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A Survey on Simulation Efforts of 4G/LTE-based Cellular and Hybrid V2X Communications

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***Abstract*—In the past few years, the cellular telecommunication world advanced with new promised underlying technologies that enable robust communication networks with cellular communication-based approaches. Techniques such as the 4G/LTE and beyond could foster the development of the autonomous vehicle industry, and vehicular communication applications could also provide significant reliability in realistic road situations. The fourth-generation (4G) of mobile cellular telecommunication systems can be applied in Intelligent Transportation Systems (ITS) environments in terms of providing intelligent traffic solutions with an enhancement of the performance of Vehicle-to-Everything (V2X) communication and known as Cellular V2X (C-V2X). To highlight the efforts of 4G/LTE-based cellular communication in V2X technology evolution, this paper presents a comprehensive survey about the simulation evaluation papers of 4G/LTE technology in C-V2X or hybrid V2X communications.**

Keywords*— *4G/LTE, V2X, C-V2X, Simulation, C-ITS, OMNeT++, NS-3.

I. Introduction

Vehicular communication becomes a technological requirement of modern-day transportation due to the increasing number of victims on the road, often caused by inattentive or under-informed drivers, and because the evolving cooperative information exchange between vehicles could help a lot in such situations. Bad weather conditions, drivers not following the road signs, careless driving, etc., can be avoided and prevented by exchanging safety messages between the vehicles directly or indirectly relying on the roadside infrastructure.

The fourth generation of mobile cellular technology (4G) brings insights into the financial and social benefits by introducing unlimited 4G connected and automated mobility solutions such as Cellular Vehicle-to-Everything (C-V2X) [1]. Vehicle-to-Everything (V2X) communications provide connectivity with the surrounded environment and information resources in various use cases aiming to enable available road safety, traffic efficiency and to be one of the fundamentals of autonomous driving using a mobility ecosystem that contains heterogeneous sensors and devices under the concept of Internet of Things (IoT). Nowadays, there are two available types of V2X communication technologies. On one other hand, there are wide-scale deployments and a pretty rich market of the Wi-Fi-based Dedicated Short Range Communication (DSRC) or ITS-G5 solutions between vehicles, relying on the IEEE 802.11p (IEEE Std 802.11-OCB) standard. On the other hand, there are also available products using the cellular communications-based techniques (4G/LTE Long Term Evolution for V2X), commonly referred to as LTE-V2X, LTE-V, or cellular V2X. The LTE-V2X standard consists of two radio interfaces (and the 5G standard as well, but please note that 5G New Radio V2X is outside of the scope of this paper). The first radio interface is a cellular interface known as (Uu) enables and supports Vehicle-to-Infrastructure (V2I) communication. In contrast, the second one is the PC5 interface that supports Vehicle-to-Vehicle (V2V) communications based on direct LTE sidelink. LTE Mode 4 was introduced in Release 14 with a design explicitly for vehicles able to select the radio resources autonomously for their V2V communication and operate without the availability of cellular coverage with the advantage of usage for traffic safety applications[2].

Cellular V2X provides available privileges that involve changing driving such as slicing, edge computing, and in general integrating V2X into the 3GPP cellular ecosystem. Applications are wide-scale: in addition to platooning and cooperative driving, C-V2X can support emergency cases, such as informing the drivers about the emergency vehicles on the road and enabling the hazards ahead warning such as obstruction and weather abnormal status, for instance, fog unclear vision. Trends show that the number of connected and autonomous vehicles (AVs) will increase significantly soon. C-V2X is considered the main technology to provide considerable amounts of data from applications such as 360 None-Line-of-Sight (NLOS) sensing (Radar, Lidar, Camera, Ultrasonic), intent, and situation awareness, 3D HD maps, infotainment, and diagnostics. These applications utilize safety, navigation, and entertainment services for passengers, such as video streaming which requires high throughput, low latency, and ultra-reliable C-V2X communication [3]. Moreover, the various connectivity for V2X with using communications patterns known as Vehicle to Networks (V2N) will involve increasingly autonomous driving use-cases, and for road users, V2X can be used for collecting road tolls and especially will be beneficient for pedestrians (V2P) using their smartphones where the Wi-Fi-based V2X techniques are not considered as a feasible technique. In general, C-V2X will help in reducing accidents by assisting the vehicles to avoid vulnerable road users such as cyclists and pedestrians in several use-cases [4].

