dots, 130\}$.



(a) $T = 100ms$, $B = 100Bytes$, $N_{PRB} = 100$ (b) $T = 100ms$, $B = 500Bytes$, $N_{PRB} = 25$

Figure 4.5: Average of maximum time between message generation and reception at the server vs. vehicle number.



(a) $T = 100ms$, $B = 100Bytes$, $N_{PRB} = 100$ (b) $T = 100ms$, $B = 500Bytes$, $N_{PRB} = 25$

Figure 4.6: Maximum difference between actual location and location information on the server vs. vehicle number.

Figure 4.7 shows the Average of maximum time between message generation and reception at the server for vehicles with different speeds. When Round-Robin is used, all vehicles experience similar latencies. As the Proportional Fair scheduler prioritize the users based on their channel condition, the faster vehicles which usually have worse

channel condition will have worst latencies. However, the proposed scheduler provides lower latencies to the faster vehicles by giving higher priority to them. Thus, the proposed scheduler can provide a similar level of location accuracy to vehicles regardless of their speed. While RR, PF and WFQ schedulers lead to high location information errors for fast vehicles as it is shown in Figure 4.8.

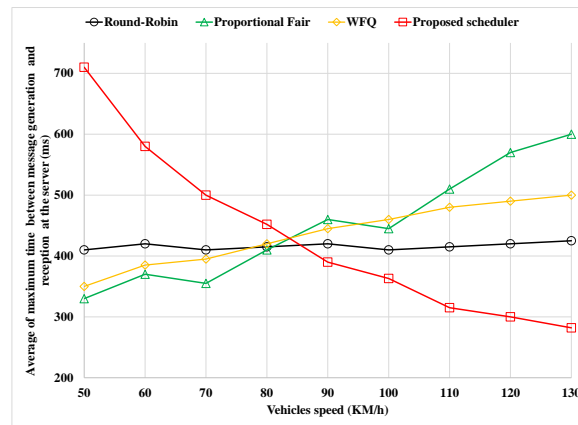


Figure 4.7: Average of maximum time between message generation and reception at the server vs. vehicles speed. $T = 100ms$, $B = 500Bytes$, $N_{PRB} = 25$, $N = 700$.

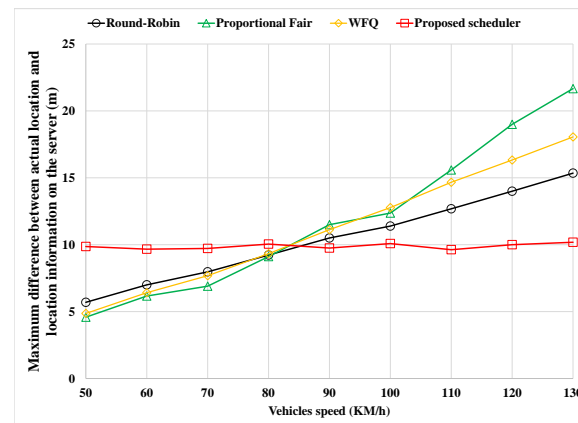
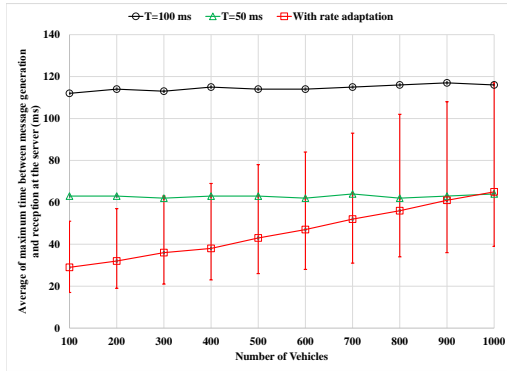


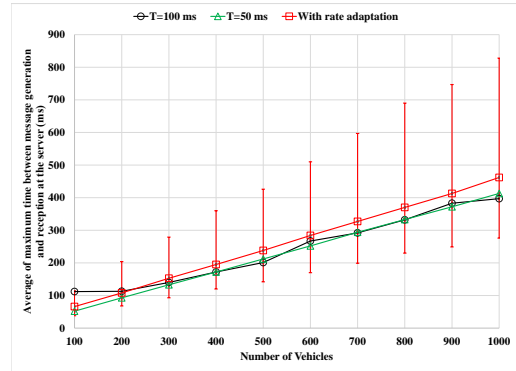
Figure 4.8: Maximum difference between actual location and location information on the server vs. vehicle number. $T = 100ms$, $B = 500Bytes$, $N_{PRB} = 25$, $N = 700$.

4.4.3 Performance Evaluation of Safety Message Generation Adaptation

Finally, we compare the results from the proposed message generation adaptation algorithm and scenarios without adaptation (i.e., fixed generation periods for all vehicles). We consider two generation periods: $50ms$ and $100ms$. When the size of the safety messages are 100 Bytes , and the number of available PRBs is 100 , the load is not high. As shown in Figure 4.6a, the adaptation algorithm results in smaller generation periods and hence, shorter time between generation and reception of the safety messages. Thus adaptation provides better location accuracy as shown in Figure 4.10a. When the message size is 500 Bytes , and the number of available PRBs is 25 , all three cases have similar average time according to Figure 4.9b. However, message generation adaptation increases the generation period for slower vehicles to let faster vehicles transmit with shorter periods (i.e., higher rates). Thus, adaptation provides similar location accuracy for all vehicles. Although using fixed periods leads to the same average location accuracy, the location accuracy of individual vehicles is much different. Figure 4.10b shows that there might be more than $20m$ difference between the actual location of some vehicles and the location information on the server which is not acceptable for safety applications.

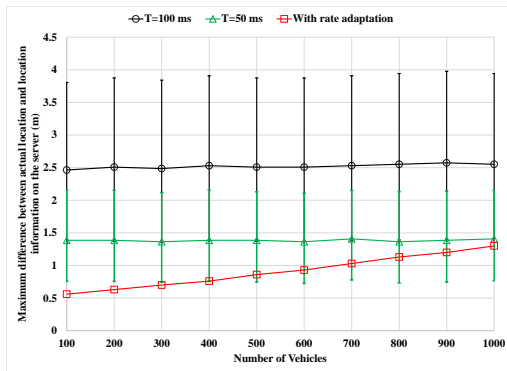


(a) $B = 100\text{Bytes}$, $N_{PRB} = 100$

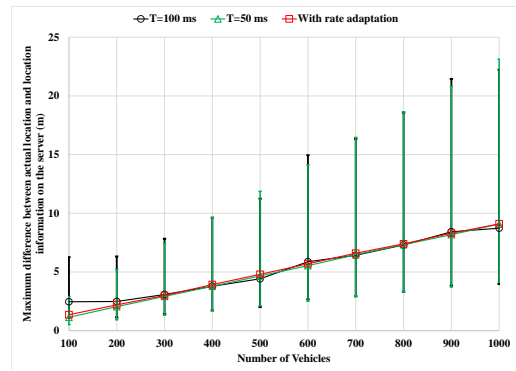


(b) $B = 500\text{Bytes}$, $N_{PRB} = 100$

Figure 4.9: Average of maximum time between message generation and reception at the server vs. vehicle number.



(a) $B = 100\text{Bytes}$, $N_{PRB} = 100$



(b) $B = 500\text{Bytes}$, $N_{PRB} = 25$

Figure 4.10: Maximum difference between actual location and location information on the server vs. vehicle number.

4.5 Summary

In this Chapter, we present an approach that uses only LTE cellular communication. In this approach, vehicles transmit their safety messages to a central server in the uplink, which forwards back the messages to the neighboring vehicles of the transmitter. When network load is high, congestion may occur causing large delays for some vehicles. These delays lead to higher location information error of vehicles (especially faster vehicles) on the server. We propose two solutions to tackle this issue. On the LTE side, we propose a new scheduler, which takes into account the vehicles' speed and the last time their message was received at the server for resource allocation. Thus, faster vehicles obtain resources before slower vehicles. The other solution is an adaptation of safety message generation periods. We propose an algorithm that considers vehicles' speed and available bandwidth to adapt the message generation periods. Our proposed solutions provide the same level of location information accuracy for all vehicles, regardless of speed.

Chapter 5

Analytical Model for Vehicular Safety Message Generation Rate Adaptation in LTE

5.1 Introduction

In this Chapter, we propose a solution to efficiently adapt the generation rate of safety messages based on the vehicles' speeds, so as to increase the fairness among the different vehicles. The general idea is simple: decreasing the message generation rate of the vehicles undergoing better location precision, while allowing other vehicles with worse precision to send their measurements at higher rates. However, determining the current location precision for each vehicle is not straightforward. Indeed, it is a function of both the end-to-end delay between the vehicle taking the GPS measurement and the vehicle receiving this data and the rate at which periodic safety messages are generated.

We estimate the location precision of each vehicle using an analytical model that captures the competing access of vehicles to the resources of the LTE network, as specified

by the LTE scheduler. The solution to the model returns the rate at which safety messages are transmitted and received based on the current number of vehicles in the LTE cell, and on the rate at which periodic safety messages are generated.

Our proposed model is conceptually simple, computationally scalable with the number of vehicles, and in general, delivers accurate results. Together with the GPS measurements and the speed of vehicles, our model provides the missing piece for evaluating the overall precision (or committed error) of the location of neighboring vehicles. Our approach is different from other adaptation techniques as we used an analytical model for predicting the expected performance of the network, while others rely on observed performance metrics such as delay and loss. Moreover, unlike other existing techniques, our solution provides fairness in location accuracy by considering the speed of vehicles in rate adaptation.

Another contribution of this Chapter is to help the LTE operator determine how many resources from LTE should be allocated, so as to meet some guarantees regarding the location precision experienced by the vehicles. Of course, the amount of required resources highly depends on the current number of vehicles and on their speeds. We propose a simple approach for addressing this type of capacity planning issue.

5.2 Location Precision and Safety Message Periods

We now discuss the relations between the generation, transmission, and reception rates of safety messages, and the precision of vehicle location. Let T_{g_i} , T_{t_i} and T_{r_i} denote the corresponding periods for the message generation, transmission, and reception of vehicle i , respectively. Note that, for the sake of simplicity, we temporarily assume that all vehicles generate safety messages at the same rate so that we can drop the index i . The rate at which safety messages are effectively transmitted over the wireless channel depends on the degree of contention. If there is no congestion, safety messages are

scheduled by the eNB at the next TTI immediately after their generation. It follows that T_g and T_t match as shown by Figure 5.1a (in fact, they may differ at most one TTI). On the other hand, if LTE resources are not enough, some safety messages may have to wait before being assigned to a PRB, and eventually, a packet may be overwritten (dropped) by newer one if its waiting time exceeds T_g . Figure 5.1b illustrates this situation, in which T_t exceeds T_g . Once safety messages have been transmitted over the access part, they are conveyed through the core network of LTE up to the server. The delay associated with the core network, denoted by D , is typically small and, more importantly, close to deterministic. Under this deterministic assumption, T_t and T_r coincide. Now, from the server point of view, the freshness of information, which contributes the determination of the overall accuracy of the vehicles' coordinates, is a function of both T_r and D . As a reminder, we refer to freshness as the length of time since the measurement was taken. Clearly, from Figure 5.1, it follows that the freshness value is at least equal to D and is bounded above by $D + T_r$.

For any given vehicle, we define the location precision for a given vehicle i as being the distance that the vehicle has traveled since the last measurement at the server disposal was taken. We denote by e_i the location precision of vehicle i . Recall that the freshness of measurements precisely denotes the time period between the measurement generation at the vehicle and the current time at the server.

It follows that the location precision of each vehicle i , can be calculated as follows:

$$e_i = (T_{r_i} + D) \cdot v_i \quad (5.1)$$

where v_i is the speed of vehicle i whose value is embedded in the safety messages, and is hence known by the server.

Of course, Eq. 5.1 indicates that the greater the speed of a vehicle, the larger its error on its location and worse location precision.

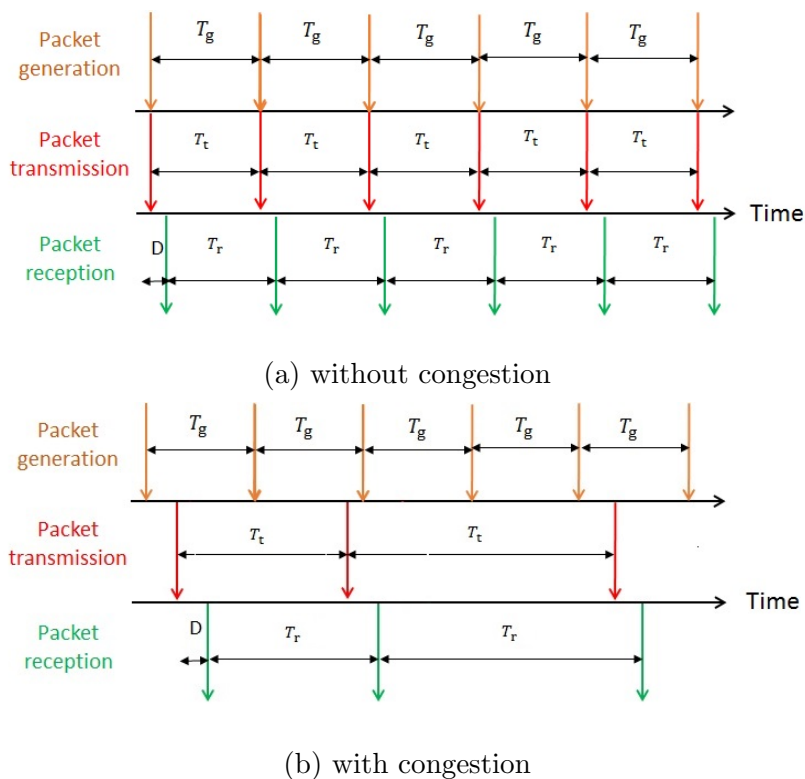


Figure 5.1: Generation, transmission and reception times.

Assuming that the error on the location for a set of vehicles is deemed too large (or equivalently, their precision is too low), a tempting solution could consist of increasing their safety message rates, i.e. decrease their generation periods T_g . This simple solution will work as long as the LTE access network is not congested. Otherwise, it may actually worsen the situation, because increasing the safety message rates of vehicles may, in fact, lead to more congestion. Therefore, in the next section, we propose an adaptive solution that increases the message generation rate for some vehicles while reducing it for others, so that vehicles experiencing the worst precision get a better location precision and the overall strain on the network resources is kept to a moderate level.

5.3 Adapting the Generation Rate of Safety Messages

Setting vehicles' safety message rates so that vehicles all experience the same level of location precision is not an easy task. Indeed, if every vehicle generates safety messages at the same rate, then their safety messages should undergo, on average, the same level of freshness. However, because vehicles run at different speeds, they will experience various degrees of precision on their location. This unfairness seems rather unfit for safety applications. A more desirable situation would be that all vehicles undergo the same (good enough) level of precision on their location.

In this section, we propose a solution to adapt generation rates of safety messages so that each vehicle ultimately experiences a similar degree of precision on their location. However, our solution assumes that the freshness of safety messages are known. Hence, prior to the solution description, we come up with an analytical model to calculate these freshness values.

5.3.1 Analytical Model to Approximate the Freshness of Safety Messages

Computing the freshness of safety messages is not a straightforward matter because they are not a linear function of the aggregated generation rate of safety messages of all vehicles (representing the workload) and of the available LTE resources. To derive their values, we introduce an analytical model that captures the way that safety messages generated by vehicles compete to gain access to the radio channel.

