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COMPARATIVE ANALYSIS BETWEEN 4G LTE AND 5G NR: AN EVALUATION OF CELLULAR COMMUNICATIONS FOR V2X TECHNOLOGY

BY

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Abstract. Cellular Vehicle-to-Everything (C-V2X) technologies are to allow vehicles to exchange information with each other, with the network, but also with other road users, based on secure, reliable, and high-capacity communication links. The use of C-V2X leads to improved road safety and traffic efficiency, over-the-air software updates, pollution reduction, and remote driving, which in the end support the implementation of autonomous vehicles. The main cellular communication standards used within the C-V2X technology are the following: 4G Long-Term Evolution (LTE) and 5G New Radio (NR). This paper follows both a theoretical analysis of cellular communications in the V2X technology, through a comparative analysis of the contribution of each of them concerning the offered technical specifications, and a practical part, where various performance indicators were validated using the Simu5G simulator, which can simulate wireless communication networks and network components with a behavior close to that experienced in real-life.

Keywords: C-V2X, 4G LTE, 5G NR, Simu5G, performance metrics.

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1. Introduction

As globalization accelerates, we are observing the widespread effects of our increasingly interconnected world in numerous aspects of daily life, such as the Internet of Things (IoT) and smart cities. This interconnectedness necessitates data communication among various endpoints, incorporating the concept of networking, where networked endpoints can exchange information and resources. In particular, wireless networking is crucial for its ease of deployment, scalability, and support for new applications. The automotive industry has greatly benefited from these advancements, leading to significant innovations and the emergence of concepts like vehicular networking and intelligent transportation (Tomar *et al*., 2017).

Vehicular networking involves wireless communication between vehicles and roadside infrastructure, enhancing user comfort, road safety, and traffic efficiency. It is a key component of Intelligent Transport Systems (ITSs), which leverage information and communication technologies to deliver these benefits. The dissemination of information within vehicular networking can take various forms, with many applications relying on geographical broadcasting to target all vehicles within a specific area (Chaurasia *et al*., 2012). Vehicle-to-Everything (V2X) communications are essential for implementing ITS, serving as the foundational technologies for inter-vehicle networks. These networks enable automated driving functions and intelligent mobility (Militaru *et al*., 2022). V2X facilitates information exchange between vehicles and various components of the traffic system, encompassing several communication modes: Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Network (V2N), and Vehicle-to-Pedestrian (V2P). V2X technology implementation relies on two main technologies: Dedicated Short-Range Communication (DSRC), which is based on IEEE 802.11p, and Cellular-V2X (C-V2X), which utilizes cellular networks (Lazar *et al*., 2023).

This paper focuses on V2X communications based on cellular systems, known as Cellular V2X (C-V2X). C-V2X uses the 3rd Generation Partnership Project (3GPP) 4G LTE and 5G NR technologies for signal transmission and reception (Hakeem *et al*., 2020). The paper provides a comparative evaluation of the performance of these cellular communication standards for V2X technology. It also assesses the reliability of LTE-V2X and 5G-V2X, highlighting the differences and innovations introduced by 5G NR.

The remainder of the paper is structured as follows. Section II provides a general overview of the communication standards, detailing the specifications for 4G LTE and 5G NR within the context of C-V2X technology. The third section presents C-V2X available transmission modes and their description. In section IV, the simulator used and the scenario chosen for the practical approach are detailed. The illustrated results can be found in Section V, as well as the comparative analysis of the performances of the two standards (4G LTE and 5G NR). The final section presents the conclusions and suggests future research directions.

2. C-V2X communication standards

The specifications for cellular technologies are developed by 3GPP and being organized in versions. Therefore, starting with Release 14 (Rel. 14), 3GPP developed technologies for connected vehicles, known as C-V2X technologies, where "Everything" can refer to road infrastructure, a pedestrian, a network server, or another vehicle (Soto *et al.*, 2021).