Evaluation is a crucial part of validating the above techniques and use-cases. Simulation-based efforts are very useful in reducing the initial cost of experiments of communication technologies in real-time, testing different use cases with distinguished input parameters in real-life scenarios because of the difficulty of testing and examination with actual communication modules. Therefore, evaluating promising communication technologies' performance to be used in diverse V2X applications must involve simulations to test the available technologies and how they improve safety on the road [5].

The vehicle manufacturers, OEMs, Tier 1s, and even the governments worldwide are competing in the automotive industry. The goal is to build and develop future electric and autonomous vehicles ecosystem through supporting advanced deployment models, already started testing solutions to verify safety-critical V2X scenarios, using a variety of services through 4G/LTE and beyond technologies, and enhancing the development of end-to-end specifications for future intelligent transportation and mobility features and services. Therefore, it is highly motivated to group the most relevant research papers concerning LTE-V and hybrid V2X communication-related simulation efforts and provide a clear vision about LTE cellular communication performance in the C-ITS/V2X application domain.

This paper surveys and introduces the simulation efforts in the V2X communication domain to highlight current state-of-the-art V2X simulation techniques to test and evaluate 4G/LTE cellular and hybrid V2X schemes. In section II, we shortly introduce the components of simulation tools and the difference between network and traffic simulators. Section III presents our survey in addition to the comparison table for the simulation effort research papers in terms of simulation tools investigation and conclusions. The article ends with concluding in a summary of our key findings in Section IV.

II. BACKGROUND

Nowadays, V2X technology is still mainly in the investigation and exploration stage because of its continuous evolution, application complexity, unprecedented security issues, and potential safety problems in its applications. This keeps the simulation efforts uninterrupted in verification and laboratory testing in performance and communication protocol evaluation to achieve latency and reliability requirements and find and solve vulnerabilities and potential application risks [6].

Researchers are working hard on the commonly used simulation tools for evaluation for the 4G/LTE communication technology in V2X communications resulting in an enormous number of results that could help understand the requirements of performance achievement in any V2X deployment vehicular communication.

A Vehicular Ad-hoc Network (VANET) is a temporary network created for communication purposes among moving vehicles. Due to the difficulty of physical implementation and simulating a vehicle's network scenario, a network simulator, and traffic simulator with a mediation framework run close to realistic scenarios and functions to minimize the probability of failure in the deployment phase [7].

A. Network Simulators

The first task of the network simulator is to implement networking models and relating protocol stacks. These models will use road data traffic and rely on determined mobility models of nodes (e.g., vehicles) from the traffic simulator. After that, the network simulator performs the appropriate routing strategy for data packets transmission and confirms whether these packets are successfully sent and received over the radio channel. It models radio transmission, implements complex protocols, and performs the relating calculations and data gathering.

There are a variety of network simulators that are commercial or even open-source such as OMNET++ [8], NS-3 [9], OPNET [10], JiST/SWANS [11], and GloMoSim [12]. These simulators have a common feature, namely that they are discrete-event scheduling network simulators, enabling the efficient simulation of vehicular ad-hoc networks.

Network simulators	Reference papers with V2X communications-related topics
OMNET++	[13],[14],[15]
NS-3	[16],[17],[18]
OPNET	[19],[20],[21]
JiST/SWANS	[22],[23],[24]
GloMoSim	[12],[25],[26]

Table 1 - Network simulators applied papers dealing with different V2X communications topics

B. Mediation frameworks

Mediation or middleware or modular framework is located in the middle between the network and the traffic simulators to create interaction between the two main components or even extend the network simulator to create simulation models. Veins [27], with its TraCI interface, is a well-known example of this. Veins is a mediation framework between OMNetT++ network simulator and Simulation in Urban mobility (SUMO) traffic simulator [28]. The mediation framework can also contain, integrate with, and extend other mediation frameworks that enable support features and open complete simulation power analysis. Artery [29] is a modular framework for V2X simulations based on ETSI ITS-G5 protocols such as GeoNetworking and Basic Transport Protocol (BTP). The Artery framework was built to integrate with many mediation frameworks such as Veins, INET [30], and Vanetza as a model of ITS-G5 protocols [31].