We decided to make use of the queueing theory to model the interactions between safety messages. Alternately, Petri nets could be applied, provided that the more complex timed Petri nets are considered in order to take into account the timing.

Table 5.1: Notations used for the analytical model

N	Number of vehicles
C	Number of available PRBs in each slot
T_{g_i}	Safety message generation period of vehicle i
T_{t_i}	Safety message transmission period of vehicle i
T_{r_i}	Safety message reception period of vehicle i
$\lambda_i = 1/T_{g_i}$	Safety message generation rate of vehicle i
T_{v_i}	Expected value of vacation time for queue i
p_i^{full}	Probability that queue i has a message to send when server arrives
N_{PRB}	Required number of PRBs for each message transmission
τ	Duration of one time slot

Table 5.1 summarizes the notations used in the model. The model comprises a set of N queues representing the N vehicles and a set of C servers representing the C PRBs allocated by LTE. Each queue i ($i = 1, \dots, N$) is fed according to the generation rate of the corresponding vehicle i whose period is given by T_{g_i} . For the sake of simplicity, we refer to $\lambda_i = 1/T_{g_i}$ as being the message generation rate at node i . The size of queues is limited to 1 because newer messages overwrite unsent messages. Each server requires exactly one time slot, i.e. 1 ms, to complete the transmission of a safety message. Finally, the C servers (which are shown as PRB_1, \dots, PRB_C) simultaneously exhaust the N queues in a way that is determined by the LTE scheduler. Therefore, we represent the entire system architecture by a polling model, as depicted in Figure 5.2.

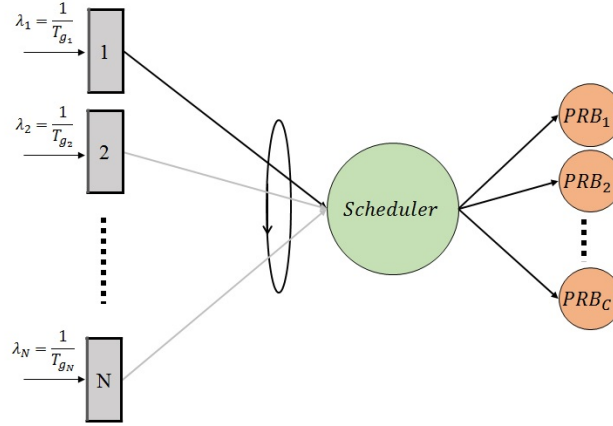


Figure 5.2: Model of transmission of safety messages through LTE.

The solution to a polling system has been vastly documented in the literature [179],[180]. However, even under simplifying assumptions (e.g. Poisson arrivals and exponential distributed service times), the exact solutions to polling system remain complex, involving typically numerical Laplace transforms, and become unscalable with a growing number of queues (N here) and of servers (C here) due to the exponential growth in the number of states within the associated Markov chain.

Instead, we propose a simple and approximate solution that relies on the use of servers with vacation [181] to capture the involved interactions between queues and servers. We decompose the original polling system into a set of N separated queueing models with server vacation, as illustrated in Figure 5.3. Upon its processing by a server, queue i becomes and remains empty until the next message generation, at most T_{g_i} . It may then have to wait until a server serves it again. This waiting time, corresponding to the processing of packets by servers at other queues is denoted as the vacation time.

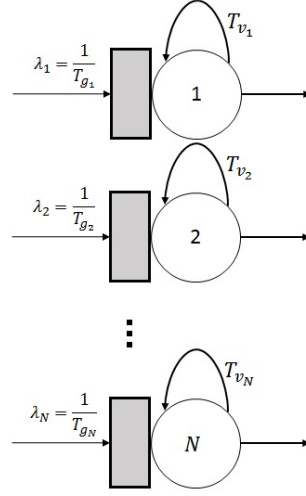


Figure 5.3: Decomposition of the polling system into N queues with server vacation.

Thus, we are now dealing with N separate queues, each with constant inter-arrivals (aka deterministic), a queueing room restricted to one, constant service times, and a single server that leaves on vacation upon completing message processing. Let T_{v_i} denote the expectation of the duration of a vacation for queue i . We express it as:

$$T_{v_i} = \left(\sum_{j=1: j \neq i}^N p_j^{\text{full}} \right) \frac{N_{PRB}}{C} \cdot \tau + \tau \quad (5.2)$$

where p_j^{full} is the probability that queue j has a message to send when one of the C servers arrives, N_{PRB} is the required number of PRBs for each message transmission, and τ is the duration one PRB, which represents the transmission time of one message and is equal to 1 ms. Note that the first term in Eq. 5.2 reflects the the mean number of vehicles that have a message to be sent and the second term is the number of required PRBs for each each message over the number of servers C , leading to an estimation of the waiting time a message has to be kept before getting processed. The computation of T_{v_i} involves p_i^{full} which can be calculated as follows:

$$p_i^{\text{full}} = \begin{cases} \frac{T_{v_i}}{T_{g_i}}, & T_{g_i} > T_{v_i} \\ 1, & T_{g_i} \leq T_{v_i} \end{cases} \quad (5.3)$$

Indeed, if the message generation period of a queue is smaller than its vacation time, i.e. $T_{g_i} \leq T_{v_i}$, then at least one safety message will be generated during the vacation time, and the corresponding queue is sure to be found full when the server returns from its leave. On the other hand, if the message generation period is larger than the vacation time, Eq. 5.3 simply states that the probability that the queue is found full when the server returns from its leave increases linearly with its generation period.

The time between two successive transmissions for node i can be viewed as a geometric random variable with parameter p_i^{full} re-drawn every T_{v_i} time unit. Therefore, its expectation, i.e. T_{t_i} , can be computed as follows:

$$T_{t_i} = \sum_{n=1}^{\infty} nT_{v_i} (1 - p_i^{\text{full}})^{n-1} p_i^{\text{full}} = \frac{T_{v_i}}{p_i^{\text{full}}} \quad (5.4)$$

Finally, because we assume that potential delays beyond the LTE uplink are negligible, we have:

$$T_{r_i} \simeq T_{t_i} \quad (5.5)$$

Note that Eq. 5.2 (resp. Eq. 5.3) expresses T_{v_i} (resp. p_i^{full}) as a function of p_j^{full} ($j = 1, \dots, N : j \neq i$) (resp. T_{v_i}). Therefore, we first resort to a fixed-point iteration to discover the values of T_{v_i} , and then apply Eq. 5.4 and 5.5 to obtain T_{r_i} (as shown by Algorithm 1).

We now evaluate the accuracy of the proposed approximate solution in obtaining the mean inter-reception time between 2 successive messages of a vehicle i , i.e. T_{r_i} ($i = 1, \dots, N$). This validation step is carried out by comparing the results provided by our solution with those delivered by a discrete-event network simulator (NS-3). We set the length of each simulation to 60 seconds and the size of safety messages to 300 Bytes.

Algorithm 1: Computing Inter-Reception time, T_r

```

1 ComputeIRtime ( $\{T_g\}$ )
   inputs :  $\{T_g\}$ 
   output :  $\{T_r\}$ 
2 foreach node  $i$  do
3    $T_{v_i} \leftarrow \frac{N}{C}\tau$ ;
4 while Convergence do
5   foreach node  $i$  do
6     if  $T_{g_i} > T_{v_i}$  then
7        $P_i^{full} \leftarrow T_{v_i}/T_{g_i}$  ;
8     else
9        $P_i^{full} \leftarrow 1$  ;
10   foreach node  $i$  do
11      $T_{v_i} \leftarrow \tau * \left( 1 + \frac{(\sum_{j \neq i} p_j^{full} * N_{PRB})}{C} \right)$ ;
12 foreach node  $i$  do
13    $T_{r_i} \leftarrow \frac{T_{v_i}}{P_i^{full}}$ ;
14 return ( $\{T_r\}$ );

```

To begin with, we consider a scenario with 200 vehicles, categorized into two groups of 100 vehicles each. Vehicles belonging to group 1 (resp. 2) generate safety messages at a period of $T_g = T$ (resp. $T_g = 1.5T$). The number of PRBs available in each time slot is set to $C = 25$. In order to carefully investigate the behavior of our approximation under various levels of workload, we introduce a new parameter, Λ , that represents the total workload of the network. Because each vehicle generates a single safety message every T_{g_i} , Λ can be calculated as:

$$\Lambda = \sum_{i=1}^N 1/T_{g_i} \quad (5.6)$$

Then, we can derive a new parameter, ρ , which is intended to reflect the level of congestion on the LTE resources by normalizing the total workload by the available resources:

$$\rho = \Lambda * N_{PRB}/C = \left(\sum_{i=1}^{100} 1/T + \sum_{i=101}^{200} 1/1.5T \right) * 8/25 = 53.3/T \quad (5.7)$$

We refer to ρ as the normalized workload. We also assume that 8 PRBs (i.e, $N_{PRB} = 8$) is required to transmit each message. Note that a value of ρ less than 1 indicates a network capable of handling the workload, while a value larger than 1 corresponds to an overloaded network.

Figure 5.4a represents the values of T_{r_i} of Group 1 obtained by our approximate solution and those delivered by the simulator for a wide range of values of T , varying from 25 to 175 ms. Note that the corresponding values of the normalized workload ρ ranges from 0.3 to 2.1. The results exhibit an interesting pattern. For low values of ρ , the network is far from congested, so increasing ρ (or equivalently the message generation rates of vehicles) results in decreasing the inter-reception time. This tendency holds until the tipping point where the network begins to be overloaded due to a workload that is too large. Vehicles must then wait before transmitting their messages, which in turn increases the inter-reception times. Finally, for the highest levels of workloads, in which every vehicle has always a packet waiting to be sent, the inter-reception times come close $\frac{N}{C}\tau$. We observe that the proposed approximation successfully captures the pattern exhibited by T_{r_i} , and furthermore, that its values are very close to those of the simulation.

Figures 5.4b shows similar results for group 2. Here, we also notice that the discrepancy between the approximation and the simulation results is small, usually less than 6%.

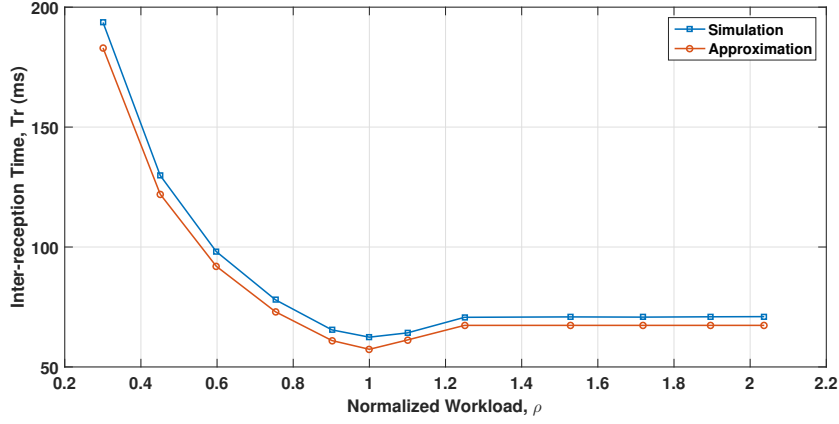
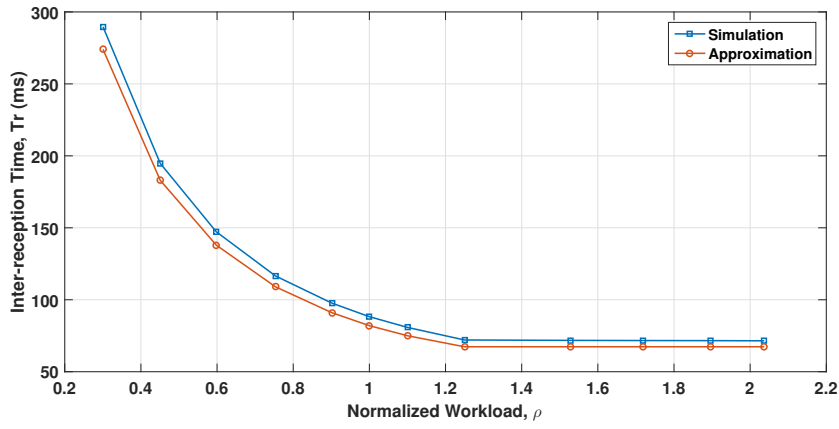

 (a) 1st group generating safety message every $T_g = T$

 (b) 2nd group generating safety message every $T_g = 1.5T$

 Figure 5.4: Accuracy of the proposed solution to approximate T_r with $N=200$ and $C=25$.

To provide a better outlook on the accuracy of our approximation, we perform hundreds of other scenarios with different values for the number of vehicles, N ranging from 100 to 300, for the number of available PRBs, C between 1 and 6, as well as for the message generation periods of each vehicle, T_{g_i} , randomly selected between 20 and 200 *ms*. The corresponding results are reported in Table 5.2. This table indicates that with a total number of 100, 200 and 300 vehicles, and only a single PRB, the maximum error is less than 10%, and the average error is less than 7%. For larger numbers of vehicles, the accuracy of the approximation seems to deteriorate slightly. However, interestingly,

its accuracy tends to improve with increasing values of C . For example, considering 300 vehicles, the average error committed by our approximation is close to 7% when there is only 1 PRB, while this average error decreased to less than 5% with 6 PRBs. Finally, it is worth noting that over the hundreds of scenarios that we explored, we never met a case where our approximation resulted in an error of more than 10%.

Table 5.2: Average and maximum errors committed by the proposed approximation over hundreds of examples.

N	C	Average error (%)	Maximum error (%)
100	6	4.3	6.3
200	6	5.4	7.9
300	6	7.1	9.8
100	25	3	5.1
200	25	4.2	6.6
300	25	5.9	8.4
100	50	1.4	2.5
200	50	2	4.3
300	50	4.9	7.6

5.3.2 Adapting the Rates of Safety Message Generation

We now describe the proposed iterative algorithm 2 that the server can run in order to unify the location precision experienced by vehicles moving at different speeds.

Algorithm 2: Rate adaptation algorithm

```

1   $\{T_g\} \leftarrow \frac{N}{C}\tau$ 
2  RateAdaptation ( $\{v\}, N, C$ )
   | inputs :  $\{v\}, N, C$ 
   | Initialization:  $\alpha$ 
   | output:  $\{\lambda\}, \{e\}$ 
3  while Convergence do
4  |    $\{T_r\} \leftarrow \text{ComputeIRtime}(\{T_g\})$ 
5  |   foreach node  $i$  do
6  |   |    $e_i \leftarrow T_{r_i} * v_i;$ 
7  |   |    $\{\lambda\} \leftarrow \frac{1}{T_g};$ 
8  |   |    $\beta = 1 + \frac{(1-\alpha) \sum_{i:e_i \leq \bar{e}} \lambda_i}{\sum_{i:e_i > \bar{e}} \lambda_i};$ 
9  |   |   foreach node  $i$  do
10 |   |   |   if  $e_i \leq \bar{e}$  then
11 |   |   |   |    $\lambda_i \leftarrow \lambda_i * \alpha$ 
12 |   |   |   else
13 |   |   |   |    $\lambda_i \leftarrow \lambda_i * \beta$ 
14 |   return ( $\{\lambda\}, \{e\}$ );
```

At each iteration, given the current values of λ_i (recall that $\lambda_i = \frac{1}{T_{g_i}}$), the algorithm determines the corresponding values of T_{r_i} and e_i for all vehicles using the previously described modeling application. The algorithm then calculates the average location precision computed over all vehicles, i.e. $\bar{e} = \sum_{i=1}^N e_i$. Based on these values, the algorithm updates the values of λ_i . It decreases λ_i for vehicles having a lower value of e_i (i.e. better location precision) than the average value of vehicles by a multiplicative factor, α ($\alpha < 1$). On the other hand, it increases λ_i for vehicles experiencing worse precision than the average value by another multiplicative factor, β ($\beta > 1$). Therefore, the new

value of the total workload is as follows: $\Lambda = \sum_{i:e_i \leq \bar{e}} (\alpha \lambda_i) + \sum_{i:e_i > \bar{e}} (\beta \lambda_i)$. In order to keep its value constant once the values of λ_i have been updated, it suffices to set a given value for α (e.g. 0.99), and select β so that:

$$\beta = 1 + \frac{(1 - \alpha) \sum_{i:e_i \leq \bar{e}} \lambda_i}{\sum_{i:e_i > \bar{e}} \lambda_i} \quad (5.8)$$

This iteration is repeated until convergence is found, namely when the values of e_i are sufficiently close to \bar{e} . Then, the server can request vehicles to modify their generation period of safety messages according to the values of T_{g_i} found at the convergence. Figure 5.5 depicts the corresponding block diagram, while the associated algorithm is given in Algorithm 2.