Based on 3GPP, the 4G LTE was the first standard used for C-V2X technology, it was first developed under Rel. 14 and improvements have been made to it in Rel. 15 (Harounabadi *et al*., 2021). For the LTE-V2X application, two resource allocation modes are considered: mode 3 and mode 4. In mode 3 (managed mode), the UE uses the 4G base station, also called evolved Node B (eNB), to request the various resources needed for V2X communication. Mode 4 (unmanaged mode) assumes an autonomous mode in which UEs do not communicate with the network, the communication being independent and carried out directly between UEs (Edgar *et al*., 2022). LTE-V2X utilizes Single-Carrier Frequency Division Multiple Access (SC-FDMA) and is compatible with both 10 MHz and 20 MHz channels. These channels are subdivided into Resource Blocks (RBs) consisting of 180 kHz, each containing 12 subcarriers, each with a bandwidth of 15 kHz. Temporally, the channel is organized into 1 ms subframes (Garcia, *et al*., 2021). Moreover, LTE-V2X offers support for all coverage scenarios, including in-coverage, out-of-coverage, and partial-coverage situations. It was developed to increase road safety and reduce traffic congestion by periodically broadcasting a Cooperative Awareness Message (CAM), thus informing participating vehicles about the condition of the vehicle that sent the message (Lazar *et al.*, 2023).

The 5G NR-V2X was first introduced in Rel. 16, which was developed as a complement to LTE-V2X, not as a replacement for it. Its advantages are linked to the increase in reliability and capacity, and a decrease of latency, coming with some new use cases, such as: vehicle platooning, remote driving, and advanced driver assistance functionalities (Miao *et al*., 2021). Moreover, using NR for V2X communication, different cast types are possible in addition to broadcasting, such as unicast which allows direct communication between a pair of UEs, and multicast which involves sending a message from a UE to a set of group receivers (Harounabadi *et al*., 2021). Similar to LTE-V2X, 5G NR-V2X introduces two communication modes: mode 1 and mode 2. Mode 1 mirrors LTE-V2X's mode 3, where the 5G base station, referred to as gNodeB (gNB), assigns radio resources to the vehicle. Conversely, mode 2, similar to LTE-V2X's mode 4, facilitates direct vehicular communications when the vehicle operates beyond the cellular network's coverage area (Miao *et al*., 2021). The 5G

NR-V2X operates within Frequency Range 1 (410 MHz - 7.126 GHz) and Frequency Range 2 (24.25 GHz - 52.6 GHz). Channel bandwidths of 10, 20, 30, and 40 MHz are supported across both frequency bands. Additionally, the 5G NR-V2X accommodates various Orthogonal Frequency Division Multiplexing (OFDM) numerologies, including sub-carrier spacings (SCS) of 15, 30, and 60 kHz for Frequency Range 1 (FR1), and 60 and 120 kHz for Frequency Range 2 (FR2) (Garcia *et al*., 2021). Further distinctions between LTE-V2X and 5G-V2X can be found in Table 1.

Table 1
Difference between LTE-V2X and 5G-V2X

Items	*LTE-V2X*	*5G-V2X*
Specification	*3GPP Rel-14/Rel-15*	*3GPP Rel-16/Rel-17*
Message Category	*Broadcast*	*Broadcast, Unicast and Groupcast*
Usage Scenario	*Safety related/Enhanced*	*Advanced Application*
Cellular Network Coverage	*Mode 3*	*Mode 1*
Out of Cellular Network Coverage	*Mode 4*	*Mode 2*
Latency (ms)	*Low latency: 10~100*	*Ultra-low latency: 1*
Reliability (%)	*99*	*99.99*
Peak data rate (Gbps)	*1*	*20*
Channel broadband (MHz)	*20* *200*	*100 (lower than 6 GHz)* *400 (larger than 6 GHz)*
Mobility support (kmph)	*350*	*500*
Connection density (devices/km^2)	*1000000*	*10000000*
Spectral efficiency (bps/Hz)	*3*	*10*

3. C-V2X communication modes

C-V2X utilizes two complementary transmission modes to accommodate various applications: the Uu interface and the PC5 interface. In Fig. 1, the two modes of transmission can be observed in a more explicit form. In what follows, the two will be presented in detail.

