applied sciences

MDPI

Article

Benchmarking 4G and 5G-Based Cellular-V2X for Vehicle-to-Infrastructure Communication and Urban Scenarios in Cooperative Intelligent Transportation Systems

Tibor Petrov [1,*], Peter Pocta [2] and Tatiana Kovacikova [1]

1 Department of International Research Projects-ERAdiate+, University of Zilina, Univerzitna 1, 010 26 Zilina, Slovakia
2 Department of Multimedia and Information-Communication Technology, Faculty of Electrical Engineering and Information Technology, University of Zilina, Univerzitna 1, 010 26 Zilina, Slovakia
* Correspondence: tibor.petrov@uniza.sk

Abstract: Vehicle-to-Infrastructure (V2I) communication is expected to bring tremendous benefits in terms of increased road safety, improved traffic efficiency and decreased environmental impact. In 2017, The 3rd Generation Partnership Project (3GPP) released 3GPP Release 14, which introduced Cellular Vehicle-to-Everything communication (C-V2X), bringing Vehicle-to-Everything (V2X) communication capabilities to cellular networks, hence creating an alternative to Dedicated Short-Range Communications (DSRC) technology. Since then, every new 3GPP Release including Release 15, a first full set of 5G standards, offered V2X capabilities. In this paper, we present a complex simulation study, which benchmarks the performance of LTE-based and 5G-based C-V2X technologies deployed for V2I communication in an urban setting. The study compares LTE and 5G deployed both in the Device-to-Device in mode 3 and in infrastructural mode. Target performance indicators used for comparison are average end-to-end (E2E) latency and Packet Delivery Ratio (PDR). The performance of those technologies is studied under varying communication conditions realized by a variation of vehicle traffic intensity, communication perimeter and message generation frequency. Furthermore, the effects of infrastructure deployment density on the performance of selected C-V2X communication technologies are explored by comparing the performance of the investigated technologies for three infrastructure density scenarios, i.e., involving two, four and eight base stations (BSs). The performance results are put into a context of the connectivity requirements of the most popular V2I communication services. The results indicate that both C-V2X technologies can support all the considered V2I services without any limitations in terms of the communication perimeter, traffic intensity and message generation frequency. When it comes to the infrastructure density deployment, the results show that increasing the density of the infrastructure deployment from two BSs to four BSs offers a remarkable performance improvement for all the considered V2I services as well as investigated technologies and their modes. Further infrastructure density increase (from four BSs to eight BSs) does not yield any practical benefits in the investigated urban scenario.

Keywords: cellular-V2X; 4G networks; 5G networks; vehicle-to-infrastructure communication; packet delivery ratio; end-to-end latency

check for updates

Citation: Petrov, T.; Pocta, P.; Kovacikova, T. Benchmarking 4G and 5G-Based Cellular-V2X for Vehicle-to-Infrastructure Communication and Urban Scenarios in Cooperative Intelligent Transportation Systems. *Appl. Sci.* **2022**, *12*, 9677. https://doi.org/10.3390/app12199677

Academic Editors: Omar Sami Oubbati and Abderrezak Rachedi

Received: 24 August 2022
Accepted: 20 September 2022
Published: 26 September 2022

1. Introduction

Over the past decade, the transport demand as well as transport volume per capita in Europe has steadily risen [1]. Apart from the positive effects such as economic growth and better access to education and healthcare, this phenomenon brings along many challenges including safety, road congestion and negative environmental impact. To help to address these challenges, the transport sector increasingly relies on advanced technology, e.g., vehicular communication, to streamline its operations.

Vehicular communications have experienced a rapid increase of interest in the last years. It is believed that establishment of communication links between vehicles and the rest of the traffic actors, known as the vehicle-to-everything (V2X) communication, will dramatically improve the road traffic safety and efficiency. This belief represents a main driving force behind the increased interest in the vehicular communications experienced in the last years. This paradigm is entitled the Cooperative Intelligent Transportation Systems (C-ITS) in the literature and its benefits are naturally very important. Therefore, this research area has been considered as a strategic research area in the European Union and most developed countries. It should be noted here that when it comes to the V2X communication, it covers different kinds of communication between vehicles or vehicles and infrastructure or even pedestrians, i.e., Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Network (V2N) and Vehicle-to-Pedestrian (V2P).