Note that although we have no mathematical proof that our algorithm converges, it never failed to converge within typically several dozens of iterations in the thousands of scenarios (not shown in this Thesis) that we have explored.

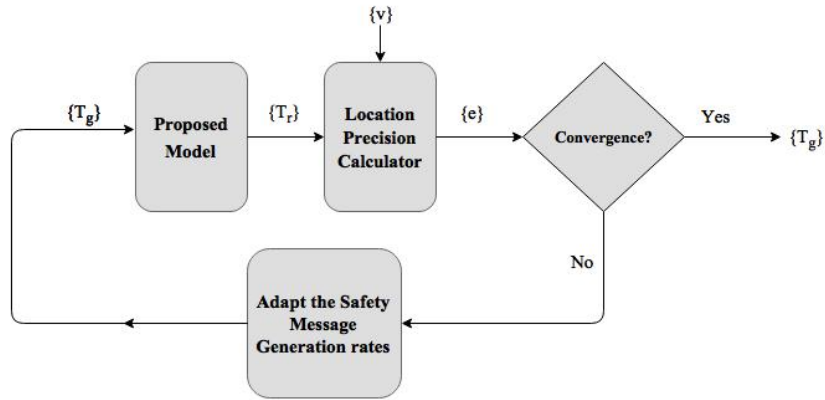


Figure 5.5: Block diagram for adapting the rates of safety messages.

5.3.3 Simulation Results

Table 5.3: Simulation parameters

Carrier frequency	2 GHz
Maximum transmission power of vehicle UE	23 dbm
Noise figure at base station	5 dB
Number of Vehicles	100 - 320
Vehicles' speed	5 - 30 m/s
Safety message size	300 Bytes
Simulation time	100 s

In this section, we introduce two scenarios to illustrate the behavior of our proposed solution to adapt the generation rates of safety messages. The parameter used in the simulation is summarized in Table 5.3.

In scenario A, we consider a total of $N = 320$ vehicles and $C = 6$ available PRBs per time slot. We categorize the vehicles into four groups, each comprising 80 vehicles, and with a moving speed of 5, 10, 25 and 30 m/s, respectively. We initialize the generation period of safety messages, T_{g_i} , at the same value for all vehicles, and we run our proposed algorithm. Figure 5.7 shows the corresponding results. It depicts the evolution of the location precision for each group, e_i , as well as the average location precision as a function of the number of iterations. Because all vehicles initially have the same value for T_{g_i} , the values of e_i start with higher values for the fast vehicles than for the slower ones. Initially, the fastest vehicles (group 4) have a location precision close to 10 meters, while that of the slowest vehicles (group 1) are around 2 meters. However, after several dozens of iterations and changes of the generation periods of safety messages, our algorithm

ultimately converges to a solution wherein all vehicles, regardless of their speed, share the same level of precision, which is around 5.5 meters.

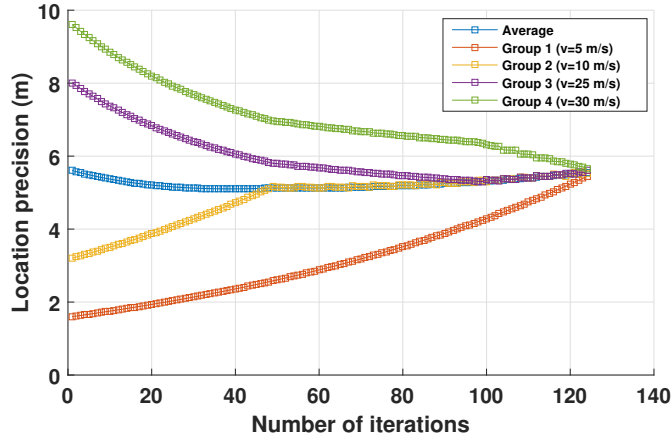


Figure 5.6: Scenario A: Location precision vs. number of iteration with $N = 320$ vehicles, $C = 6$ PRB.

In scenario B, we consider $N = 500$ vehicles with a total of $C = 25$ PRBs available in each slot. Unlike scenario A, each vehicle has its own speed, which is randomly selected between 5 to 35 m/s. We run our proposed algorithm and represent the found results in Figure 5.6. We show the average, maximum and minimum location precision of the vehicles. Initially, the worst location precision (which corresponds to the fastest vehicle) is 4.5 meters, while the best location precision (which corresponds to the slowest vehicle) is only 0.5 meters. Once the algorithm is done, the generation periods of safety messages have been modified in a way that all vehicles experience a location precision of around 2.5 meters.

These two scenarios and many others demonstrate the ability of our proposed solution to efficiently and automatically set the generation rates of safety messages so that every vehicle undergoes the same level of location precision despite their different speeds. This kind of fairness between vehicles is a desirable feature for road security.

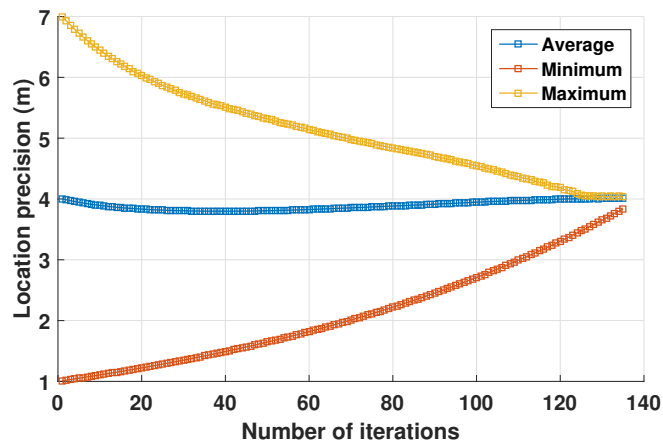


Figure 5.7: Scenario B: Average, minimum and maximum location precision vs. number of iteration with $N = 500$ vehicles, $C = 25$ PRBs.

Finally, Figure 5.8 shows the effect of safety message generation rate adaptation on location precision. When there is no adaptation (i.e. vehicles transmit with period of 100 ms), the faster vehicles experience worst location while slower vehicles have very good location precision. However, using the message rate adaptation, all vehicles will have similar location precision with a small difference.

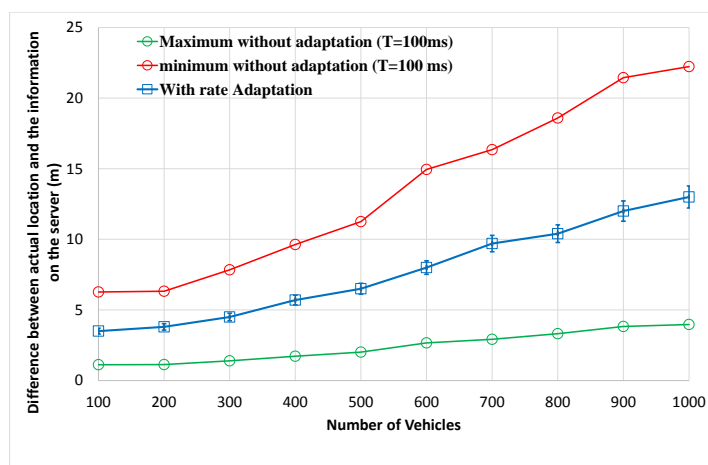


Figure 5.8: Comparison of location precision with rate adaptation and without rate adaptation.

5.4 Sizing the Number of PRBs

In the previous section, we addressed the issue of unfairness by proposing an algorithm to let vehicles with different speeds experience the same level of precision on their location by differently tuning their generation rate of safety messages. However, even though all vehicles experience the same location precision, the found solution may be regarded as inadequate. Such a situation is likely to occur in cases with overloaded networks, because the number of allocated PRBs is too low in regard to the aggregated demands of vehicles. On the other hand, it may be possible for a good level of precision to be obtained with fewer PRBs than currently allocated so that the network could assign more resources for other vehicular applications without affecting the safety message transmissions. More generally, because the number of vehicles and their current speeds are quantities that vary with time, the required number of PRBs is also likely to vary with time. Fortunately, the LTE scheduler is capable of dynamically (de)-allocating PRBs.

In this section, we present a solution for discovering the minimum number of PRBs needed to meet a given level of precision on the vehicles' location. The proposed solution makes use of the algorithm described in Section 5.3, and works as follows. Initially, the current numbers of vehicles together with their speed are known. We also determine an objective in terms of location precision (expressed in meters). Starting with a number of PRBs equal to 1, we will iteratively increase the number of allocated PRBs until the solution delivered by message generation adaptation (see Section 5.3) satisfies the desired location precision. Figure 5.9 sketches the main steps of our algorithm.

We now present an example that illustrates how to exploit our algorithm. We assume that vehicles are uniformly distributed within 4 groups, with respective speeds of 10, 20, 30 and 40 m/s .

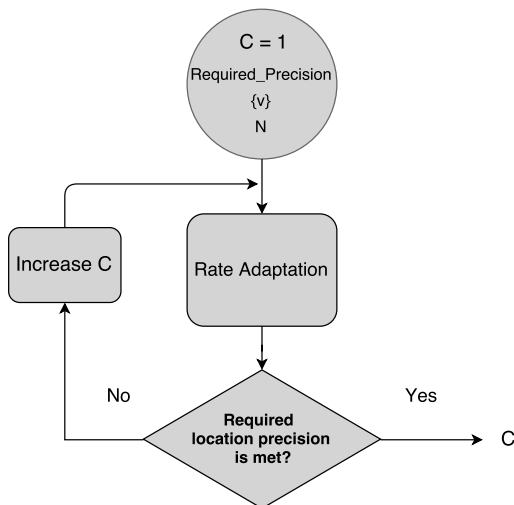


Figure 5.9: Block diagram for dynamically provisioning LTE resources.

We set the objective for the location precision to 1.5 meters. We now run our algorithm to properly size the number of PRBs for 3 different sizes for the vehicle fleet, namely 100, 200 and 300 vehicles. The corresponding results are reported in Figure 5.10. If the total number of vehicles is around 100, then 11 PRBs are sufficient for providing the desired level of precision. However, for a number of vehicles close to 200, it becomes necessary to provision 24 PRBs and even 36 PRBs if the number of vehicles grows to 300. We also include similar results for a different value of targeted location precision. Not surprisingly, when the location precision is less stringent, the number of needed PRBs is less. Indeed, a total of 5, 12, and 17 PRBs are sufficient for handling a fleet of 100, 200, and 300 vehicles, respectively. Finally, note that because the procedure involves little computational complexity, it can be periodically re-executed to take into account new numbers and speeds of vehicles.

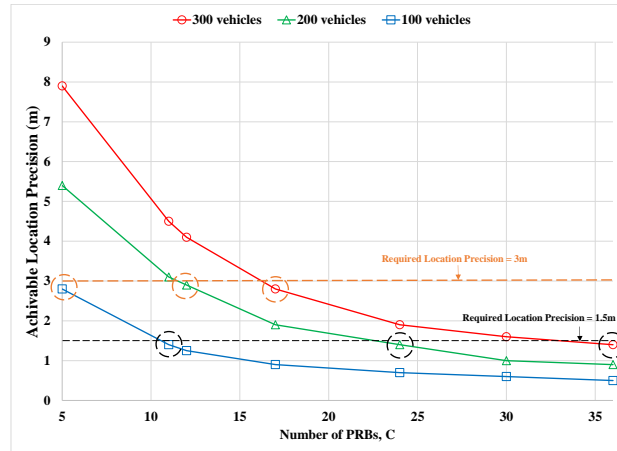


Figure 5.10: Sizing the number of required PRBs.

5.5 Summary

In this Chapter, first, we propose an efficient solution for adapting the generation rate of vehicles' safety messages, so that each of them experiences the same level of location precision. This fairness is attained using an analytical model, based on a queueing model that approximates the level of precision for each vehicle based on their motion speed and their generation rate of safety messages. Second, we present a solution for dynamically discovering the minimum number of resources, i.e. PRBs, that should be allocated by LTE, so as to meet a certain level of location precision for all vehicles. Our numerical results show the effectiveness of our two proposed solutions.

Chapter 6

D2D Scheme for Vehicular Safety

Message Transmissions in

LTE-Advanced Networks

6.1 Introduction

Direct D2D communication is introduced in 3rd Generation Partnership Project (3GPP) release 12 [3], which is aka LTE-Advanced. This feature allows devices in proximity to one another to establish a direct connection and transfer data without passing through the infrastructure. Using only D2D communications for safety message transmission is not a proper solution. First, as the vehicular environment is highly dynamic, the D2D pair changes quickly and vehicles should consume lots of energy to actively discover the vehicles in their proximity. Second, the initial time required to establish a D2D communication is too long for safety applications. We propose a scheme that relies on both cellular and D2D communications. Vehicles transmit their safety messages with a longer period to the server, using cellular communications. The location information at

the server is used for D2D pair detection and resource allocation. In the following period, vehicles use the established D2D connections and allocated resources to transmit their safety messages to the neighboring vehicles. With our resource allocation algorithm, vehicles are categorized into subsets. Transmission of vehicles in each subset does not produce any interference on other vehicles in that subset. Thus, the same resources can be allocated to all vehicles in a subset, increasing the reusability of the resources.

6.2 D2D Communication for Vehicular Safety Messages Transmission

Although the approach of using only LTE cellular connections, as introduced in the previous section has some advantages, such as collection of the data at the server, it suffers from scalability and congestion issues. Increasing the number of vehicles in the cell or when vehicles transmit the safety messages with higher rates (i.e., lower period) to improve the location information accuracy, the load on the network increases dramatically. Due to the limited number of available radio resources, this can cause congestion on the LTE network which leads to significant latencies. These latencies are not suitable for safety applications that are sensitive to delay, as large latencies are equivalent to less fresh and accurate information. Thus, using direct communication can be an alternative for transmission of vehicle safety messages.