The Uu interface represents the conventional radio interface of the cellular communication network, accessing the network by terminals through a base station in the infrastructure. Therefore, for the Uu interface, uplink (UL) and downlink (DL) transmissions are used to communicate with the base station.

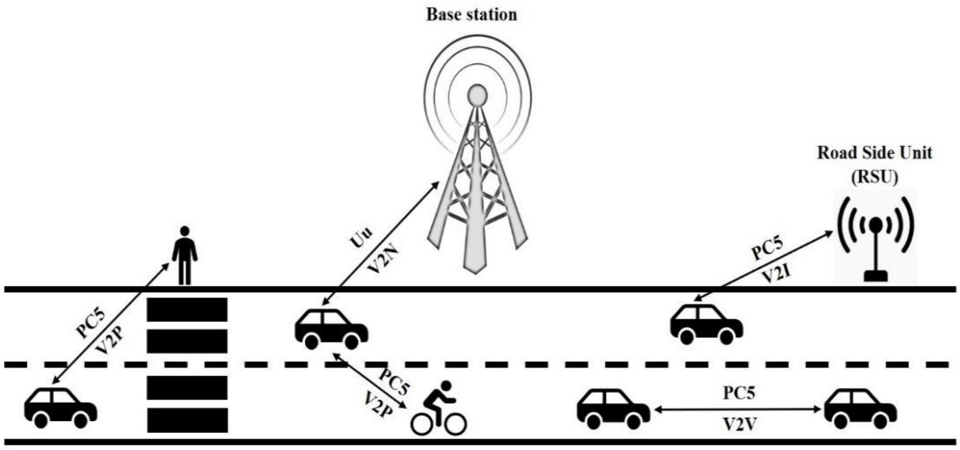

Fig. 1 – C-V2X communication modes.

LTE Uu serves as the 4G iteration of this interface, while NR Uu denotes its 5G iteration. In the case of 5G NR Uu, a series of additional advantages can be discussed, such as higher reliability, lower latency, and higher throughput, these being obtained by using 170 new frequency bands by 5G NR Uu (including mmWave) (Soto *et al.,* 2021). This mode is also called network communications, in which C-V2X operates in traditional mobile broadband licensed spectrum to provide connectivity. The Uu interface facilitates V2N communication, in which vehicles access the network for cloud-based services, especially for long-range applications, e.g., accident ahead (Giordani *et al*., 2018).

The PC5 interface enables direct communication among vehicles (V2V), between vehicles and infrastructure (V2I), and between vehicles and other road users like cyclists and pedestrians (V2P). Utilizing sidelink (SL) transmission, the PC5 interface facilitates these interactions. Consequently, C-V2X operates within the 5.9 GHz ITS band autonomously from the cellular network. Each vehicle autonomously allocates resources for communication, independent of the need to be within the radio coverage of a cellular base station. The PC5 interface facilitates short-range applications, covering distances of less than 1 km, such as location and speed monitoring (Miao *et al*., 2021). Similar to the Uu interface, LTE PC5 represents the 4G version, whereas NR PC5 signifies the 5G version. In the context of 5G, the PC5 interface incorporates the Hybrid Automatic Repeat Request (HARQ) procedure to enhance the reliability of unicast and groupcast communication through retransmissions based on receiver feedback (Soto *et al.*, 2021).

4. Simulation evaluation

In this section, the simulation performed for C-V2X will be presented, which aims to highlight the characteristics of cellular networks, 4G LTE and 5G NR, used in C-V2X technologies. Moreover, the simulator used will be presented in detail, as well as the description of the used scenario. Finally, a comparative analysis of the performances obtained for the two cellular communication standards will be performed.