V2V communication refers to the exchange of communication messages between vehicles, usually through a self-organized ad hoc communication network, i.e., a network without central management. The messages are exchanged directly between vehicles equipped with V2X-capable Onboard Units (OBUs). In the case of V2I communication, the messages are transmitted between a vehicle and a Roadside Unit (RSU), which is an electronic device capable of receiving and processing communication messages generated by vehicles and generating and transmitting compatible messages to vehicles and other digital devices composing the transport infrastructure. V2I communication can be facilitated either by ad hoc or a centrally managed communication network. V2P communication refers to the exchange of communication messages between vehicles and V2X-enabled wearable or handheld devices carried by pedestrians, cyclists, etc. The communication is, in this case, usually facilitated by a centrally managed infrastructural network, such as LTE- or 5G-based cellular network. Finally, V2N communication is exclusive to cellular networks and facilitates the communication between vehicles and the remaining parts of the Intelligent Transport System (ITS), i.e., the V2X management system and also the V2X application server, using the existing cellular infrastructure.

Regarding V2X communication technologies, two key technologies are currently deployed. First of them is Dedicated Short-Range Communications (DSRC), which is also referred as the IEEE 802.11p. The second technology is Cellular-V2X (C-V2X), which is portrayed in the corresponding specifications of The 3rd Generation Partnership Project (3GPP) Release 14. This represents the so-called 4G-based C-V2X. Moreover, there is an extension of the C-V2X concept towards 5G cellular networks, entitled 5G-based C-V2X, described in the corresponding specifications of the 3GPP Release 16. The main reason to develop the DSRC technology was to allow a deployment of collision prevention applications [2]. It is perceived as reliable, rather easy to implement and cheap, almost patent-free and, most importantly, immediately available. However, an application range of the C-V2X is wider in the areas of navigation, traffic data, entertainment, and, most notably, driving automation. In contrast to the DSRC/IEEE 802.11p, it deploys the existing infrastructure and requires less infrastructural equipment while covering potentially larger areas, reducing the operational and capital costs for infrastructure operators [3].