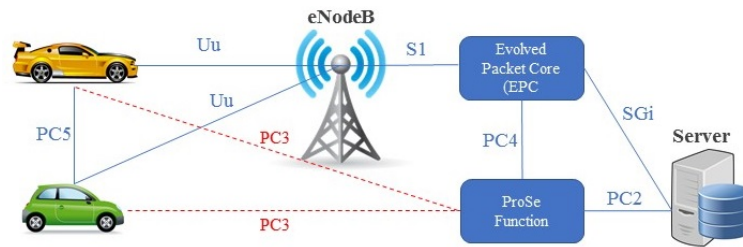


Figure 6.1: D2D architecture.

Figure 6.1 shows a general architecture for D2D communications which consists of two main phases: device discovery and data transmission. Device discovery phase intends to let the transmitting UE discover the UEs in its proximity, and determine if they are close enough to establish direct communication. The process of device discovery can be performed in two modes:

Direct discovery: this mode is similar to traditional ad-hoc networks, wherein users find devices in their proximity without any network involvement. There are two types of direct discovery. In Type 1 ("I am here") the transmitter UE announces its presence by periodically broadcasting a message that contains its information at pre-defined discovery periods. In Type 2 ("Who is there?"), the discoverer UE transmits a request message about what is interested to discover, and the discovered UE can respond to this request with some information.

Network assisted discovery: in this mode the discovery process is completely done at the core. Users register with the ProSe function, which is a logical function in the EPC and is responsible for different tasks related to a ProSe communication. The location of users is reported to the ProSe function periodically. It then detects users that are in proximity and informs them about the D2D communication possibilities.

There are also two modes of direct communication between users. In communication Mode 1, the eNB determines dedicated radio resources for data transmission. The role of the eNB in this mode is similar to that used for uplink traffic. It allocates resource blocks to the UEs based on the information it receives from them, such as buffer status reports (BSR). The eNB also informs the receiver of the scheduling assignment (SA). Thus, the receiver can decode the transmitted data using the information in the SA. In contrast, Mode 2 communication lets UEs transmit information autonomously. In this mode, the eNB broadcasts the configuration of the communication resources. Each transmitting UE selects resource blocks randomly from the resource pool and uses it to deliver the SA and data communication. The communication Mode 2 without infrastructural involvement

resembles Mobile Ad hoc Networks (MANETs) and is only desirable when the UEs are out of the coverage area of the network. However, when the UEs are in the coverage area of LTE, they can exploit the LTE network feature, which provides security and a QoS guarantee to establish the D2D communication and to mitigate the interference and security challenges from which ad hoc networks suffer.

6.3 Proposed D2D Scheme for Vehicular Safety Messages Transmissions

As mentioned above, there are two types of discovery. Direct discovery is suitable for scenarios in which some users are only transmitting (service providers), and some users are only receiving (service clients). In these situations, the service provider (e.g., shopping store) transmits discovery signals periodically to announce its presence. On the other hand, other users listen to the discovery channel to detect users in their proximity. As in vehicular scenarios, each vehicle acts as both transmitter (to transmit its safety message to neighboring vehicles) and receiver (to receive neighboring vehicle safety messages). therefore, it should transmit and listen to the discovery channel at the same time which may be impossible. Moreover, as vehicles share the discovery resources and there is no dedicated resource allocation, it suffers from scalability issues and is not suitable for a vehicular environment in which there might be a significant number of vehicles. Similarly, communication Mode 2 (i.e., users select resources autonomously) is not proper for the vehicular environment with a large number of vehicles transmitting simultaneously.

We propose a scheme that uses both D2D and cellular communication to support the transmission of safety messages to neighboring vehicles. The proposed scheme consists of these phases:

1. Transmission of safety messages to the central server using LTE cellular communication

2. Centralized proximity discovery and D2D pair detection by the server
3. Centralized resource allocation by eNodeB for D2D communications between vehicles
4. Transmission of safety messages to neighboring vehicles using D2D communications

We show these phase by an example and then explain each step in detail in the following of this Section. The scenario that we used to explain the steps of our proposed scheme is shown in Figure 6.2. There are 4 vehicles: V_1, V_2, V_3 and V_4 . By this example, we show the procedure of safety message transmission from vehicle V_2 to the vehicles that are in its awareness area (i.e., V_1 and V_3). It is obvious that the same procedure is performed for all other vehicles, and each vehicle should periodically transmit safety messages to the vehicles in their awareness areas. However, to simplify the demonstration, we consider only the safety message transmission of vehicle V_2 .

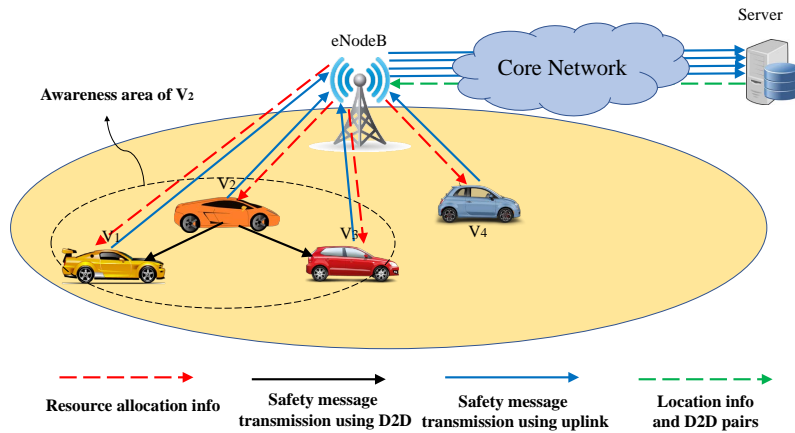


Figure 6.2: A scenario for transmission of safety messages using proposed D2D scheme.

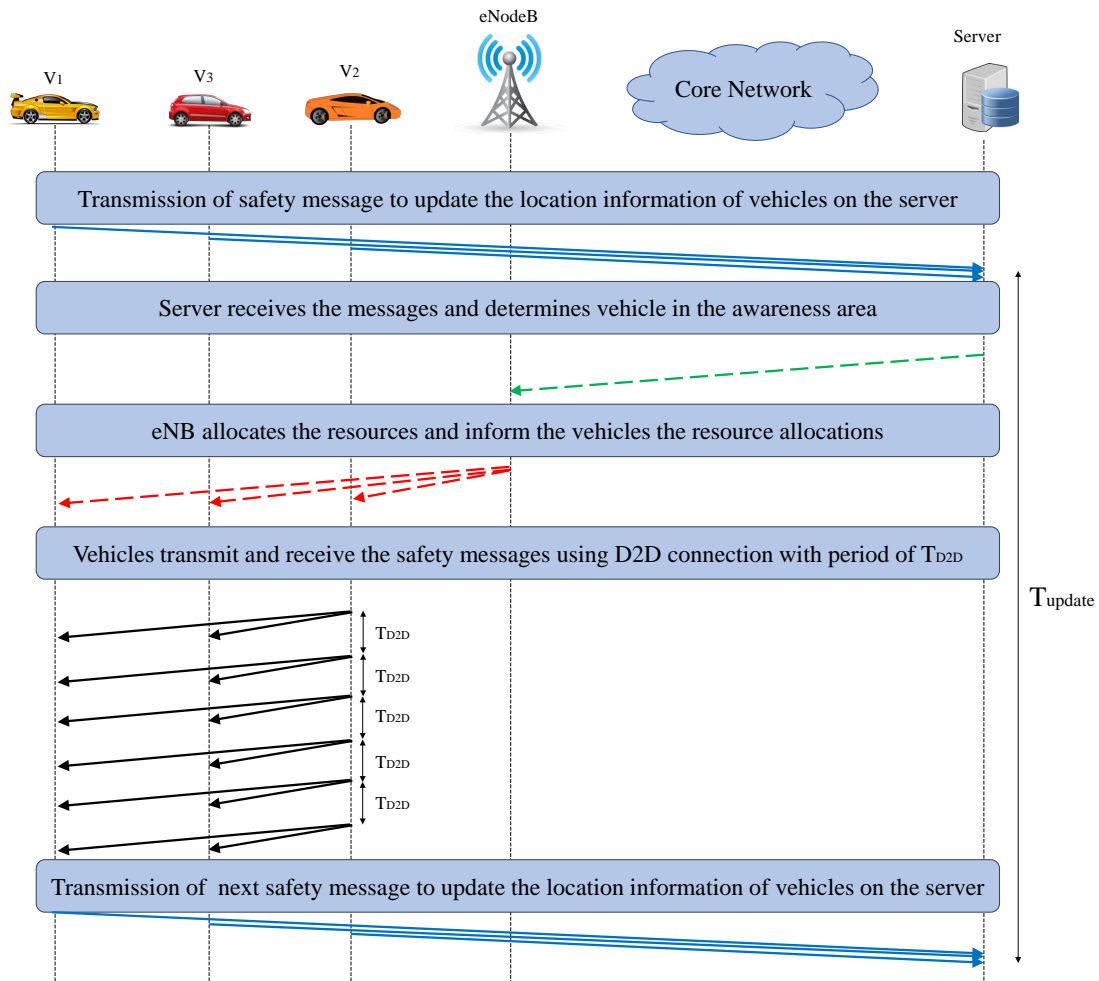


Figure 6.3: The time-line of proposed D2D scheme.

Figure 6.3 shows the time-line of the proposed scheme. Vehicles generate safety messages containing their basic information, such as location, speed, etc., and transmit them to the server using the LTE link with a period T_{update} . The server receives this message and uses the information obtained from it (i.e. location and speed), as well as messages received from other vehicles to estimate vehicles' locations, in the following period.

It then determines the vehicles in awareness area of each vehicle and sends the information

of potential pairs and their location information to the eNB. The eNB determines the required resources (PRBs) for the message transmission between the vehicles and allocate the resource based on the proposed resource allocation that we explain later. The resource allocation information is broadcast to the vehicles. Thus, each vehicle will know when and use which resources it should transmit its safety message. Also, vehicles are informed to when and in which resources they should receive safety messages. At t_4 vehicles start to transmit the safety messages using the allocated resource in D2D mode and with a period of T_{D2D} , where $T_{D2D} \ll T_{update}$. at $t_5 = t_1 + T_{update}$, vehicles transmit another messages to the server to update the server's information. The server will recalculate the D2D pairs for another period. It is worth to mention that the time scales in the chart is not real scales. The time $t_4 - t_1$ which is required to establish the D2D connection is relatively small. However, it is shown longer in the Figure to better represent the control steps for D2D connection establishment and resource allocation.

6.3.1 Transmission of Safety Messages to the Central Server

This step is like the scenario in Chapter 3. However, it only includes the uplink part, i.e., vehicles transmit their safety messages toward the central server using cellular communication. Moreover, as the goal of these messages are to provide updated information about the location of vehicles to the server, the required location accuracy is less than what is required for safety applications. therefore, they use a transmission period of T_{update} which is several times longer than necessary safety messages transmission period (i.e., $100ms$).

6.3.2 Proximity Discovery and D2D Pair Detection by the Server

The server receives these messages and update the location information of the vehicles. This information can be used for other vehicular applications such as traffic efficiency applications. However, the primary goal of this information is to let the server determine

the vehicles that are within the awareness range of each vehicle. The awareness range which is presented by R_{AW} is a parameter that is selected based on the particular safety application. Thus the server forms subsets $S_{V_1}, S_{V_2}, \dots, S_{V_N}$:

$$S_{V_i} = \{V | V \in \{V_1, V_2, \dots, V_N\}, |\chi_V - \chi_{V_i}| \leq R_{AW}\} \quad (6.1)$$

where χ_{V_i} is the latest location information of vehicle i at the server. The server provides this information as well as location information of vehicles to the eNodeB, which is responsible for allocating the resources to the vehicles for D2D communication.

6.3.3 Resource Allocation for D2D Communications Between Vehicles by eNodeB

The eNodeB is responsible for allocating the required resources (PRBs) to the vehicles to let them transmit their safety messages with a period of T_{D2D} (which is less than $100ms$) to the vehicles in their awareness area. As the server provides the vehicle location information to the eNodeB, it can use this information resources and allocate the same resources to vehicles that are far enough and will not cause interference with each other. Reusing a resource by several vehicles, dramatically reduces the required amount of resource for D2D communication. In the following, we describe the proposed resource allocation algorithm.

The first step is to determine the vehicles that can interfere with each other. It is worth mentioning that the interference level of an interferer vehicle should be calculated at neighboring vehicles of the transmitting vehicle that receives its messages. Thus, to determine if vehicle V_i can cause interference with vehicle V_j , it is necessary to calculate the SINR at the vehicles in S_j (i.e., vehicles in the awareness area of V_j which is defined in equation (6.1)). Thus, we can form a conflict matrix, C , with binary elements, c_{ij} , equal to 1, if V_i cause interference on at least one of the vehicles in the awareness area of V_j (i.e., vehicles in S_j), and Otherwise, is equal to 0. In order to compute the elements of

matrix C , $c_{i,j}$, first we calculate the SINR at the vehicles in the awareness area of vehicle V_j assuming that Vehicle V_i uses the same resources as V_j to transmit its messages.

$$\gamma_{s_j} = \frac{P_{D2D}^j PL(V_j, s_j)}{P_{D2D}^i PL(V_i, s_j) + N_0} \quad (6.2)$$

where γ_{s_j} is the SINR at Vehicle s_j ($\in S_j$) when Vehicle i and j transmit on the same resources. P_{D2D}^i and P_{D2D}^j is the transmitted powers of Vehicles i and j respectively. $PL(a, b)$ is the path loss between Vehicles a and b . If the SINR at all vehicles in S_j is above the minimum required SINR (γ_{min}), then it means Vehicle V_i does not conflict with Vehicle V_j . Thus, they can use same resources for transmission (i.e., c_{ij} is equal to 0). Note that it is enough to check the vehicle with the lowest SINR in S_j , as if it is above γ_{min} , it guarantees that all vehicles in S_j have SINR above γ_{min} .

$$c_{ij} = \begin{cases} 0 & \text{if } \min_{s_j \in S_j} \gamma_{s_j} > \gamma_{min} \\ 1 & \text{if } \min_{s_j \in S_j} \gamma_{s_j} \leq \gamma_{min} \end{cases} \quad (6.3)$$

After the conflict matrix, C is created, the resources are allocated to the vehicles. The algorithm consists of two parts. First, vehicles are categorized into subsets M_1, M_2, \dots, M_n using Algorithm 3 that satisfy the following conditions:

$$\begin{aligned} \forall_{i \neq j} V_i, V_j \in M_k : c_{ij} &= 0 \\ M_1 \cup M_2 \dots \cup M_n &= \{V_1, V_2, \dots, V_N\} \\ M_1 \cap M_2 \dots \cap M_n &= \emptyset \end{aligned} \quad (6.4)$$

These conditions guarantee that these subsets include all vehicles while not having any overlaps. Also, vehicles in one subset do not have any conflict with each other. therefore they can use the same PRBs for transmission. In the second part, the number of required PRBs are calculated and PRBs are allocated to the vehicles in each subset using Algorithm 4.