Considering the technical requirements of the intended scenario, the Simu5G simulator was selected for the implementation phase of the simulation. This simulator, as described by (Nardini *et al*., 2020), builds upon the SimuLTE simulator, enhancing it with the inclusion of 5G NR capabilities. Compared to alternative simulators, Simu5G offers additional functionalities such as Frequency Division Duplexing (FDD), enabling simultaneous uplink (UL) and downlink (DL) transmissions on different frequency bands; device-to-device (D2D) communications for direct communication without infrastructure involvement; and dual-connectivity (DC) scenarios for information exchange between an LTE base station and a 5G base station.

In the simulated scenario, information exchange occurs not only among vehicles but also between vehicles and road infrastructure. Vehicles utilize the PC5 interface for communication among themselves and the Uu interface to communicate with base stations (BSs). The objective is to evaluate communication performance between vehicles and among vehicles and BSs, employing both 4G LTE and 5G NR cellular communication standards.

The simulated scenario involves cellular communication in an urban intersection. In the simulation, the following components are present: i) 4 vehicles: 2 senders (0,2) and 2 receivers (1,3); and ii) 2 4G/5G base stations. The defined scenario can be better observed in Fig. 2 and Table 2 shows the complete list of simulation parameters used. Within the simulator, the role of each vehicle in the communication as well as the simulation parameters were defined with the help of the *omnetpp.ini* file. In this sense, car 0 will transmit to car 1, so it will act as the transmitter, with car 1 set as the receiver. Similarly, car 2 transmits to car 3, as seen in Fig. 2. The communication mode is set to D2D, and CQI reporting for each transmission link has been initialized via the **.enableD2DCqiReporting* parameter. To define the vehicle routes, the *heterogeneous.rou.xml* file, specific to Simulation of Urban Mobility (SUMO) traffic simulator, is configured, where the route of each vehicle is defined and different properties can be set, to develop the desired simulation scenario. Also, the vehicle IDs are set in this file, as the route to travel, and the time to start.

Vehicles start from the initial position illustrated in Fig. 2, after which they follow the route suggested by the dashed arrows. In the initial phase of the simulation, each vehicle establishes communication with the nearest BS within its coverage area, resulting in a traditional two-hop communication setup. Specifically, vehicle 0 or 2 is connected and capable of transmitting/receiving data and control messages to/from BS1, while vehicle 1 or 3 can do the same with BS2. As the vehicles progress along their designated routes, they gradually move away from the BSs. However, their movement brings them closer to each other, eventually meeting the conditions for D2D communication: being within the same cell coverage of the antenna and in close proximity. At this point, the vehicles can exchange control and data messages directly with each other.

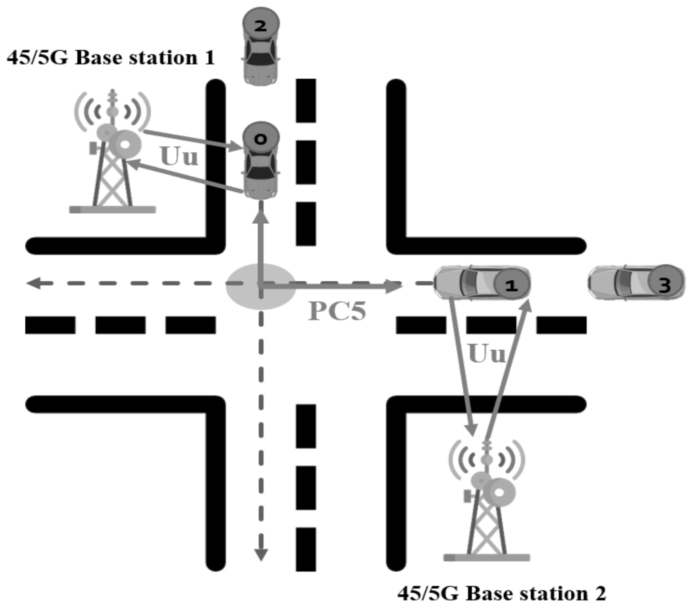

Fig. 2 – Simulation scenario.