C. Traffic simulators

A traffic simulator is also known as the presentation of realistic road traffic or other mobility patterns. It can use real maps such as maps from, e.g., OpenStreetMap [32] for generating the road system to manage mobility patterns or models of moving vehicles with specific predefined mobility models such as SUMO which is an open-source traffic simulator [33], VanetMobiSim [34], MObility model generator for VEhicular networks (MOVE) [35] and Advanced Interactive Microscopic Simulator for Urban (AIMSUN) [36].

Traffic simulators	Reference papers with V2X communications-related topics
SUMO	[37],[38],[39]
VanetMobiSim	[40],[41],[42]
MOVE	[43],[44],[45]
AIMSUN	[46],[47],[48]

Table 2 - Traffic simulators applied papers dealing with different V2X communications topics

D. Other tools for 4G/LTE V2X simulations

There is another group of widely used tools or frameworks that could execute or enhance 4G/LTE simulations but cannot implement complex protocol simulation or datagram-level models. A good example is Matlab with multiple use-cases, such as in [49], where authors present the development of a Matlab/SIMULINK-based technique to evaluate analytical models without taking vehicles' or communications' models into account. Also, in [50], a mathematical analysis is presented depending on simulations performed with Matlab models to evaluate the network architecture in 5G vehicular networks. The authors of [51] proposed a complete PHY features modeling in a Matlab-based simulation framework to obtain realistic performance measurements closer to the real-world scenarios to evaluate the performance of V2X usage.

III. Simulation efforts Of 4G-Based Cellular And Hybrid V2X Communications

There are strenuous efforts in different investigation topics that emphasize the significance of simulations to be performed before the development and deployment stage of any V2X solutions, and valuable results have to be taken into account to build V2X communications dependent on 4G/LTE technology and beyond. It can be seen that simulations of 4G/LTE-based cellular and hybrid V2X communications are a topic of compartmentalized analysis in the context of communication, performance, and reliability. Table 3 below presents the four focus topics of researches we identified from the literature survey, investigation domains, environmental and simulation parameters, conclusions, and example papers related to the focus topics.

A. Focus Topic #1: LTE vs. DSRC

Both the DSRC and C-V2X are undergoing extensive investigation to evaluate the support of vehicular applications characterized by low latency, high throughput, and high-reliability requirements. In papers [52] and [53], the authors introduce comparison and evaluation of cellular LTE and DSRC communications with conclusions that the performance of LTE cellular communication is better than that of the DSRC in terms of range and packet delivery ratio. LTE-based alternatives, including LTE multicast and LTE sidelink are extensively discussed in [54] and stated that these LTE alternates provide better performance than IEEE 802.11p in all studied scenarios in addition to LTE multicast/broadcast is seen to be more reliable than LTE sidelink at longer communication ranges. However, practical experiments like [55] are showing that this debate has not yet been concluded. In papers [56] and [57], authors present that the performance of a competitive DSRC device provides similar performance to the C-V2X device in lab conditions and significantly better performance under field trial conditions. Even DSRC achieves better range performance over long distances under the same circumstances.

B. Focus Topic #2: LTE-V2X Rel-14 Mode 4 performance

Rel-14 Mode 4 of LTE-V2X uses an interface known as the sidelink or PC5 direct communication link and introduces an alternative to 802.11p or DSRC. Mode 4 can operate without cellular coverage, resulting in safety applications without depending on cellular coverage availability, enabling vehicles to select the radio resources for their direct V2V communications autonomously. We identified several papers dealing with LTE-V2X Mode 4, where the main goal usually is to obtain the performance KPIs of that technique. E.g., in paper [58], the authors present analysis and evaluation of Mode 4 configuration under different traffic scenarios and channel load. In paper [59], an open-source C-V2X Mode 4 simulator was introduced and implemented for the NS-3 network simulator, while in paper [60] for OMNeT++.