Several studies have been conducted to benchmark the performance of the LTE-based (4G-based) C-V2X and IEEE 802.11p/ITS-G5 as well as to evaluate the LTE-based C-V2X performance. In [4], the authors investigated, by simulations, the performance of the LTE-based C-V2X in terms of the V2V and I2V communications. Moreover, the authors of [5] dealt with the performance of the LTE-based C-V2X (mode 4) from the packet reception ratio and packet inter-reception perspective in the context of the V2V communication. The performance of the LTE-based C-V2X (mode 4) in the context of the traffic collision avoidance applications based on sharing occupancy maps between the infrastructure and vehicles was investigated in [6] in terms of the packet delivery ratio. In [7], the authors also investigated the performance of the mode 4 of the LTE-based C-V2X, but in a multiapplication context, considering both Cooperative Awareness Messages (CAM) as well as event-based Decentralized Environmental Notification Messages and the V2V communication. The authors in [8] compared mode 3 and mode 4 of the LTE-based C-V2X for the V2V communication in terms of the packet delivery ratio. Regarding the IEEE 802.11p/ITS-G5 and LTE-based (4G-based) C-V2X performance benchmark, the following studies were found: [9–21]. In [9], the LTE-based C-V2X and IEEE 802.11p were benchmarked from the average packet reception ratio perspective while taking into account typical urban and freeway scenarios and the V2V communication. The authors in [10] compared, considering again only the V2V context, these two technologies, i.e., the IEEE 802.11p and LTE-based C-V2X, in the context of packet delivery ratio in different traffic scenarios, i.e., cities and highways. In [11], the LTE-based C-V2X (mode 3) and ITS-G5 were compared from the end-to-end (E2E) latency and communication channel conditions perspective in two scenarios; first, considering the effects of realistic data traffic on an ITS alert service, and second, the impact of handover on an ITS safety service. This was again only done in the V2V communication scenario. The authors in [12] benchmarked the corresponding technologies in the V2V context and an urban micro-cell highway scenario in terms of the packet reception ratio and transmitter-receiver distance. In [13,14], the corresponding communication systems were compared, in the context of the V2V communication scenario, in terms of the E2E latency, Packet Delivery Ratio (PDR), and throughput and in terms of the average packet reception ratio, respectively. To be more precise, the authors of [13] benchmarked the performance of the LTE-based C-V2X and IEEE 802.11p under various network conditions and parameter values from delay, reliability and scalability perspective. When it comes to the work published in [14], the benchmark highlighted the fact that LTE-based alternatives, i.e., the LTE multicast and LTE sidelink, offer a higher performance than the IEEE 802.11p from the reliable communication range reached in all of the studied scenarios perspective. In [15], the authors compared, by means of system level simulation, the performance of the ITS-G5 and LTE-based C-V2X (mode 4) in terms of the packet delivery rate in order to provide statistics about CAM transmission reliability in typical urban scenario. In [16], the performance of the IEEE 802.11p and LTE-based C-V2X, i.e., LTE in the infrastructural mode and LTE Device-to-Device mode (mode 3), was benchmarked in terms of the average E2E latency and packet delivery ratio under varying communication conditions achieved through the variation of the communication perimeter, message generation frequency and road traffic intensity in the V2I communication context and an urban scenario. The obtained results were put into the context of the communication requirements of the most popular V2I C-ITS services. In [17], the authors benchmarked the IEEE 802.11p and LTE-based C-V2X (mode 3 and 4) in the context of the V2V communication and cooperative awareness in a realistic highway scenario from the packet reception ratio and beacon update delay perspective. In [18], the benchmark of the ITS-G5 and LTE-based C-V2X (mode 4) in terms of the packet error rate versus signal-to-noise ratio (a physical layer perspective) and in terms of the packet error rate, range, latency and network load (a medium access control layer perspective) was presented. The authors in [19] conducted an exhaustive and fair evaluation of the LTE-based C-V2X (mode 4) and ITS-G5 in a real-life highway environment under the identical conditions for the V2I and V2V communications and different C-ITS services. In [20], the authors compared the IEEE 802.11p and 4G-based C-V2X (mode 4) in the highway scenarios through a system-level simulation in terms of the packet reception ratio, packet delivery ratio, signal to interference plus noise ratio and data packet delay during resource selection for the V2V communication. Finally, the IEEE 802.11p and LTE-based C-V2X (mode 4) were benchmarked from periodic and aperiodic messages of constant and variable sizes perspectives in [21]. To sum up, the above mentioned studies mostly focused on the performance of the LTE-based C-V2X, as well as its performance comparison with the IEEE 802.11p in the context of the V2V communication, and just two of them considered the V2I communication.

To the best of our knowledge, no work so far has benchmarked the performance of the 4G-based and 5G-based C-V2X in the context of the V2I communication. It should be noted here that V2I communication is very important in the context of traffic management. That is the main reason why we have decided to extend our previous work published in [16] towards 5G-based C-V2X and by doing so to benchmark the 4G-based and 5G-based C-V2X in the corresponding communication context. So, in this paper, we benchmark both C-V2X technologies operating either in the infrastructural mode or in the device-to-device mode (mode 3) from the E2E latency and Packet Delivery Ratio (PDR) perspective in terms of the traffic intensity, communication perimeter and message generation frequency in the context of urban scenarios and naturally the V2I communication. Moreover, fixed and varying infrastructure density scenarios are considered in this study in order to investigate the impact of the infrastructure density on the performance of both C-V2X technologies from the deployed context and metrics perspective. The achieved results are put into the context of the communication requirements of the most popular V2I C-ITS services from the E2E latency and PDR perspective.

The remaining parts of this paper are organized as follows. A simulation environment as well as test setup are described in Section 2. Section 3 presents and discusses the experimental results. Section 4 concludes the paper and discusses future work.

2. Test Setup and Simulation Environment

The C-V2X communication technologies performance evaluation was performed using a federated telco-traffic simulation [22–25]. We have used Objective Modular Network Testbed in C++ (OMNeT++) [26] as a communication network simulator. Vehicle flows have been simulated using Simulation of Urban Mobility (SUMO) [27] microscopic traffic simulation package. To interconnect the two simulators in real time, we have adopted the commonly used Veins [22] simulation framework. Technology-specific communication stacks have been modeled using the following simulation frameworks, i.e., SimuLTE [28] for LTE-based C-V2X and Simu5G [29] for 5G-based C-V2X communications.