Table 2
Simulation parameters

Parameter name	Value	Unit
Network	*4G/5G*	-
Number of cars	*4*	-
Cars Speed	*50*	*Km/h*
Cars Tx Power	*26*	*dBm*
Number of BSs	*2*	-
BSs Tx Power	*46*	*dBm*
Carrier Frequency	*2*	*GHz*
NumBands	*25*	-
Transport Protocol	*UDP*	-
Simulation time	*70*	*s*

5. Illustrative results

The same scenario was run for each of the previously mentioned communication standards. For the comparative analysis of the obtained results, a series of performance indicators were evaluated, significant for V2X communication and the chosen scenario. Performance indicators are the following (Lazar *et al.*, 2022):

1) *Signal-to-interference-plus-noise ratio (SINR)* - This metric assists in assessing signal quality in relation to the level of interference. In the simulation, this indicator was measured for the Uu interface. Therefore, in Figs. 3, 4, 5, and 6, the values for this indicator are represented for 4G and 5G. Moreover, for each communication standard, the values for both UL and DL are illustrated. Table 3 shows the average values for the SINR indicator. In the case of 5G NR, higher values were obtained, this also implies improved signal quality and an enhancement in the data throughput of the channel. In both scenarios, notably satisfactory values are achieved, with a difference of less than 3 dB noted between them.

Table 3
SINR values

Network	Average SINR UL (dB)	Average SINR DL (dB)
4G	*39.9445*	*56.5127*
5G	*41.2640*	*58.7510*

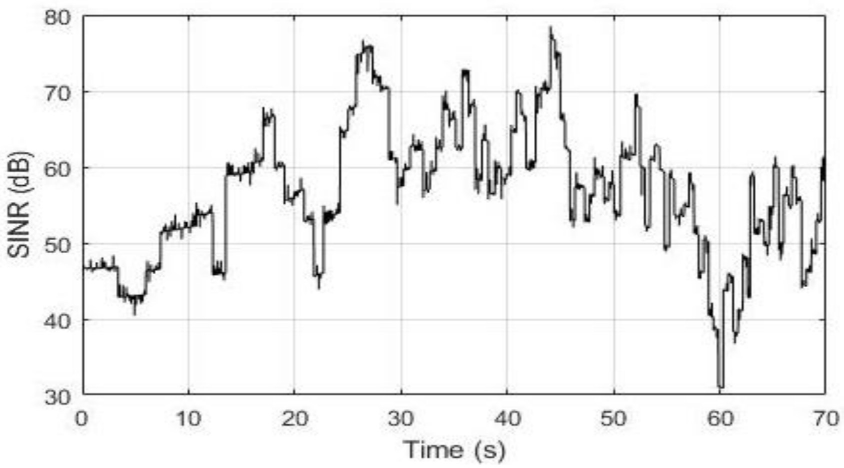

Fig. 3 – The SINR values for 4G DL.

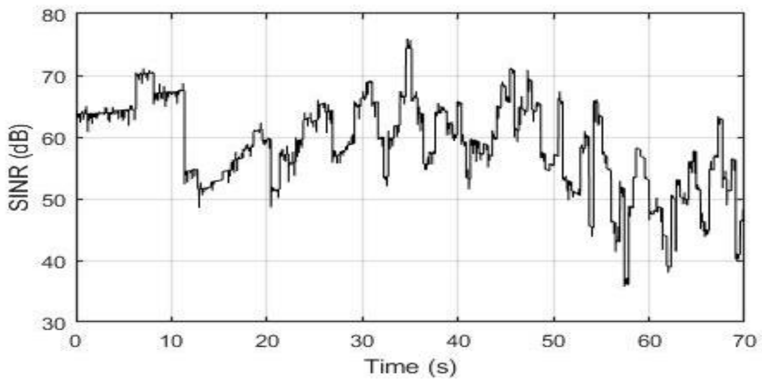

Fig. 4 − The SINR values for 5G DL.