1- Forming the subsets:

In this part, we propose an algorithm that forms the vehicles in an efficient way that fits more vehicles in each subset and hence minimize the number of subsets. More vehicles in subsets (and fewer number of subsets) means that more vehicles can reuse the same

Algorithm 3: Categorize vehicles in subsets

```

1  $V \leftarrow \{V_1, V_2, \dots, V_N\}$ ;
2 Compute Conflict Matrix, C;
3  $k \leftarrow 1$ ;
4  $M_1 \leftarrow \{\phi\}$ ;
5 while  $\bigcup_{i=1}^k M_i \neq V$  do
6    $T \leftarrow \{\phi\}$ ;
7   while  $\bigcup_{i=1}^k M_i \cup T \neq V$  do
8     Sort vehicle in  $(V - (\bigcup_{i=1}^k M_i \cup T))$  based on  $N_C$ ;
9     Select the vehicle with lowest  $N_C$ ;
10    if Conflict with any vehicles in  $M_k$  then
11      | add vehicle to T;
12    else
13      | add vehicle to  $M_k$ ;
14    for  $V_i \in M_k$  do
15      | for  $j=1:N$  do
16        |  $c_{ij} \leftarrow 0$ ;
17        |  $c_{ji} \leftarrow 0$ ;
18     $k \leftarrow k + 1$ ;
19     $M_k \leftarrow \{\phi\}$ ;
20 return  $M_1, M_2, \dots, M_k$ 

```

First, the conflict matrix, C, is created. For each column, representing a particular vehicle, the sum of the rows shows the number of vehicles that have conflict with that

vehicle. Thus:

$$N_C^i = \sum_{j=1}^N c_{ij} \quad (6.5)$$

The vehicle with the lowest number of conflicting vehicles is selected and added to M_1 . Then, another vehicle with the lowest number of conflicting vehicles is selected. This vehicle will be added to M_1 , if it has no conflict with any elements of this subset. If it has conflict with at least one element of M_1 , it cannot be added to this subset. This loop is done for all vehicles to determine whether they can be an element of M_1 or not. Then, the conflict matrix is updated by setting the elements related to the vehicles in M_1 to 0, as these vehicle will not interfere with the vehicles in other subsets. The subset M_2 is then created with the same method and the creation of subsets will continue until all of the vehicles are added to their relevant subsets.

2- Resource allocation:

after all subsets M_1, M_2, \dots, M_n have been created, the required PRBs can be allocated to the vehicles. First, the number of required PRBs to transmit a safety message, N_{PRB}^{Tx} , is calculated. This number depends on the size of the safety message and the MCS that the vehicle uses. For example, the number of required PRBs for message size of 50 Bytes and MCS index of 10 is 3 PRBs, and for a message size of 200 Bytes and MCS index of 15, 6 PRBs are required.

Then, the eNodeB starts from the first sub-frame and allocates N_{PRB}^{Tx} PRBs to the vehicles in M_1 , the next N_{PRB}^{Tx} PRBs to the vehicles in M_2 , etc., until there are no more available PRBs in that sub-frame. It then starts to allocate PRBs to the next sub-frames until all of the subsets and vehicles get their required PRBs. As mentioned above, T_{update} can be several times of T_{D2D} ; these resource allocations can be used for the periodic safety messages transmission with a period of T_{D2D} like semi-persistent scheduling.

Let us assume $T_{update} = KT_{D2D}$. If the PRBs in sub-frame j are allocated to a vehicle, then same PRBs in sub-frames $j + iT_{D2D}$ ($i=1,2, \dots, K-1$) are also allocated to that vehicle

in order to prevent additional control overheads.

Algorithm 4: Physical resource allocation

```

1  $M_1, M_2, \dots, M_n$ ;
2  $N_{PRB} \leftarrow$  # of available PRBs in each sub-frame ;
3  $N_{PRB}^{Tx} \leftarrow$  # of required PRBs for each message transmission;
4  $i \leftarrow 1$ ;
5  $j \leftarrow 1$ ;
6 for  $k = 1 : n$  do
7   if  $N_{PRB} - i < N_{PRB}^{Tx}$  then
8      $j \leftarrow j + 1$ ;
9   else
10    for  $v \in M_k$  do
11      Allocate PRBs #  $i$  to PRB #  $i + N_{PRB}^{Tx}$  in subframe  $j$ 
12     $i \leftarrow i + N_{PRB}^{Tx}$ 

```

Finally, the eNodeB transmits the resource allocation map on the Physical Downlink Control Channel (PDCCH) to inform the vehicles about the resource allocation in the upcoming period. The process of resource allocation is performed with the period of $T_{discovery}$ when the new vehicle information is available. The parameter T_{update} should be carefully selected. A Short T_{update} provides more up-to-date and accurate location information on the server and central nodes. Thus, it helps resource allocation and neighbor determinations to be done more accurately. However, shorter T_{update} means more cellular resource usage, and in an extreme condition, will be similar to the cellular-only case that we introduced in the previous Section. On the other hand, choosing a longer T_{update} period uses fewer resources. However, as the vehicle location information on the central node gets updated less frequently, the location information is less accurate. This inaccuracy can cause errors in neighbor determination and also in resource allocation.

6.4 An Example for the Resource Allocation

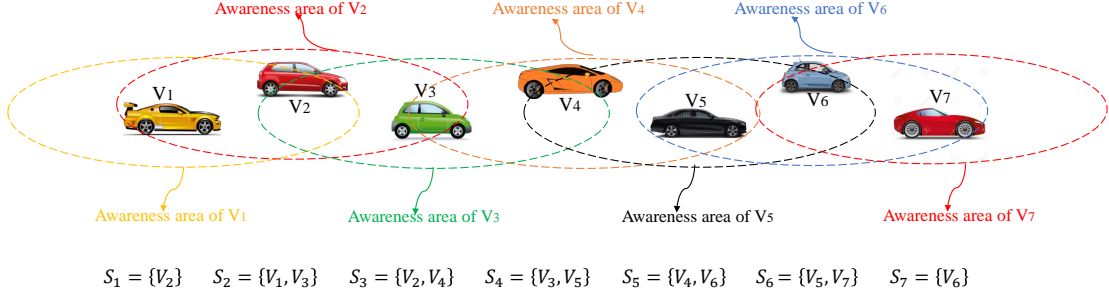


Figure 6.4: Scenario of the D2D resource allocation example

In this Section, we provide an example to show the procedure of resource allocation. Figure 6.4 shows the scenario that consists of seven vehicles. The awareness area of each vehicle and subsets S_1, S_2, \dots, S_7 are shown in the figure. Vehicles in S_j should receive the vehicle j 's safety messages. Then the Conflict Matrix is formed according to the definition in the Section 5.3.3. For simplicity, we assume that the interfering range is the same as the awareness range. Thus, two vehicles have a conflict if they are in the awareness range of one another, or a common vehicle exists in both vehicles' awareness range. The initial Conflict Matrix of this example is shown in Figure 6.5.

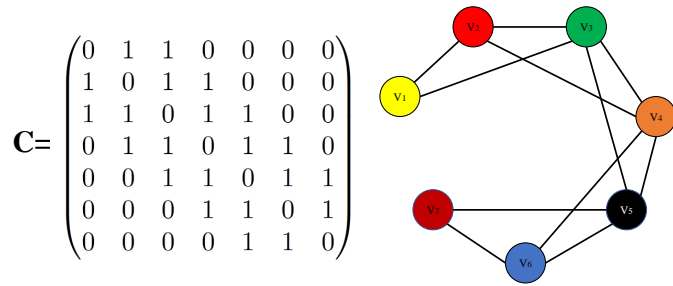


Figure 6.5: Conflict Matrix creation

For example, V_1 and V_3 are considered as conflicting vehicles as their simultaneous transmission makes interference on V_2 . However, V_1 and V_4 does not have any conflict and the can transmit their messages at a same time using same PRBs.

Figure 6.6 shows how the non conflicting subsets are formed. At the first iteration, it starts with the C^1 which is the original Conflict Matrix in Figure 6.5. Among the vehicles, V_1 has the lowest number of conflicting vehicles which is two (V_2 and V_3). Thus, it is added to the M_1 . The next vehicle with lowest N_c is V_7 . As it does not have conflict with any member of M_1 (i.e., V_1) it is added to this subset. The V_4 is also added to M_1 in the next step. The next vehicle to be checked is V_3 . However it has conflict with two members of M_1 and cannot be added to this subset. The same reason applies for other vehicles and no more vehicle can be added to M_1 .

In the next iteration, the Conflict Matrix is updated by setting the relevant element of M_1 to zero and C^2 is obtained. V_2 which has the lowest N_C among remaining vehicles (i.e., V_2, V_3, V_5, V_6) is added to the next subset, M_2 . Vehicle V_6 is also added to this subset as it has no conflict with V_2 . However, V_3 and V_5 cannot be added to this subset as they have conflict with V_2 and V_6 respectively.

The C^3 is calculated by setting the related elements of V_2 and V_6 to zero. In this step, only V_3 can be added to M_3 as V_3 and V_5 cannot be in the same subset. Finally, V_5 is assigned to the last subset, M_4 . Thus, there are four subsets which satisfy the

$$C^1 = \begin{pmatrix} 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 \end{pmatrix} \quad M_1 = \{V_1, V_7, V_4\}$$

$$C^2 = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \quad M_2 = \{V_2, V_6\}$$

$$C^3 = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \quad M_3 = \{V_3\}$$

$$C^4 = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \quad M_4 = \{V_5\}$$

Figure 6.6: Forming the non conflicting subsets

6.5 Performance Evaluation

In this Section, we present the simulation results to evaluate the performance of the D2D scheme for safety message transmission through the LTE-Advanced network. Table 6.1 summarizes the parameters that are used in the simulation.

Table 6.1: Simulation parameters

Carrier frequency	2 GHz
Duplexing mode	FDD
Maximum transmission power of eNB	40 dbm
Maximum transmission power of vehicle UE	23 dbm
Path loss model	WINNER II - C2
Shadow fading standard deviation	4 dB
Noise figure	9 dB
Number of Vehicles	100 - 1000
Vehicles' speed	50 - 120 Km/h
Safety message size	100 - 500 Bytes
Safety message period	100 ms
Road length	1 Km

6.5.1 Simulation Setup

We consider a highway with four lanes. Each lane has a width of 4 meters, and its length is 1Km. The position of N vehicles is determined randomly at the beginning of the simulation. The speed of each vehicle is also selected randomly between 50 and 120 Km/h and is updated every 500ms. We use two values for the size of each safety message, 100 and 500 bytes. The safety message generation period is 100 ms. The operating band of the LTE network is considered as 2 GHz. We also used the well-known model, WINNER-II (C2) [178] to calculate the path loss.

6.5.2 Performance Metrics

We used some metrics to evaluate the performance of the D2D scheme for the transmission of safety messages in the LTE networks. The first metric is the number of resources, PRBs, that is used for transmission of safety messages. It is desirable to lower the resource usage to keep the resources other applications. Moreover, using LTE resources is costly; Thus, it is always better to use as fewer resources as possible.

The other metric that we use to evaluate the performance of the proposed D2D scheme is the percentage of error in determining the D2D pair vehicles. As D2D pair determination is performed centrally by the server, its accuracy depends on the accuracy of location information on the server. There are two types of errors that can occur: false negative and false positive. False negative errors refer to the situations that a vehicle is in another vehicle awareness area. Thus, they should be determined as a D2D pair to receive safety message of the other vehicle; but the server (because of the inaccuracy of the location information) does not consider it to be in the awareness area of the transmitting vehicle. On the other hand, false positive is the situation that a vehicle is not in another vehicle awareness area, but server distinguished it in the transmitting vehicle awareness area. In other words, false negative errors lead to inaccuracy, as the vehicle does not receive the message that it was supposed to receive. On the other hand, false positive errors lead to resource usage inefficiency, as some resources are used to transmit unnecessary messages. In the following, we will evaluate the performance of proposed solutions base on the introduced metrics.

6.5.3 Performance Evaluation of the Proposed D2D Scheme

Figure 6.7 shows the number of required PRBs for transmission of safety messages. When using only cellular uplink communication, the required PRBs increases dramatically, exceeding the maximum number of available PRBs, which leads to congestion and high

delay. Using D2D communication noticeably reduces the required PRBs by reusing the resources. The amount of resource reused depends on the vehicles awareness range (R_{AW}). Larger values of R_{AW} mean that vehicles should transmit with higher power. therefore, the re-usability of resources decreases and required number of PRBs increases. therefore, it is important to choose a proper value for the awareness area to make sure all concerned vehicles receive the message while using as few as possible resources.

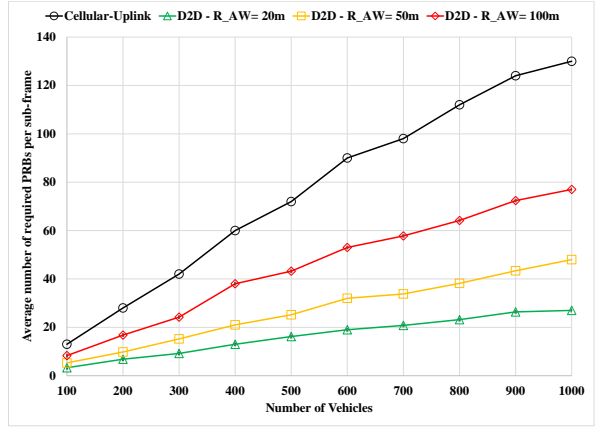


Figure 6.7: Required PRBs for cellular uplink and D2D with different awareness ranges

Another parameter that affects the required number of PRBs is the period at which vehicles transmit their message to the server (i.e., T_{update}). As is shown in Figure 6.8, longer values of T_{update} need fewer PRBs. However, longer T_{update} means that the vehicle location information on the server is updated less frequently. Because the server uses this location information to determine the vehicles in the awareness area of a transmitting vehicle, inaccuracy in location information leads to errors in pair detection. Figure 6.9 shows the effect of T_{update} on the percentage of detection errors.

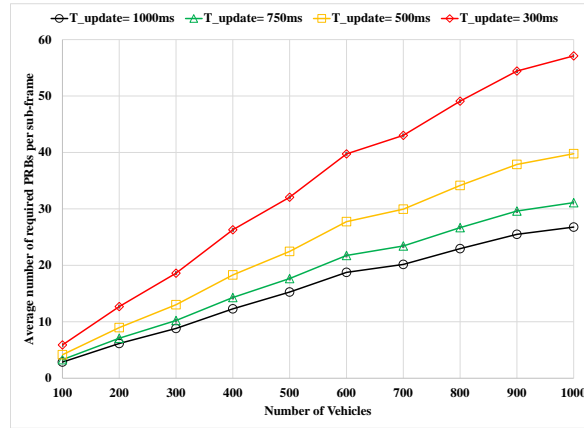


Figure 6.8: Required PRBs for different T_{update} values, $B = 500bytes$, $T_{D2D} = 100ms$



Figure 6.9: Percentage of pair detection error for different T_{update} values, $B = 500bytes$, $T_{D2D} = 100ms$

6.6 Summary

Using only D2D communications for safety message transmission is not a proper solution. First, as the vehicular environment is highly dynamic, the D2D pair changes quickly and vehicles should consume lots of energy to actively discover the vehicles in their proximity. Second, the initial time required to establish a D2D communication is too long for safety applications. We propose a scheme that relies on both cellular and D2D communications. Vehicles transmit their safety messages with a longer period to the server, using cellular communications. The location information at the server is used for D2D pair detection and resource allocation. In the following period, vehicles use the established D2D connections and allocated resources to transmit their safety messages to the neighboring vehicles. With our resource allocation algorithm, vehicles are categorized into subsets. Transmission of vehicles in each subset does not produce any interference on other vehicles in that subset. Thus, the same resources can be allocated to all vehicles in a subset, increasing the reusability of the resources.