It is worth noting here that this study represents an extension of our previous study published in [16] towards 5G-based C-V2X communication, while it deploys the same methodology in order to maintain the backward comparability of the results. Preliminary simulation runs have suggested that the infrastructure density might severely impact the performance of the cellular technologies, especially the 4G-based one, in the investigated context, i.e., urban scenarios and V2I communication. Therefore, we have extended our investigation to two different simulation scenarios, i.e., one involving a fixed infrastructure density and the other one focusing on a varying infrastructure density to study the impact of infrastructure density on the V2I C-V2X communication performance. In comparison to the previous study published in [16], the default number of cells has been increased from two to four. This change was necessary due to an inability of 5G-enabled devices to maintain connection reliably throughout the simulated area with just two cells.

2.1. Simulation Scenarios

The topology of the simulated communication scenarios can be seen in Figure 1. It is worth reiterating here that two different scenarios were investigated in this study, i.e., one involving a fixed infrastructure density and the other one focusing on a varying infrastructure density in order to study the impact of infrastructure density on the V2I C-V2X communication performance, which are clearly highlighted in Figure 1. We simulated vehicular communications in the vicinity of a large, signalized intersection in the city of Zilina, Slovakia. This specific intersection has been selected due to its strategic location, where intercity and long-distance traffic crosses at the same spot, causing frequent congestion and traffic safety issues. Being a part of the frequent international passenger and freight transport route from the Czech Republic and Poland to eastern parts of Slovakia, the road infrastructure we have selected for our simulation experiment is also heavily loaded in terms of traffic. This fact gives us a chance to benchmark both C-V2X communication technologies in a wide variety of traffic conditions, while maintaining realistic traffic volumes. Selecting this intersection and its surrounding infrastructure comes with yet another practical benefit - the communication and traffic models developed within this study can be further used to evaluate the impact of 4G- and 5G-based V2X services on the traffic performance of this challenging road infrastructure.

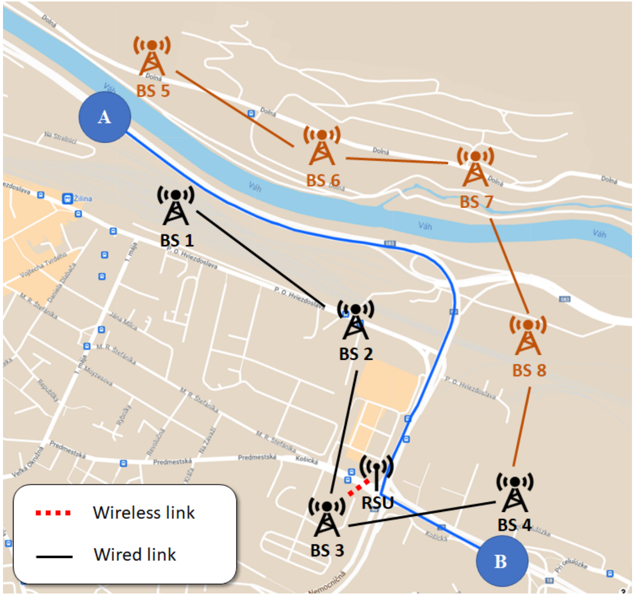


Figure 1. Visualization of the simulation scenario. Base stations depicted in black represent the cellular infrastructure used to simulate the fixed infrastructure density scenario. To study the impact of infrastructure density on the performance of Cellular-V2X (C-V2X) technologies, i.e., the varying infrastructure density scenario, four additional base stations (in red) were added.

Vehicles entered the simulation 1.8 km from the intersection (Figure 1 point "A" in the map). We have simulated a V2I communication from a vehicle to a Roadside Unit (RSU) located at the intersection. High-level simulation scenario parameters are detailed in Table 1.

Table 1. Simulation scenario parameters.

Parameter	Value
Simulated technologies	LTE infrastructural, LTE device-to-device in mode 3, 5G infrastructural and 5G device-to-device in mode 3
Application protocol	Periodic vehicle-to-infrastructure fixed-length message transmission service
Transport protocol	User Datagram Protocol
Message length	300 bytes (including a security header)
Number of cells	4/8 [1]
Base station spacing	800/400 metres [2]
Simulation length	600 s
Number of repetitions	10

[1] applied only in the varying infrastructure density scenario; [2] valid only for the varying infrastructure density scenario.