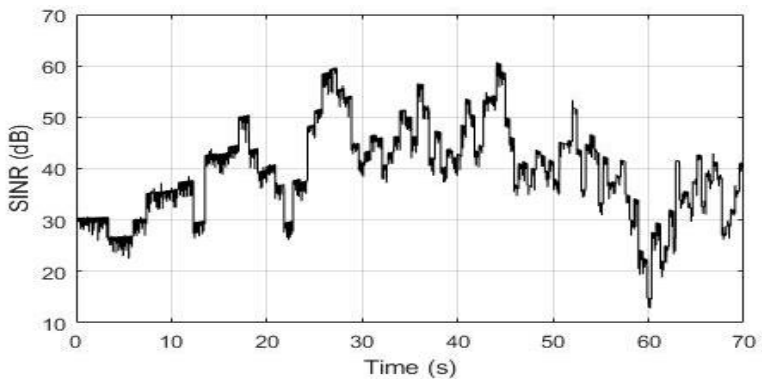

Fig. 5 − The SINR values for 4G UL.

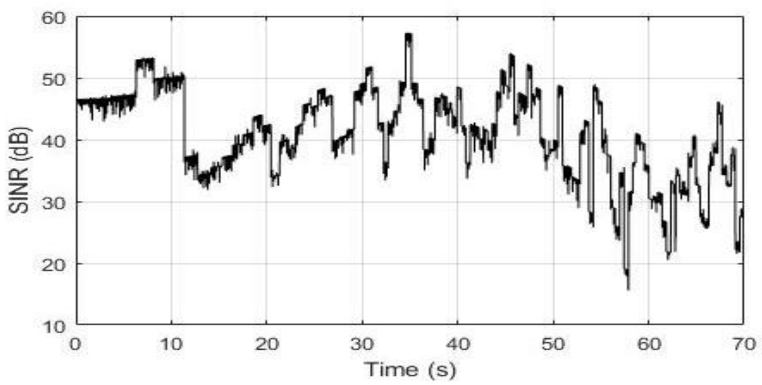

Fig. 6 − The SINR values for 5G UL.

2) *Frame delay or Latency* - This indicator evaluates the time required for a packet to arrive from the source to the destination. Also, this indicator was measured at reception within the PC5 interface. In other words, the frame delay indicator measures the packet data delay between the two vehicles communicating D2D. The values for this indicator can be seen in Figs. 7 and 8. According to the technical specifications, the 5G standard promises a substantial reduction in latency, something that can also be seen in the two figures. For 5G, an average value of 14.7 ms was obtained, compared to 34.3 ms in the case of 4G.

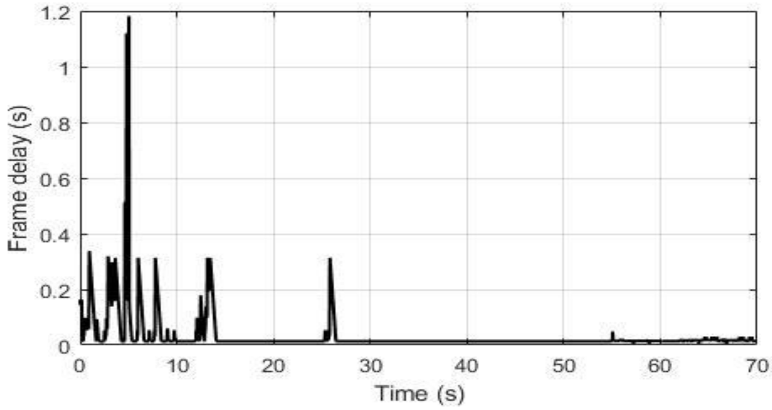

Fig. 7 – Frame delay values for 4G.