Chapter 7

Conclusion and Future Work

The transmission of vehicular safety messages through LTE may cause congestion on the infrastructure, leading to high delay for some vehicles. As the location information accuracy is highly dependent on the freshness of information, these latencies can cause location inaccuracy, which is not suitable for vehicular safety applications. In this thesis, we focused on proposing solutions to make LTE networks more suitable for safety applications. After providing a brief introduction and describing the problem statement in Chapter 1, we studied the state-of-the-art in the areas of LTE networks for vehicular applications, safety message rate adaptation, LTE schedulers and D2D feature of LTE-Advanced networks in Chapter 2. We present a summary of the major contributions of this thesis which focused on LTE/LTE-Advanced for vehicular safety applications, in the following:

We proposed two solutions to tackle this issue. On the LTE side, we proposed a new scheduler, which takes into account the vehicles' speed and the last time their message was received at the server for resource allocation. Thus, faster vehicles obtain resources before slower vehicles. The other solution is an adaptation of safety message generation periods. We proposed an efficient solution for adapting the generation rate of vehicles' safety messages. We used an analytical model, based on a queueing model, that

approximates the level of precision for each vehicle based on their movement speed and their generation rate of safety messages. Both solutions increased the location accuracy of faster vehicles (which is low in normal situations) by giving higher priority to them in resource allocation (in the scheduler case) or letting faster vehicles to transmit safety messages more frequently (in the period adaptation case). Hence, all vehicles experience a similar level of location accuracy at the server.

In the downlink, we presented three possible approaches for delivering the safety messages to the appropriate vehicles, which can be determined by the server based on the previously received information. In unicast mode, the server transmits the received message to the neighboring vehicles of the transmitter separately. Although the delay is reduced, as the server forwards messages as soon as they are received, this mode generates lots of load on the downlink and is not resource-efficient. In the second mode, the server forms a multicast group of vehicles neighboring the transmitters, and multicasts the message to them. This method is more resource-efficient. However, some delays occur with the creation of multicast groups, as these groups change quickly. The last approach for the delivery of safety messages is broadcasting. The server aggregates the received messages from vehicles, and broadcasts the aggregated message to the cell. Each vehicle receives the message and uses the relevant information. Broadcasting is the most resource-efficient method. However, the neighboring vehicles residing in the border of cells might connect to different cells, and do not receive information from one another. Thus, we propose a mechanism to include such information in a message that is broadcast to neighboring cells, to ensure that all vehicles receive information from their neighbors.

Direct D2D communication is introduced in 3rd Generation Partnership Project (3GPP) release 12 [3], also known as LTE-Advanced. This feature allows devices in proximity to one another to establish a direct connection and transfer data without passing through the infrastructure. Using only D2D communications for safety message transmission is not a proper solution. First, as the vehicular environment is highly dy-

dynamic, the D2D pair changes quickly, and vehicles should consume a large amount of energy to actively discover the vehicles in their proximity. Second, the initial time required to establish a D2D communication is too long for safety applications. We propose a scheme that relies on both cellular and D2D communications. Vehicles transmit their safety messages with a longer period to the server, using cellular communications. The location information at the server is used for D2D pair detection and resource allocation. In the following period, vehicles use the established D2D connections and allocated resources to transmit their safety messages to the neighboring vehicles. With our resource allocation algorithm, vehicles are categorized into subsets. The transmission of vehicles in each subset does not produce any interference on other vehicles in that subset. Thus, the same resources can be allocated to all vehicles in a subset, increasing the reusability of the resources.

7.1 Future Work

As parts of the future work, some of the possible future directions of this research are as follows:

- We considered the Round-Robin scheduler as an analytical model to estimate the freshness of information at the server. The queueing model can be extended to support other scheduling algorithms, including the proposed scheduler, in this thesis.
- We used an iterative algorithm to adapt the generation rates. Other algorithms will be proposed for other possible goals. The adaptation can be formulated as an optimization problem to find the optimum message generation rates based on the available resources (PRBs) and vehicles' speeds.

- Although the vehicular UEs are assumed to have sufficient energy supply, as they can be connected to the vehicle's battery, it would be interesting to study the energy efficiency of the proposed D2D scheme compared to cellular-only or D2D-only solutions.
- In this thesis, the solutions are evaluated using simulators. However, simulation results may not entirely reflect the real scenarios. A collaboration between automotive companies and mobile operators is needed to test these solutions in the real scenarios.
- This thesis focused on safety applications, which have to distinguish features such as periodic transmission of a small amount of data, and engaging all vehicles, which are challenging issues. However, more study is needed of the performance of the network in the coexistence of other applications, such as traffic efficiency.
- We focused on LTE/LTE-Advanced network, as these networks are currently deployed widely. Studies on the 5G network have recently begun and its requirements such as the throughput, latency, etc., have been introduced. By standardization and deployment of the 5G network, new applications use cases such as fully autonomous cars may be considered for support.

Bibliography

- [1] IS-Wireless. <http://www.is-wirelesstraining.com/trainings>. Accessed: 2017-10-30.
- [2] TBS in LTE. <https://tech.queryhome.com/44622>. Accessed: 2017-10-30.
- [3] 3GPP TR 23.703: Study on architecture enhancements to support Proximity-based Services (ProSe) (Release 14). Technical report, 3GPP, 2014.
- [4] simTD project Deliverable. <http://www.3gpp.org/technologies/keywords-acronyms/97-lte-advanced>. Accessed: 2018-01-30.
- [5] R. Gordon. ITS and the Connected Vehicle. In *Intelligent Transportation Systems*, chapter 13, pages 225–235. Springer International Publishing, 2016.
- [6] M. Houbraken, S. Logghe, P. Audenaert, D. Colle, and M. Pickavet. Examining the potential of floating car data for dynamic traffic management. *IET Intelligent Transport Systems*, 12(5):335–344, 2018.
- [7] European Telecommunications Standards Institute, Intelligent Transport Systems (ITS); Vehicular Communications ETSI EN 302 636-5-1. Technical report, ETSI, 2014.
- [8] ETSI TR 102 962, Intelligent Transport Systems (ITS); Framework for Public Mobile Network. Technical report, ETSI, 2012.

- [9] ISO 17515: Intelligent Transport Systems Communications Access for Land Mobiles (CALM) LTE Cellular Systems. Technical report, ISO, 2012.
- [10] Intelligent Transportation Systems Joint Program Office. Core System Concept of Operations (ConOps). Technical report, RITA, 2012.
- [11] E. Uhlemann K. Bilstrup and E. Strom. Scalability issues of the mac methods STDMA and CSMA of IEEE 802.11 p when used in VANETs. In *IEEE International Conference on Communications Workshops*, 2010.
- [12] E. Uhlemann K. Bilstrup and E. Strom. Evaluation of the IEEE 802.11p MAC method for vehicle-to-vehicle communication. In *IEEE Vehicular Technology Conference*, pages 1–5. IEEE, 2008.
- [13] FOTsis. <http://www.fotsis.com>. Accessed: 2017-10-30.
- [14] DRIVE C2X. <http://www.drive-c2x.eu/project>. Accessed: 2017-10-30.
- [15] G. Araniti, C. Campolo, M. Condoluci, A. Iera, and A. Molinaro. LTE for vehicular networking: a survey. *IEEE Communications Magazine*, 51(5):148–157, May 2013.
- [16] IEEE Standard for Information technology– Local and metropolitan area networks– Specific requirements– Part 11. *IEEE Standard*, pages 1–51, July 2010.
- [17] M. I. Sanchez and A. Boukerche. On IEEE 802.11k/r/v amendments: do they have a real impact? *IEEE Wireless Communications*, 23(1):48–55, February 2016.
- [18] simTD project Deliverable. <http://www.simtd.de/>. Accessed: 2017-10-30.
- [19] DRIVE C2X. <http://www.drive-c2x.eu/project>. Accessed: 2017-10-30.
- [20] SCORE@F (Système Coopratif Routier Experimental @ France). <https://project.inria.fr/>. Accessed: 2017-10-30.

- [21] Cooperative ITS Corridor. <https://itscorridor.mett.nl>. Accessed: 2017-10-30.
- [22] Connected Vehicle Pilot Deployment Program. www.its.dot.gov/pilots/. Accessed: 2017-10-30.
- [23] M. Amadeo, C. Campolo, and A. Molinaro. Enhancing IEEE 802.11p/WAVE to provide infotainment applications in VANETs. *Ad Hoc Networks*, 10(2):253 – 269, 2012.
- [24] Intelligent Transport Systems (ITS); Framework for Public Mobile Networks in Cooperative ITS (C-ITS). Technical report, ETSI, 2013.
- [25] A. Vinel. 3GPP LTE versus ieee 802.11p/WAVE: Which technology is able to support cooperative vehicular safety applications? *IEEE Wireless Communications Letters*, 1(2):125–128, April 2012.
- [26] CoCarX Project. <http://www.aktiv-online.org/deutsch/aktiv-cocarX.html>. Accessed: 2017-10-30.
- [27] A. Nshimiyimana, D. Agrawal, and W. Arif. Comprehensive survey of V2V communication for 4G mobile and wireless technology. In *International Conference on Wireless Communications, Signal Processing and Networking (WiSPNET)*, pages 1722–1726, March 2016.
- [28] T. Mangel, T. Kosch, and H. Hartenstein. A comparison of UMTS and LTE for vehicular safety communication at intersections. In *IEEE Vehicular Networking Conference (VNC)*, pages 293–300, Dec 2010.
- [29] Wenlu Hu, Ziqiang Feng, Zhuo Chen, Jan Harkes, Padmanabhan Pillai, and Mahadev Satyanarayanan. Live synthesis of vehicle-sourced data over 4g lte. In *ACM International Conference on Modelling, Analysis and Simulation of Wireless and Mobile Systems, MSWiM*, pages 161–170, New York, NY, USA, 2017.

- [30] 3GPP TR 36.300: Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN), (Release 8). Technical report, 3GPP, 2010.
- [31] C. Lottermann, M. Botsov, P. Fertl, G. Araniti, C. Campolo, M. Condoluci, A. Iera, , and Antonella Molinaro. LTE for vehicular communications. In *Vehicular ad hoc Networks*, chapter 16, pages 457–501. Springer International Publishing, 2015.
- [32] Z. Fethi H. Filali. LTE and IEEE 802.11p for vehicular networking: a performance evaluation. *EURASIP Journal on Wireless Communications and Networking*, pages 1–15, 2014.
- [33] H. Seo, K. D. Lee, S. Yasukawa, Y. Peng, and P. Sartori. LTE evolution for vehicle-to-everything services. *IEEE Communications Magazine*, 54(6):22–28, June 2016.
- [34] S. Chen, J. Hu, Y. Shi, and L. Zhao. LTE-V: A TD-LTE-based V2X solution for future vehicular network. *IEEE Internet of Things Journal*, 3(6):997–1005, Dec 2016.
- [35] A. Mder¹ R. Baldessari¹ M. Sakata² T. Tsukahara² M. Kato² L. Le¹, A. Festag¹. Infrastructure-assisted communication for CAR-2-X communication. In *18th ITS World Congress*, Sept 2011.
- [36] M. Wiecker A. Festag and N. Zahariev. Safety and traffic efficiency applications for geomessaging over cellular networks. In *19th ITS World Congress*, Sept 2012.
- [37] M. Wiecker A. Festag and N. Zahariev. A capacity analysis for the transmission of event and cooperative awareness messages in LTE networks. In *18th ITS World Congress*, Sept 2011.
- [38] 3GPP TR 36.885: Study on LTE-based V2X Services (Release 14). Technical report, 3GPP, 2016.

- [39] 3GPP TD RP-151109: New SI proposal: Feasibility study on LTE-based V2X services. Technical report, 3GPP, 2016.
- [40] S. Chen, J. Hu, Y. Shi, Y. Peng, J. Fang, R. Zhao, and L. Zhao. Vehicle-to-everything (V2V) services supported by LTE-based systems and 5G. *IEEE Communications Standards Magazine*, 1(2):70–76, 2017.
- [41] W. Li, X. Ma, J. Wu, K. S. Trivedi, X. L. Huang, and Q. Liu. Analytical model and performance evaluation of long-term evolution for vehicle safety services. *IEEE Transactions on Vehicular Technology*, 66(3):1926–1939, March 2017.
- [42] Y. Park, J. Ha, S. Kuk, H. Kim, M. Liang, and J. Ko. A feasibility study and development framework design for realizing smartphone-based vehicular networking systems. *IEEE Transactions on Mobile Computing*, 13(11):2431–2444, Nov 2014.
- [43] Network Simulator 3. <https://www.nsnam.org>. Accessed: 2017-10-30.
- [44] Z. Hameed Mir and F. Filali. LTE and IEEE 802.11p for vehicular networking: a performance evaluation. *EURASIP Journal on Wireless Communications and Networking*, May 2014.
- [45] F. Tila, A. Nix, A. Doufexi, J. Cao, D. Kong, A. Goulianos, D. Berkovsky, and G. Hilton. Design and verification of a virtual drive test methodology for vehicular LTE-A applications. *IEEE Transactions on Vehicular Technology*, PP(99):1–1, 2018.
- [46] A. Costa, P. Pedreiras, J. Fonseca, J.N. Matos, H. Proenca, A. Gomes, and J.S. Gomes. Evaluating WiMAX for vehicular communication applications. In *IEEE International Conference on Emerging Technologies and Factory Automation*, pages 1185–1188, Sept 2008.

- [47] L. Tung, J. Mena, M. Gerla, and C. Sommer. A cluster based architecture for intersection collision avoidance using heterogeneous networks. In *12th Annual Mediterranean Ad Hoc Networking Workshop (MED-HOC-NET)*, pages 82–88, June 2013.
- [48] G. Rmy, S. M. Senouci, F. Jan, and Y. Gourhant. LTE4V2X; collection, dissemination and multi-hop forwarding. In *IEEE International Conference on Communications (ICC)*, pages 120–125, June 2012.
- [49] S. Ucar, S. Coleri Ergen, and O. Ozkasap. Multi-hop cluster based IEEE 802.11p and LTE hybrid architecture for VANET safety message dissemination. *IEEE Transactions on Vehicular Technology*, PP(99):1–1, 2015.
- [50] A. Bazzi, M. Masini, A. Zanella, and G. Pasolini. IEEE 802.11p for cellular offloading in vehicular sensor networks. *Computer Communications*, 60:97 – 108, 2015.
- [51] N. M. Sadek, H. H. Halawa, R. M. Daoud, H. H. Amer, and N. A. Ali. Heterogeneous LTE/Wi-Fi architecture for ITS traffic control and infotainment. In *International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles (ESARS)*, pages 1–6, March 2015.
- [52] C. Ye, P. Wang, C. Wang, and F. Liu. Mobility management for LTE-based heterogeneous vehicular network in V2X scenario. In *IEEE International Conference on Computer and Communications (ICCC)*, pages 2203–2207, Oct 2016.
- [53] Narcisse Nya and Bruno Baynat. Performance model for 4G/5G heterogeneous networks with different classes of users. In *Proceedings of the 20th ACM International Conference on Modelling, Analysis and Simulation of Wireless and Mobile Systems*, MSWiM, pages 171–178, New York, NY, USA, 2017.
- [54] Douglas F.S. Nunes, Edson S. Moreira, Bruno Y.L. Kimura, Nishanth Sastry, and Toktam Mahmoodi. Attraction-area based geo-clustering for LTE vehicular crowd-

- sensing data offloading. In *Proceedings of the 20th ACM International Conference on Modelling, Analysis and Simulation of Wireless and Mobile Systems, MSWiM*, pages 323–327, New York, NY, USA, 2017.
- [55] K. Zheng, Q. Zheng, P. Chatzimisios, W. Xiang, and Y. Zhou. Heterogeneous vehicular networking: A survey on architecture, challenges, and solutions. *IEEE Communications Surveys Tutorials*, 17(4):2377–2396, Fourthquarter 2015.
- [56] C. Wu, T. Yoshinaga, X. Chen, L. Zhang, and Y. Ji. Cluster-based content distribution integrating LTE and IEEE 802.11p with fuzzy logic and Q-Learning. *IEEE Computational Intelligence Magazine*, 13(1):41–50, Feb 2018.
- [57] Q. Zheng, K. Zheng, L. Sun, and V. C. M. Leung. Dynamic performance analysis of uplink transmission in cluster-based heterogeneous vehicular networks. *IEEE Transactions on Vehicular Technology*, 64(12):5584–5595, Dec 2015.
- [58] H. P. Luong, M. Panda, H. Vu, and B. Q. Vo. Beacon rate optimization for vehicular safety applications in highway scenarios. *IEEE Transactions on Vehicular Technology*, PP(99):1–1, 2017.
- [59] D. Barbieri, I. Thibault, D. Lister, A. Bazzi, B. M. Masini, and O. Andrisano. Adaptive beaconing for safety enhancement in vehicular networks. In *15th International Conference on ITS Telecommunications (ITST)*, pages 1–6, May 2017.
- [60] E. Egea-Lopez and P. Pavon-Mario. Fair congestion control in vehicular networks with beaconing rate adaptation at multiple transmit powers. *IEEE Transactions on Vehicular Technology*, 65(6):3888–3903, June 2016.
- [61] S. Zemouri, S. Djahel, and J. Murphy. Smart adaptation of beacons transmission rate and power for enhanced vehicular awareness in VANETs. In *IEEE 17th International Conference on Intelligent Transportation Systems (ITSC)*, pages 739–746, Oct 2014.