In papers [61] and [62], the authors present an analysis of LTE-V2X Mode 4 in terms of implementation of ETSI Decentralized Congestion Control (DCC) as a wireless congestion control mechanism with interaction LTE-V2X/ C-V2X to obtain optimal performance in congested environments in addition to a better understanding of C-V2X Mode 4 and its exemplary configuration using different simulation tools such as OMNeT++ and NS-3.

C. Focus Topic #3: LTE-V2X vs. ITS-G5

While the DSRC standard was developed in the US, European Telecommunications Standards Institute (ETSI) developed ITS-G5 is an Intelligent Transportation System (ITS)-G5 short-range communication protocol. Both DSRC and ITS- G5 standards rely on 802.11p-based protocols for vehicular ad-hoc communication networks. Papers in this group tend to focus on dissimilarities and evaluation of European ITS-G5 and LTE-V2V techniques. A good example is paper [63], where a performance comparison between both standards is presented. In papers [64] and [65], authors evaluate and compare ITS-G5 and LTE-V2X standards by assessing both the lower layers and protocol stack performance. The authors conclude that the C-V2X outperforms ITS-G5 for low vehicle density levels while ITS-G5 eventually outperforms C-V2X in latency. In contrast, research papers like [66] show that ITS-G5 outperforms LTE-V2X in the claimed range of the simulated LTE-V2X solutions.

D. Focus Topic #4: LTE-V2X and 5G

V2X communication technology is considered to be one of the emerging services of fifth-generation mobile cellular telecommunications (5G). 5G will support both cellular Uu and sidelink PC5 communication interfaces that have different transmission characteristics. There is ongoing research about LTE-V evolutions under discussion in Release 15 to support 5G V2X communications applications and meet the corresponding demand of V2X communication services requirements.

In paper [67], the authors presented a comprehensive overview of the LTE-V standard for sidelink or V2V communications based on the PC5 interface in order to evaluate LTE-V2X to enable 5G communication technology in V2X applications. The paper concludes that LTE-V can represent an alternate of 802.11p DSRC or ITS-G5 protocols. In Paper [68], a system-level simulator is introduced with the implementation of sidelink communication on highway scenarios to obtain the performance of Mode 4 LTE-V2X communication and provide an analysis of traffic load for 5G communication technology.