Communication from a vehicle to the RSU was initiated once the Euclidean distance between the vehicle and the RSU dropped below a predefined perimeter. Vehicles continued to periodically send communication messages to the RSU with a specific message generation frequency until they left the network (Figure 1 point "B" in the map). The message generation frequency has been set to follow the standard used for the CAM [30]. It is worth noting here that individual communication messages were sent at uniformly spaced time intervals and were generated 2, 4, 6, 8 and 10 times per second. So, for instance, in the case of 2 messages per second, the time interval was 500 ms. We have not considered background traffic in this study because it is foreseen in the literature [31,32] that the channels purely dedicated for C-ITS services in 4G-based and 5G-based C-V2X will be deployed in the real implementations. All the simulation runs simulated 600 s of traffic. A 100 s long initialization period was introduced to populate the network with vehicles and achieve the target traffic intensity. To study their impact on the communication network performance, we varied the values of the message generation frequency, communication perimeter and traffic intensity. These simulation variables values (Table 2) have remained constant within a single simulation run. Each combination of the simulation variables has been simulated 10 times using a different random seed for each simulation run, resulting in a total of 2100 simulation runs per technology and infrastructure density deployment. So, in total, 16,800 simulation runs were made. We have recorded E2E latency of each communication packet and Packet Delivery Ratio (PDR) for each simulation run. It should be noted here that each simulation run generated tens of thousands of data points for calculation of the evaluation metrics , i.e., E2E latency and PDR.

Table 2. Variables deployed in simulations.

Variable	Values Considered in Simulations
Intensity of traffic	250, 500, 750, 1000, 1250 and 1500 vehicles per hour
Frequency of message generation	2, 4, 6, 8 and 10 messages per second (Hz), generated at uniformly spaced time intervals
Perimeter of communication	200, 400, 600, 800, 1000, 1200 and 1400 m

2.2. Technologies and Technology-Specific Parameters

The cellular network consisted of 4 base stations (BSs) in the case of the fixed infrastructure density scenario or 8 BSs in the case of the varying infrastructure density scenario, a RSU at the intersection connected wirelessly to the BS No.3 and cellular-enabled vehicles following the route depicted in Figure 1. The BS represents a single eNodeB in the case of the 4G-based communication technology or a single gNodeB in the case of the 5G-based communication technology. To limit the probability of poor resource scheduling due to an insufficient signal coverage, cells have been spaced uniformly with a spacing of 800 m between two adjacent BSs (the fixed infrastructure density scenario) and 400 metres in the case of the varying infrastructure density scenario (8 BSs deployment). The locations of the BSs were randomly selected. The technology-specific parameters used within the simulation experiments are listed in Table 3. The corresponding parameters were set up according to these standardization documents [33,34]. Parameters, which are not explicitly mentioned in the corresponding table, were set to their default values according to the documentation of the respective simulation framework.

Table 3. Technology-specific simulation parameters.

Parameter	5G Value	LTE Value
Frequency band	2100 MHz	2100 MHz
Bandwidth of channel	5 MHz	5 MHz
Transmit power of base station	46 dBm	46 dBm
Transmit power of vehicle	26 dBm	26 dBm
Maximum number of HARQ retransmissions	3	3
Height of base station	25 metres	25 metres
Antenna gain of base station	18 dBi	18 dBi
Antenna gain of vehicle	0 dBi	0 dBi
Noise figure of base station	5 dB	5 dB
Noise figure of vehicle	7 dB	7 dB
Loss induced by cable	2 dB	2 dB
Fading paths number	6	6

2.3. Simulation Framework Validity and Simulation Workflow

It is worth reiterating here that we used the well established, validated and commonly accepted simulation framework to simulate the V2I communication, consisting of the OMNeT++, SUMO and Veins, which has been deployed by more than 1260 scientific studies [35] so far. To simulate the LTE-specific communication protocols, we used the SimuLTE simulation framework developed by the Computer Networking Group (CNG) of the University of Pisa and built for the OMNeT++. For the simulation of the 5G-specific communication protocols, we used the Simu5G simulation framework jointly developed by the CNG and Intel Corporation, again built for the OMNeT++. Those simulation frameworks were also verified and validated, see [28] for the SimuLTE and [36] for the Simu5G for more details, and are well accepted by the community, see [37,38] for more details. Moreover, the simulation workflow is, in detail, described in [28] for the LTE-based communication technology, i.e., the SimuLTE framework, and in [29] for the 5G-based communication technology, i.e., the Simu5G framework.