- [62] S. A. B. Mussa, M. Manaf, and K. Z. Ghafoor. Beaconing and transmission range adaptation approaches in vehicular ad hoc networks: Trends and research challenges. In *International Conference on Computational Science and Technology (ICCST)*, pages 1–6, Aug 2014.
- [63] Mohammed Alhameed and Imad Mahgoub. High awareness adaptive beaconing based on fuzzy logic in VANET. In *ACM International Symposium on Mobility Management and Wireless Access, MobiWac*, pages 153–157, New York, NY, USA, 2017.
- [64] R. K. Schmidt, T. Leinmuller, E. Schoch, F. Kargl, and G. Schafer. Exploration of adaptive beaconing for efficient intervehicle safety communication. *IEEE Network*, 24(1):14–19, Jan 2010.
- [65] S. Wang, L. Le, N. Zahariev, and K. Leung. Centralized rate control mechanism for cellular-based vehicular networks. In *IEEE Global Communications Conference (GLOBECOM)*, pages 4914–4920, Dec 2013.
- [66] Y. Feng, Y. Du, Z. Ren, Z. Wang, Y. Liu, and L. Zhang. Adaptive beacon rate adjusting mechanism for safety communication in cooperative IEEE 802.11p-3G vehicle-infrastructure systems. In *16th Asia-Pacific Conference on Communications (APCC)*, pages 441–446, Oct 2010.
- [67] R. Baldessari L. Le A. Festag M. Zorzi M. Drigo, W. Zhang. Distributed rate control algorithm for vanets (drcv). In *Proceedings of the Sixth ACM International Workshop on VehiculAr InterNETworking*, pages 119–120, New York, NY, USA, 2009.
- [68] Linying Liu, Xinhong Wang, Chao Wang, and Fuqiang Liu. An efficient beacon rate adaptation scheme for vehicular networks. In *International Conference on Wireless Communications Signal Processing (WCSP)*, pages 1–6, Oct 2013.

- [69] E. Egea-Lopez and P. Pavon Marino. Distributed and fair beaconing rate adaptation for congestion control in vehicular networks. *IEEE Transactions on Mobile Computing*, PP(99):1–1, 2016.
- [70] N. Chaabouni, A. Hafid, and P. K. Sahu. A collision-based beacon rate adaptation scheme(CBA) for VANETs. In *IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS)*, pages 1–6, Dec 2013.
- [71] F. Goudarzi and H. Asgari. Non-cooperative beacon rate and awareness control for vanets. *IEEE Access*, 5:16858–16870, 2017.
- [72] M. Sepulcre, J. Gozalvez, O. Altintas, and H. Kremo. Adaptive beaconing for congestion and awareness control in vehicular networks. In *IEEE Vehicular Networking Conference (VNC)*, pages 81–88, Dec 2014.
- [73] S. Rezaei, R. Sengupta, and H. Krishnan. Reducing the communication required by dsrc-based vehicle safety systems. In *IEEE Intelligent Transportation Systems Conference*, pages 361–366, Sept 2007.
- [74] H. H. Nguyen and H. Y. Jeong. Mobility-adaptive beacon broadcast for vehicular cooperative safety-critical applications. *IEEE Transactions on Intelligent Transportation Systems*, PP(99):1–15, 2017.
- [75] A. Boukerche, C. Rezende, and R. W. Pazzi. Improving neighbor localization in vehicular ad hoc networks to avoid overhead from periodic messages. In *IEEE Global Telecommunications Conference*, pages 1–6, Nov 2009.
- [76] J. Liu and Q. Wang. Position prediction based frequency control of beacons in vehicular Ad Hoc networks. *International Journal of Distributed Sensor Networks*, 11(8):631415, 2015.

- [77] E. Egea-Lopez, J. J. Alcaraz, J. Vales-Alonso, A. Festag, and J. Garcia-Haro. Statistical beaconing congestion control for vehicular networks. *IEEE Transactions on Vehicular Technology*, 62(9):4162–4181, Nov 2013.
- [78] G. Lei, F. Liu, P. Wang, X. Wang, and N. Wang. Power adjustment based congestion control in vehicular Ad-hoc networks. In *4th International Conference on Artificial Intelligence with Applications in Engineering and Technology*, pages 280–285, Dec 2014.
- [79] M. Torrent-Moreno, J. Mittag, P. Santi, and H. Hartenstein. Vehicle-to-vehicle communication: Fair transmit power control for safety-critical information. *IEEE Transactions on Vehicular Technology*, 58(7):3684–3703, Sept 2009.
- [80] S. Zemouri, S. Djahel, and J. Murphy. An altruistic prediction-based congestion control for strict beaconing requirements in urban VANETs. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, PP(99):1–16, 2018.
- [81] E. Wang, Y. Yang, and J. Wu. Energy efficient beaconing control strategy based on time-continuous markov model in DTNs. *IEEE Transactions on Vehicular Technology*, 66(8):7411–7421, Aug 2017.
- [82] T. Tielert, D. Jiang, Q. Chen, L. Delgrossi, and H. Hartenstein. Design methodology and evaluation of rate adaptation based congestion control for Vehicle Safety Communications. In *IEEE Vehicular Networking Conference (VNC)*, pages 116–123, Nov 2011.
- [83] C. Sommer, O. K. Tonguz, and F. Dressler. Adaptive beaconing for delay-sensitive and congestion-aware traffic information systems. In *IEEE Vehicular Networking Conference (VNC)*, pages 1–8, Dec 2010.

- [84] C. Sommer, O. K. Tonguz, and F. Dressler. Traffic information systems: efficient message dissemination via adaptive beaconing. *IEEE Communications Magazine*, 49(5):173–179, May 2011.
- [85] J. He, H. h. Chen, T. M. Chen, and W. Cheng. Adaptive congestion control for DSRC vehicle networks. *IEEE Communications Letters*, 14(2):127–129, February 2010.
- [86] W. Guan, J. He, L. Bai, and Z. Tang. Adaptive rate control of dedicated short range communications based vehicle networks for road safety applications. In *IEEE 73rd Vehicular Technology Conference (VTC Spring)*, pages 1–5, May 2011.
- [87] C. L. Huang, Y. P. Fallah, R. Sengupta, and H. Krishnan. Adaptive intervehicle communication control for cooperative safety systems. *IEEE Network*, 24(1):6–13, Jan 2010.
- [88] F. Capozzi, G. Piro, L.A. Grieco, G. Boggia, and P. Camarda. Downlink packet scheduling in LTE cellular networks: Key design issues and a survey. *IEEE Communications Surveys Tutorials*, 15(2):678–700, Second 2013.
- [89] Hatem Abou-zeid, Hossam S. Hassanein, and Ramy Atawia. Towards mobility-aware predictive radio access: Modeling; simulation; and evaluation in LTE networks. In *ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems, MSWiM*, pages 109–116, New York, NY, USA, 2014.
- [90] P. Kela, J. Puttonen, N. Kolehmainen, T. Ristaniemi, T. Henttonen, and Martti Moisio. Dynamic packet scheduling performance in UTRA Long Term Evolution downlink. In *International Symposium on Wireless Pervasive Computing*, pages 308–313, May 2008.

- [91] E. Yaacoub, H. Al-Asadi, and Z. Dawy. Low complexity scheduling algorithms for the LTE uplink. In *IEEE Symposium on Computers and Communications*, pages 266–270, July 2009.
- [92] L. A. M. Ruiz de Temino, G. Berardinelli, S. Frattasi, and P. Mogensen. Channel-aware scheduling algorithms for SC-FDMA in LTE uplink. In *IEEE 19th International Symposium on Personal, Indoor and Mobile Radio Communications*, pages 1–6, Sept 2008.
- [93] M. Al-Rawi, R. Jantti, J. Torsner, and M. Sagfors. Opportunistic uplink scheduling for 3g lte systems. In *Innovations in Information Technologies (IIT)*, pages 705–709, Nov 2007.
- [94] M. Kalil, A. Shami, A. Al-Dweik, and S. Muhaidat. Low-complexity power-efficient schedulers for LTE uplink with delay-sensitive traffic. *IEEE Transactions on Vehicular Technology*, 64(10):4551–4564, Oct 2015.
- [95] E. Yaacoub and Z. Dawy. A game theoretical formulation for proportional fairness in LTE uplink scheduling. In *IEEE Wireless Communications and Networking Conference*, pages 1–5, April 2009.
- [96] M. Proebster, C.M. Mueller, and H. Bakker. Adaptive fairness control for a proportional fair LTE scheduler. In *IEEE 21st International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC)*, pages 1504–1509, Sept 2010.
- [97] M. Ayhan, Y. Zhao, and H. A. Choi. Utilizing geometric mean in proportional fair scheduling: Enhanced throughput and fairness in LTE DL. In *IEEE Global Communications Conference (GLOBECOM)*, pages 1–6, Dec 2016.
- [98] S. Mosleh, L. Liu, and J. Zhang. Proportional-fair resource allocation for coordinated multi-point transmission in LTE-Advanced. *IEEE Transactions on Wireless Communications*, 15(8):5355–5367, Aug 2016.

- [99] D. Martin-Sacristan, J. F. Monserrat, D. Calabuig, and N. Cardona. Time-frequency coupled proportional fair scheduler with multicarrier awareness for LTE downlink. In *IEEE 81st Vehicular Technology Conference (VTC Spring)*, pages 1–5, May 2015.
- [100] S. Ryhove J. Rasool, V. Hassel and G. Oien. Opportunistic scheduling policies for improved throughput guarantees in wireless networks. *EURASIP Journal on Wireless Communications and Networking*, page 43, Jul 2011.
- [101] O. Grndalen, A. Zanella, K. Mahmood, M. Carpin, J. Rasool, and O. N. sterb. Scheduling policies in time and frequency domains for LTE downlink channel: A performance comparison. *IEEE Transactions on Vehicular Technology*, 66(4):3345–3360, April 2017.
- [102] R. Ruby and V. Leung. Towards QoS assurance with revenue maximization of LTE uplink scheduling. In *Ninth Annual Communication Networks and Services Research Conference*, pages 202–209, May 2011.
- [103] M. Kalil, A. Shami, and A. Al-Dweik. QoS-aware power-efficient scheduler for LTE uplink. *IEEE Transactions on Mobile Computing*, 14(8):1672–1685, Aug 2015.
- [104] S. Chaudhuri, I. Baig, and D. Das. Utility based QoS aware uplink scheduler scheme for LTE Small Cell Network. In *IEEE International Conference on Communications (ICC)*, pages 3149–3154, June 2015.
- [105] M. Iturralde, Anne Wei, T. Ali Yahiya, and A.-L. Beylot. Resource allocation for real time services using cooperative game theory and a virtual token mechanism in LTE networks. In *IEEE Consumer Communications and Networking Conference (CCNC)*, pages 879–883, Jan 2012.

- [106] S. Chaudhuri, I. Baig, and D. Das. QoS aware downlink scheduler for a carrier aggregation LTE-Advance network with efficient carrier power control. In *IEEE Annual India Conference (INDICON)*, pages 1–6, Dec 2016.
- [107] N. Ferdosian, M. Othman, B. M. Ali, and K. Y. Lun. Fair-QoS broker algorithm for overload-state downlink resource scheduling in LTE networks. *IEEE Systems Journal*, PP(99):1–12, 2017.
- [108] V. C. Gungor and O. G. Uyan. QoS-aware downlink scheduling algorithm for LTE networks: A case study on edge users. In *25th Signal Processing and Communications Applications Conference (SIU)*, pages 1–4, May 2017.
- [109] N. Afrin, J. Brown, and J. Y. Khan. A delay sensitive LTE uplink packet scheduler for M2M traffic. In *IEEE Globecom Workshops (GC Wkshps)*, pages 941–946, Dec 2013.
- [110] D. H. Nguyen, H. Nguyen, and . Renault. Performance evaluation of E-MQS scheduler with Mobility in LTE heterogeneous network. In *IEEE International Conference on Communications (ICC)*, pages 1–6, May 2017.
- [111] N. Afrin, J. Brown, and J. Y. Khan. Design of a buffer and channel adaptive LTE semi-persistent scheduler for M2M communications. In *IEEE International Conference on Communications (ICC)*, pages 5821–5826, June 2015.
- [112] J. T. S. Avocanh, M. Abdennebi, and J. Ben-Othman. An enhanced two level scheduler to increase multimedia services performance in LTE networks. In *IEEE International Conference on Communications (ICC)*, pages 2351–2356, June 2014.
- [113] Rima Hatoum, Abbas Hatoum, Alaa Ghaith, and Guy Pujolle. Qos-based joint resource allocation with link adaptation for SC-FDMA uplink in heterogeneous networks. In *ACM International Symposium on Mobility Management and Wireless Access, MobiWac*, pages 59–66, New York, NY, USA, 2014.

- [114] R. Ruby, V. C. M. Leung, and D. G. Michelson. Uplink scheduler for SC-FDMA-based heterogeneous traffic networks with QoS assurance and guaranteed resource utilization. *IEEE Transactions on Vehicular Technology*, 64(10):4780–4796, Oct 2015.
- [115] O. Ergul, O. Yilmaz, A. T. Koc, and O. B. Akan. DRX and QoS-aware energy-efficient uplink scheduling for long term evolution. In *IEEE Global Communications Conference (GLOBECOM)*, pages 4644–4649, Dec 2013.
- [116] Y. H. Cheng, W. C. Su, K. T. Feng, and L. C. Wang. QoS-guaranteed channel-aware scheduling and resource grouping under non-full buffer traffic for LTE-A networks. In *IEEE Wireless Communications and Networking Conference (WCNC)*, pages 1–6, March 2017.
- [117] D. Liu and Y. H. Lee. An efficient scheduling discipline for packet switching networks using earliest deadline first round robin. In *12th International Conference on Computer Communications and Networks*, pages 5–10, Oct 2003.
- [118] P. Kela, J. Puttonen, N. Kolehmainen, T. Ristaniemi, T. Henttonen, and M. Moisiö. Dynamic packet scheduling performance in UTRA Long Term Evolution downlink. In *3rd International Symposium on Wireless Pervasive Computing (ISWPC)*, pages 308–313, May 2008.
- [119] K. C. Beh, S. Armour, and A. Doufexi. Joint time-frequency domain proportional fair scheduler with HARQ for 3GPP LTE systems. In *IEEE 68th Vehicular Technology Conference (VTC)*, pages 1–5, Sept 2008.
- [120] J. Huang and Z. Niu. Buffer-aware and traffic-dependent packet scheduling in wireless OFDM networks. In *IEEE Wireless Communications and Networking Conference (WCNC)*, pages 1554–1558, March 2007.