Focus Topic #1		***LTE vs. DSRC***		**Most Related Papers**		[54],[55],[56],[63],[69],[70],[71],[72],[73],[74]
Paper	Simulation Tool	Topic of Investigation	Date and Reference	Environmental Parameters	Simulations Parameters	Conclusions of The Results
Evaluation of DSRC and LTE for V2X	NS-3, MATLAB for visual representation	Comparison of DSRC and LTE in simulation	2019, [52]	traffic type, max latency, congestion, and range.	vehicle speed, and the number of vehicles on one channel	• increasing the number of vehicles is directly proportional to latency. • Packet delivery ratio of LTE to be preferable to that of the DSRC.
A Comparison of Cellular Vehicle-to-Everything and Dedicated Short Range Communication	Own system simulator	comparison evaluation between DSRC and Cellular V2X	2017,[53]	Path loss function and Shadowing	Speed and inter-packet interval.	• Cellular V2X either significantly out-performs DSRC or perform as well as DSRC. • A more extended communication range is the critical challenge of cellular V2X.
Comparison of LTE and DSRC-Based Connectivity for Intelligent Transportation Systems	System level simulators	LTE-based alternatives including LTE multicast and LTE sidelink	2017,[54]	LTE-based alternatives performance	Cellular layout, channel, mobility, Tx power (Table 1 in the paper)	• LTE unicast difficult to achieve reliable communication. • The LTE multicast and LTE sidelink have better potential to achieve high reliability at longer communication ranges
Focus Topic #2		***LTE-V2X Rel-14 Mode 4 performance***		**Most Related Papers**		[59],[75],[76],[77],[78], [79]
A First Investigation of Congestion Control for LTE-V2X Mode 4	NS-3	the impact of wireless congestion control on LTE-V2X sidelink Rel-14 Mode 4.	2019, [61]	Packet Delivery Ratio (PDR),	The standard version, channel size, channel throughput and others.	• Sensing-based resource selection enhances the system performances compared to random scheduling. • ETSI Decentralized Congestion Control (DCC) results in worse performance than no congestion control at all.
Configuration of the C-V2X Mode 4 Sidelink PC5 Interface for Vehicular Communications	OMNeT++	New insights compared to existing studies by analyzing the most appropriate configuration of C-V2X Mode 4	2018, [58]	Probability P, Sensing Window, Reference Signal Received Power (RSRP)	Highway Slow scenario, channel, traffic, and mobility models	• The probability P can improve the performance of C-V2X Mode 4. • The paper gives a better understanding of C-V2X Mode 4 and its adequate configuration.
Analysis of Distributed Congestion Control in Cellular Vehicle-to-everything Networks	NS-3	Evaluate the performance of transmission rate and range control using relevant metrics	2019,[62]	Impact of DCC on network capacity.	Rate Control Parameters and Range Control Parameters	• Rate control has a more considerable impact on performance compared to range control.
Focus Topic #3		***LTE-V2X vs. ITS-G5***		**Most Related Papers**		[63], [66],[80],[81],[82]
System-Level Analysis for ITS-G5 and LTE-V2X Performance Comparison	NS-3	comparison of standards by evaluating both the lower layers and protocol stack performance.	2019, [64]	Packet Delivery Rate (PDR), Signal to Noise plus Interference Ratio (SINR).	Message size in Bytes, throughput, etc.	• PC5 mode 4 is outperforming ITS G5 in all cases.

A Comparison of the V2X Communication Systems: ITS-G5 and C-V2X	Physical layer sImulator	Performance evaluation between *LTE-V2X and ITS-G5*	2018, [65]	Physical layer performance assessment and V2X performance with congestion	Transmit power, Sampling Frequency, etc.	• Performance evaluation presents an advantage for the C-V2X for low vehicle density, while when the congestion increases, the performance gap decreases until ITS-G5 eventually outperforms C-V2X. In latency, the resource access duration comparison gives a preference to the ITS-G5.
Focus Topic #4		***LTE-V2X and 5G***		**Most Related Papers**		[83],[84],[85],[86]
LTE-V for Sidelink 5G V2X Vehicular Communications	Unclear which simulator used	LTE-V evolutions under discussion in Release 15 to support 5G and V2X	2019,[67]	Congestion Control, Carrier aggregation:	Transmission power, number of transmissions per packet, etc.	• LTE-V can be an alternative to 802.11p or DSRC due to its advanced link budget, • Congestion control mechanisms and more efficient distributed scheduling schemes are significant for autonomous applications.
System-Level Simulator of LTE Sidelink C-V2X Communication for 5G	System-Level simulator	Performance of the sidelink C-V2X communication	2019, [68]	Vehicle Density (IVD) and Packet Reception Ratio(PPR)	Number of UEs. central carrier frequency, transmission bandwidth, and others	• LTE-V2X simulators creation for 5G should be taken into account IVD and PPR.

Table 3 - Summary of the surveyed papers

IV. Conclusions

There are significant investigation topics and research simulation efforts available in the literature focusing on testing and evaluating 4G/LTE-based cellular V2X communication. This paper presents the surveyed literature in four main focus topics. Most related articles have been analyzed, resulting in that C-V2X has a more extended communication range and better performance from the vehicular safety application point of view than the other types such as DSRC communication. On the other hand, similar results show that DSRC or ITS-G5 outperforms C-V2X when congestion of vehicles density increases and latency in terms of resource access duration comparison. Therefore final conclusion can not be made in this debate: implementation-based analysis will be required. Furthermore, there is intensive ongoing research for the suitability of LTE-V2X schemes for 5G communication technology which has several challenges to fulfill 5G requirements. We live in very inspiring times in regards to the V2X evolution.

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