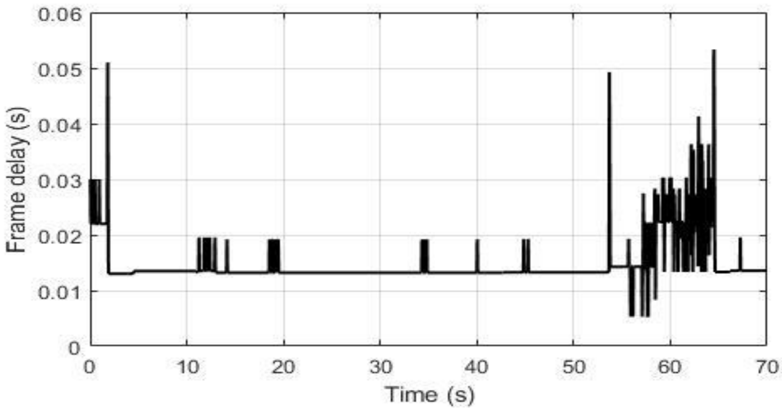

Fig. 8 – Frame delay values for 5G.

3) *Frame loss rate* - This indicator was evaluated for D2D communication between vehicles, more precisely for the PC5 interface. It assumes the percentage of the number of messages not delivered in relation to the total number of messages sent. This indicator is represented in Fig. 9, where

a major difference between the two standards can be observed. Therefore, the average value obtained for 4G LTE is 0.047%, while for 5G NR, the value is 0.001%, which denotes a higher degree of reliability in the case of 5G.

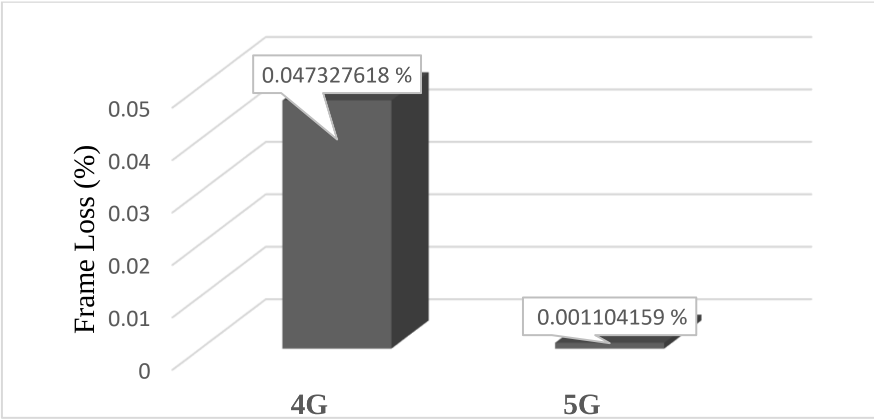

Fig. 9 – Frame loss rate results for 4G and 5G.

4) *Jitter* - This indicator allows for the observation of the stability of the cellular connection by emphasizing the delays occurring between data packets. In Fig. 10 are represented the two values for this indicator, resulting in a value of approximately 85 ms for 4G LTE and one of approximately 7 ms for 5G NR.

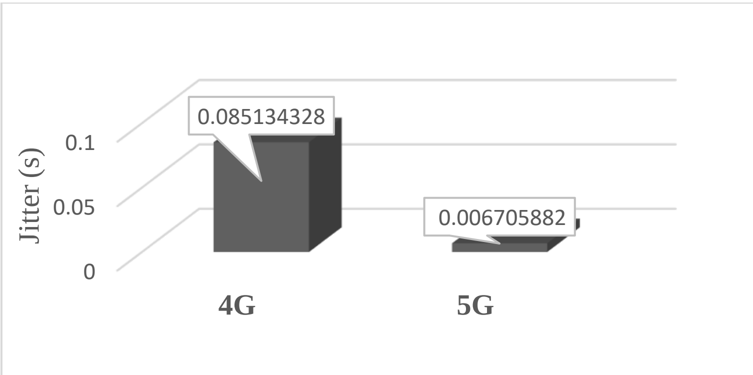

Fig. 10 – Jitter results for 4G and 5G.