- [121] C. Wengerter, J. Ohlhorst, and A. G. E. von Elbwart. Fairness and throughput analysis for generalized proportional fair frequency scheduling in OFDMA. In *IEEE 61st Vehicular Technology Conference (VTC)*, volume 3, pages 1903–1907 Vol. 3, May 2005.
- [122] H. A. M. Ramli, R. Basukala, K. Sandrasegaran, and R. Patachaianand. Performance of well known packet scheduling algorithms in the downlink 3GPP LTE system. In *IEEE 9th Malaysia International Conference on Communications (MICC)*, pages 815–820, Dec 2009.
- [123] R. Basukala, H. A. M. Ramli, and K. Sandrasegaran. Performance analysis of EXP/PF and M-LWDF in downlink 3GPP LTE system. In *Asian Himalayas International Conference on Internet (AH-ICI)*, pages 1–5, Nov 2009.
- [124] G. Monghal, K. I. Pedersen, I. Z. Kovacs, and P. E. Mogensen. QoS oriented time and frequency domain packet schedulers for the UTRAN long term evolution. In *IEEE Vehicular Technology Conference (VTC)*, pages 2532–2536, May 2008.
- [125] S. Choi, K. Jun, Y. Shin, S. Kang, and B. Choi. MAC scheduling scheme for VoIP traffic service in 3G LTE. In *IEEE 66th Vehicular Technology Conference (VTC)*, pages 1441–1445, Sept 2007.
- [126] J. Liu, Y. Kawamoto, H. Nishiyama, N. Kato, and N. Kadowaki. Device-to-device communications achieve efficient load balancing in LTE-advanced networks. *IEEE Wireless Communications*, 21(2):57–65, April 2014.
- [127] D. Xenakis, M. Kountouris, L. Merakos, N. Passas, and C. Verikoukis. Performance analysis of network-assisted D2D discovery in random spatial networks. *IEEE Transactions on Wireless Communications*, 15(8):5695–5707, Aug 2016.

- [128] M. S. Corson, R. Laroia, J. Li, V. Park, T. Richardson, and G. Tsirtsis. Toward proximity-aware internetworking. *IEEE Wireless Communications*, 17(6):26–33, December 2010.
- [129] K. Y. Park, Young-Bin Chang, Dong-Woo Kim, Jong-Han Kim, and Woon-Haing Hur. Opportunistic discovery scheme for device-to-device communication. In *IEEE 22nd International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD)*, pages 1–5, June 2017.
- [130] M. Simsek, A. Merwaday, N. Correal, and . Gven. Device-to-device discovery based on 3GPP system level simulations. In *IEEE Globecom Workshops (GC Wkshps)*, pages 555–560, Dec 2013.
- [131] K. Doppler, C. B. Ribeiro, and J. Knecht. Advances in D2D communications: Energy efficient service and device discovery radio. In *International Conference on Wireless Communication, Vehicular Technology, Information Theory and Aerospace Electronic Systems Technology (Wireless VITAE)*, pages 1–6, Feb 2011.
- [132] J. Zhang, L. Deng, X. Li, Y. Zhou, Y. Liang, and Y. Liu. Novel device-to-device discovery scheme based on random backoff in LTE-Advanced networks. *IEEE Transactions on Vehicular Technology*, PP(99):1–1, 2017.
- [133] X. Wu, S. Tavildar, S. Shakkottai, T. Richardson, J. Li, R. Laroia, and A. Jovicic. FlashLinQ: A synchronous distributed scheduler for peer-to-peer ad hoc networks. *IEEE/ACM Transactions on Networking*, 21(4):1215–1228, Aug 2013.
- [134] Qualcomm LTE direct. <http://www.qualcomm.com/solutions/wireless-networks/technologies/lte/lte-direct>. Accessed: 2017-10-30.
- [135] M. Gutierrez-Estevez S. Doumiati, H. Artail. A framework for LTE-A proximity-based device-to-device service registration and discovery. In *International Conference on Future Networks and Communications*, pages 87 – 94, Dec 2014.

- [136] S. Misra and M. Khatua. Semi-distributed backoff: Collision-aware migration from random to deterministic backoff. *IEEE Transactions on Mobile Computing*, 14(5):1071–1084, May 2015.
- [137] G. Fodor, E. Dahlman, G. Mildh, S. Parkvall, N. Reider, G. Mikls, and Z. Turnyi. Design aspects of network assisted device-to-device communications. *IEEE Communications Magazine*, 50(3):170–177, March 2012.
- [138] Y. Peng, Q. Gao, S. Sun, and Z. Yan-Xiu. Discovery of device-device proximity: Physical layer design for D2D discovery. In *IEEE/CIC International Conference on Communications in China - Workshops (CIC/ICCC)*, pages 176–181, Aug 2013.
- [139] J. Hong, S. Park, H. Kim, S. Choi, and K. B. Lee. Analysis of Device-to-Device discovery and link setup in LTE networks. In *IEEE 24th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, pages 2856–2860, Sept 2013.
- [140] K. Doppler, M. Rinne, C. Wijting, C. B. Ribeiro, and K. Hugl. Device-to-device communication as an underlay to LTE-advanced networks. *IEEE Communications Magazine*, 47(12):42–49, Dec 2009.
- [141] B. G. Choi, J. S. Kim, M. Y. Chung, J. Shin, and A. S. Park. Development of a system-level simulator for evaluating performance of device-to-device communication underlying LTE-Advanced networks. In *International Conference on Computational Intelligence, Modelling and Simulation*, pages 330–335, Sept 2012.
- [142] S. Hakola, T. Chen, J. Lehtomaki, and T. Koskela. Device-to-device communication in cellular network - performance analysis of optimum and practical communication mode selection. In *IEEE Wireless Communication and Networking Conference*, pages 1–6, April 2010.

- [143] C. H. Yu, K. Doppler, C. B. Ribeiro, and O. Tirkkonen. Resource sharing optimization for device-to-device communication underlying cellular networks. *IEEE Transactions on Wireless Communications*, 10(8):2752–2763, August 2011.
- [144] A. Asadi, Q. Wang, and V. Mancuso. A survey on device-to-device communication in cellular networks. *IEEE Communications Surveys Tutorials*, 16(4):1801–1819, Fourthquarter 2014.
- [145] L. Wei, A. Papathanassiou, Q. C. Li, and G. Wu. System-level simulations for multi-hop D2D communications overlay LTE networks. In *International Conference on Computing, Networking and Communications (ICNC)*, pages 1–5, Feb 2016.
- [146] B. Zuo, L. Jiang, C. He, and Z. Lian. Power allocation optimization for full-duplex D2D communications underlying cellular networks. In *International Conference on Networking and Network Applications (NaNA)*, pages 103–108, July 2016.
- [147] C. H. Yu, K. Doppler, C. Ribeiro, and O. Tirkkonen. Performance impact of fading interference to Device-to-Device communication underlying cellular networks. In *IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*, pages 858–862, Sept 2009.
- [148] H. Meshgi, D. Zhao, and R. Zheng. Optimal resource allocation in multicast device-to-device communications underlying LTE networks. *IEEE Transactions on Vehicular Technology*, 66(9):8357–8371, Sept 2017.
- [149] A. Moubayed, A. Shami, and H. Lutfiyya. Power-aware wireless virtualized resource allocation with D2D communication underlying LTE network. In *IEEE Global Communications Conference (GLOBECOM)*, pages 1–6, Dec 2016.
- [150] X. Chen, R. Q. Hu, and Y. Qian. Distributed resource and power allocation for device-to-device communications underlying cellular network. In *IEEE Global Communications Conference*, pages 4947–4952, Dec 2014.

- [151] B. Chen, J. Zheng, and Y. Zhang. A time division scheduling resource allocation algorithm for D2D communication in cellular networks. In *IEEE International Conference on Communications (ICC)*, pages 5422–5428, June 2015.
- [152] M. Zulhasnine, C. Huang, and A. Srinivasan. Efficient resource allocation for device-to-device communication underlying LTE network. In *IEEE 6th International Conference on Wireless and Mobile Computing, Networking and Communications*, pages 368–375, Oct 2010.
- [153] K. Doppler, C. H. Yu, C. B. Ribeiro, and P. Janis. Mode selection for device-to-device communication underlying an LTE-Advanced network. In *IEEE Wireless Communication and Networking Conference*, pages 1–6, April 2010.
- [154] D. Tsolkas, E. Liotou, N. Passas, and L. Merakos. A graph-coloring secondary resource allocation for D2D communications in LTE networks. In *IEEE 17th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD)*, pages 56–60, Sept 2012.
- [155] P. Phunchongharn, E. Hossain, and D. I. Kim. Resource allocation for device-to-device communications underlying LTE-Advanced networks. *IEEE Wireless Communications*, 20(4):91–100, August 2013.
- [156] K. Yang, S. Martin, L. Boukhatem, J. Wu, and X. Bu. Energy-efficient resource allocation for device-to-device communications overlaying lte networks. In *IEEE 82nd Vehicular Technology Conference (VTC2015-Fall)*, pages 1–6, Sept 2015.
- [157] C. Xia, S. Xu, and K. S. Kwak. Resource allocation for device-to-device communication in LTE-A network: A stackelberg game approach. In *IEEE 80th Vehicular Technology Conference (VTC2014-Fall)*, pages 1–5, Sept 2014.

- [158] X. Cheng, L. Yang, and X. Shen. D2D for intelligent transportation systems: A feasibility study. *IEEE Transactions on Intelligent Transportation Systems*, 16(4):1784–1793, Aug 2015.
- [159] A. Bazzi, B. M. Masini, A. Zanella, and I. Thibault. Beaconing from connected vehicles: IEEE 802.11p vs. LTE-V2V. In *IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, pages 1–6, Sept 2016.
- [160] A. Bazzi, B. M. Masini, A. Zanella, and I. Thibault. On the performance of IEEE 802.11p and LTE-V2V for the Cooperative Awareness of Connected Vehicles. *IEEE Transactions on Vehicular Technology*, PP(99):1–10, 2017.
- [161] C. Campolo, A. Molinaro, G. Araniti, and A. O. Berthet. Better platooning control toward autonomous driving : An LTE device-to-device communications strategy that meets ultralow latency requirements. *IEEE Vehicular Technology Magazine*, 12(1):30–38, March 2017.
- [162] A. Bazzi, B. M. Masini, and A. Zanella. How many vehicles in the LTE-V2V awareness range with half or full duplex radios? In *15th International Conference on ITS Telecommunications (ITST)*, pages 1–6, May 2017.
- [163] G. Piro, A. Orsino, C. Campolo, G. Araniti, G. Boggia, and A. Molinaro. D2D in LTE vehicular networking: System model and upper bound performance. In *7th International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT)*, pages 281–286, Oct 2015.
- [164] N. Cheng, H. Zhou, L. Lei, N. Zhang, Y. Zhou, X. Shen, and F. Bai. Performance analysis of vehicular device-to-device underlay communication. *IEEE Transactions on Vehicular Technology*, 66(6):5409–5421, June 2017.

- [165] Y. Ren, C. Wang, D. Liu, F. Liu, and E. Liu. Applying LTE-D2D to support V2V communication using local geographic knowledge. In *IEEE 82nd Vehicular Technology Conference (VTC2015-Fall)*, pages 1–5, Sept 2015.
- [166] M. Botsov, S. Staliczak, and P. Fertl. On the overhead of radio resource management schemes for mobile underlay D2D communication. In *IEEE Vehicular Networking Conference (VNC)*, pages 1–8, Dec 2016.
- [167] J. Lee and D. Chang. Performance comparison of V2V communication based on LTE-D2D with cooperative schemes. In *International Conference on Information and Communication Technology Convergence (ICTC)*, pages 921–925, Oct 2016.
- [168] M. I. Ashraf, M. Bennis, C. Perfecto, and W. Saad. Dynamic proximity-aware resource allocation in vehicle-to-vehicle (V2V) communications. In *IEEE Globecom Workshops (GC Wkshps)*, pages 1–6, Dec 2016.
- [169] I. de la Iglesia, U. Hernandez-Jayo, M. Januszewski, J. Stanczak, E. Osaba, and R. Carballado. Poster: Efficient cluster-based resource allocation for co-existing vehicle and cellular users. In *IEEE Vehicular Networking Conference (VNC)*, pages 1–2, Dec 2016.
- [170] X. Zhang, Y. Shang, X. Li, and J. Fang. Research on overlay D2D resource scheduling algorithms for V2V broadcast service. In *IEEE 84th Vehicular Technology Conference (VTC-Fall)*, pages 1–5, Sept 2016.
- [171] S. Zhang, Y. Hou, X. Xu, and X. Tao. Resource allocation in D2D-based V2V communication for maximizing the number of concurrent transmissions. In *IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, pages 1–6, Sept 2016.

- [172] W. Xing, N. Wang, C. Wang, F. Liu, and Y. Ji. Resource allocation schemes for D2D communication used in VANETs. In *IEEE 80th Vehicular Technology Conference (VTC2014-Fall)*, pages 1–6, Sept 2014.
- [173] 3GPP TR 36.213: Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures (Release 14). Technical report, 3GPP, 2017.
- [174] 3GPP TS 23.246: Multimedia Broadcast/Multicast Service (MBMS) (Release 14). Technical report, 3GPP, 2016.
- [175] R. Kwan, C. Leung, and Jie Zhang. Proportional fair multiuser scheduling in LTE. *IEEE Signal Processing Letters*, 16(6):461–464, June 2009.
- [176] Hossein Soleimani and Azzedine Boukerche. SLA: Speed and location aware LTE scheduler for vehicular safety applications. In *ACM International Symposium on Mobility Management and Wireless Access, MobiWac*, pages 13–19, New York, NY, USA, 2015.
- [177] J. Piat-J. Nezan M. Pelcat, S. Aridhi. *Physical Layer Multi-Core Prototyping*. Springer US, 2014.
- [178] T. Jamsa-L. Hentil J. Meinila, P. Kyosti. WINNER II channel models. In *Radio Technologies and Concepts for IMT-Advanced*, chapter 3, pages 39–90. John Wiley and Sons, 2015.
- [179] J. Resing. Polling systems and multitype branching processes. *Queueing Systems*, 13(4):409–426, 1993.
- [180] J. Weststrate O. Boxma. Waiting times in polling systems with markovian server routing. In *Messung, Modellierung und Bewertung von Rechensystemen und Netzen*, chapter 5, pages 89–104. John Wiley and Sons, 1989.

- [181] Naishuo Tian and Zhe George Zhang. *Vacation Queueing Models*. Springer US, 2016.