3. Experimental Results

In this section, simulation results are presented and compared in terms of PDR and average E2E latency. In particular, Section 3.1 describes the results obtained for the fixed infrastructure density scenario. Moreover, Section 3.2 deals with the varying infrastructure density scenario.

In both cases, 4G-based and 5G-based C-V2X are benchmarked for the different traffic intensity values from a perspective of the communication perimeter and message generation frequency. Finally, the obtained results are going to be put into the context of the communication requirements of the most popular V2I C-ITS services.

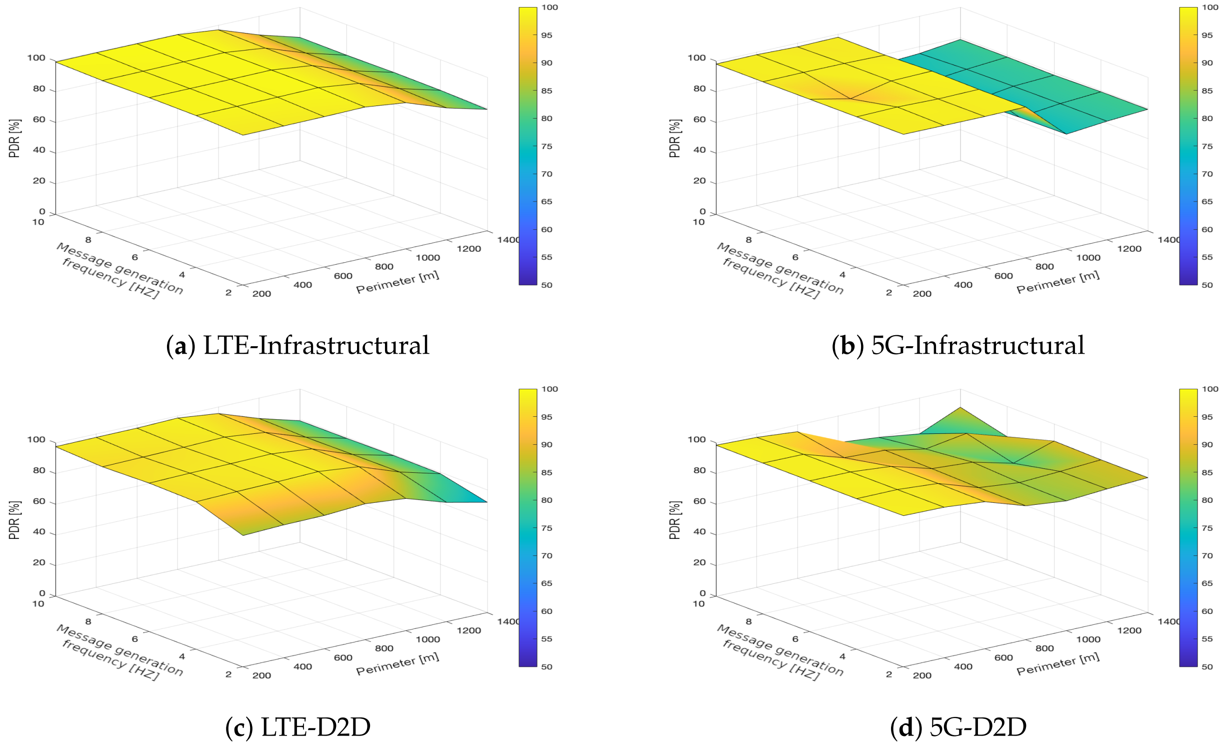
3.1. Fixed Infrastructure Density Scenario

In this subsection, we present the results of the simulation experiments obtained by simulating the fixed infrastructure density scenario involving four cells in the simulated area for each investigated technology and its mode, i.e., device-to-device mode 3 and infrastructural mode, and all the simulated traffic intensities.

3.1.1. Packet Delivery Ratio

As it can be seen in Figures 2a, 3a, 4a, 5a, 6a and 7a, 4G-based C-V2X in the infrastructural mode has steadily maintained very high values (up to 99.7%) of PDR in the perimeter of up to 1000 m. Beyond 1000 m, PDR has started to drop, reaching the lowest value of around 80% for the largest simulated perimeter, i.e., 1400 m.