5. Conclusions

This paper provided a practical comparative analysis of the performance of cellular networks, 4G LTE and 5G NR, for C-V2X technology. This analysis was performed using the Simu5G simulator to illustrate the values of certain performance metrics. The results illustrate that the 5G network offers better performance, such as faster speeds, higher bandwidth, and lower latency. Moreover, the 5G network is more expensive to implement than the 4G network, and in some countries, the existing infrastructure does not allow the use of only the 5G network (standalone version), but also the dual connectivity between 4G and 5G (non-standalone version).

Future work will focus on the extension of this analysis for a more complex scenario and a similar performance analysis using a practical scenario.

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ANALIZA COMPARATIVĂ DINTRE 4G LTE ȘI 5G NR: O EVALUARE A COMUNICAŢIILOR CELULARE PENTRU TEHNOLOGIA V2X

(Rezumat)

Tehnologiile celulare vehicul-la-tot (C-V2X) permit vehiculelor să facă schimb de informații între ele, cu rețeaua, dar și cu alți utilizatori ai drumului, pe baza unor legături de comunicații sigure, fiabile și de mare capacitate. Utilizarea C-V2X duce la îmbunătățirea siguranței rutiere și a eficienței traficului, reducerea poluării, conducerea de la distanță, care în cele din urmă sprijină implementarea vehiculelor autonome.

Specificațiile pentru tehnologiile celulare sunt dezvoltate de Proiectul de Parteneriat de a Treia Generație (3GPP), fiind organizate în versiuni. Prin urmare, începând cu versiunea 14 (emisă în 2017), 3GPP a dezvoltat tehnologii pentru vehiculele conectate, cunoscute sub denumirea de tehnologii C-V2X, unde „tot” poate fi infrastructura rutieră, un pieton, un server în rețea sau un alt vehicul. C-V2X utilizează 3GPP 4G (a patra generație) LTE (evoluție pe termen lung) sau 5G (a cincea generație) NR (noul radio) pentru a transmite și primi semnale. LTE-V2X a fost dezvoltat pentru prima dată în versiunea 14 (Rel. 14) și i-au fost aduse îmbunătățiri în versiunea 15 (Rel. 15). Acesta a fost dezvoltat pentru a crește siguranța rutieră și a reduce congestionarea traficului prin difuzarea periodică a unui Mesaj de Conștientizare Cooperativă (CAM) și informând astfel vehiculele participante despre starea vehiculului care a transmis mesajul. Standardul 5G NR-V2X a fost introdus pentru prima dată în versiunea 16 (Rel. 16), fiind dezvoltat ca o completare a LTE-V2X, nu ca un înlocuitor pentru acesta. Avantajele sale sunt legate de creșterea fiabilității și capacității, scăderea latenței, venind cu unele cazuri de utilizare noi, cum ar fi: conducerea la distanță și funcționalități avansate de asistență a șoferului. Mai mult, pentru comunicarea V2X, sunt posibile diferite tipuri de difuzare în plus față de broadcasting, cum ar fi unicast care permite comunicarea directă între o pereche de utilizatori și multicast care implică trimiterea unui mesaj de la un utilizator la un set de receptori în grup.

Această lucrare urmărește atât o analiză teoretică a comunicațiilor celulare în tehnologia V2X, printr-o analiză comparativă a contribuției fiecăruia dintre ele în raport cu specificațiile tehnice oferite, cât și o parte practică, în care au fost validați diverși indicatori de performanță cu ajutorul simulatorului Simu5G, care poate simula rețele de

comunicaţii fără fir şi componente de reţea cu un comportament apropiat de cel experimentat în viaţa reală. Rezultatele obţinute ilustrează faptul că reţeaua 5G oferă performanţe mai bune, cum ar fi viteze mai mari, lățime de bandă mai mare și latență mai mică. Mai mult, rețeaua 5G este mai costisitoare de implementat decât rețeaua 4G, iar în unele ţări infrastructura existentă nu permite doar utilizarea rețelei 5G, folosindu-se o conectivitate duală între 4G și 5G.