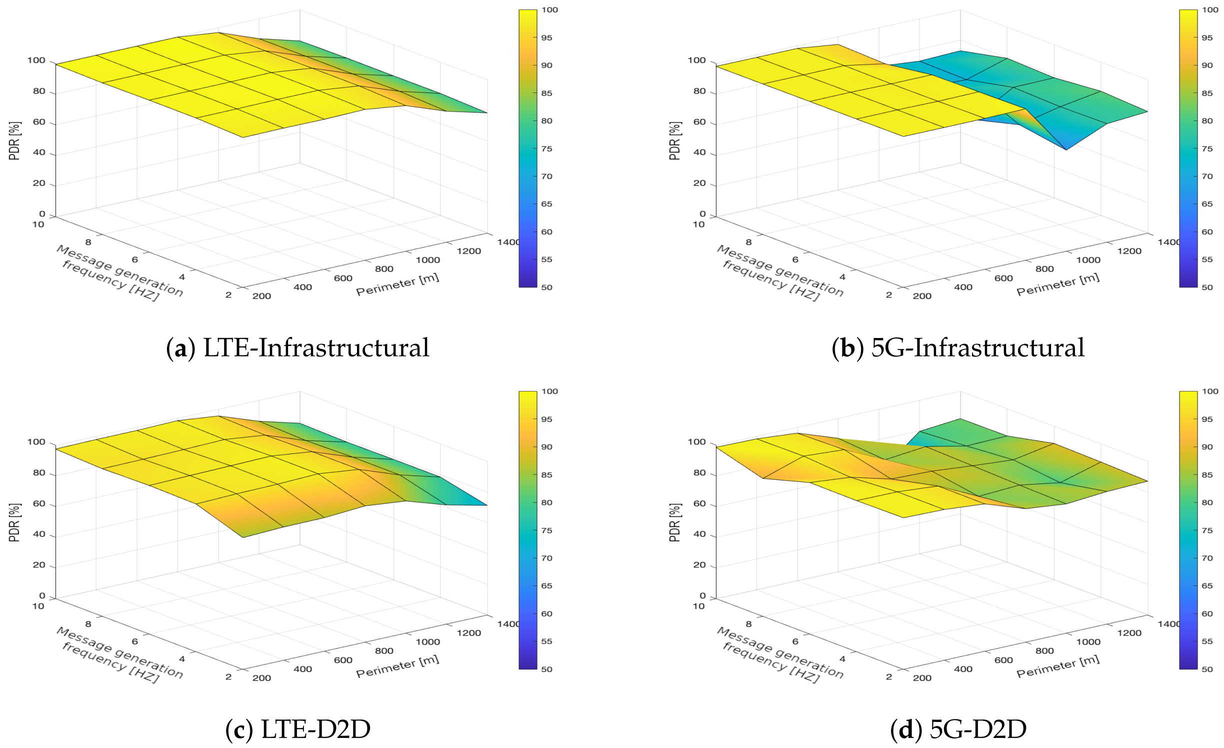
The simulation results for the 4G-based C-V2X communication in device-to-device mode 3 obtained for the traffic intensities ranging from 250 to 1500 vehicles per hour are depicted in Figures 2c, 3c, 4c, 5c, 6c and 7c. It can be seen from the above-listed figures that the best performance in terms of PDR is achieved when the messages are transmitted with the message generation frequency ranging from 4 to 10 Hz and the communication perimeters up to 1000 metres are considered. Increasing the perimeter beyond 1000 m results in a considerable drop in PDR. Interestingly, for the lowest simulated value of the message generation frequency, i.e., 2 Hz, the 4G-based C-V2X in device-to-device mode 3 has experienced approximately 10% drop of PDR compared to the higher message generation frequencies, considering the same perimeter. This performance drop was not observed among the other simulated technologies and is likely caused by an inefficient scheduling of the short and relatively infrequent messages. The 4G-based C-V2X in device-to-device mode 3 has maintained an average PDR value above 75% under all the combinations of simulation variables.



(**a**) LTE-Infrastructural (**b**) 5G-Infrastructural

(**c**) LTE-D2D (**d**) 5G-D2D

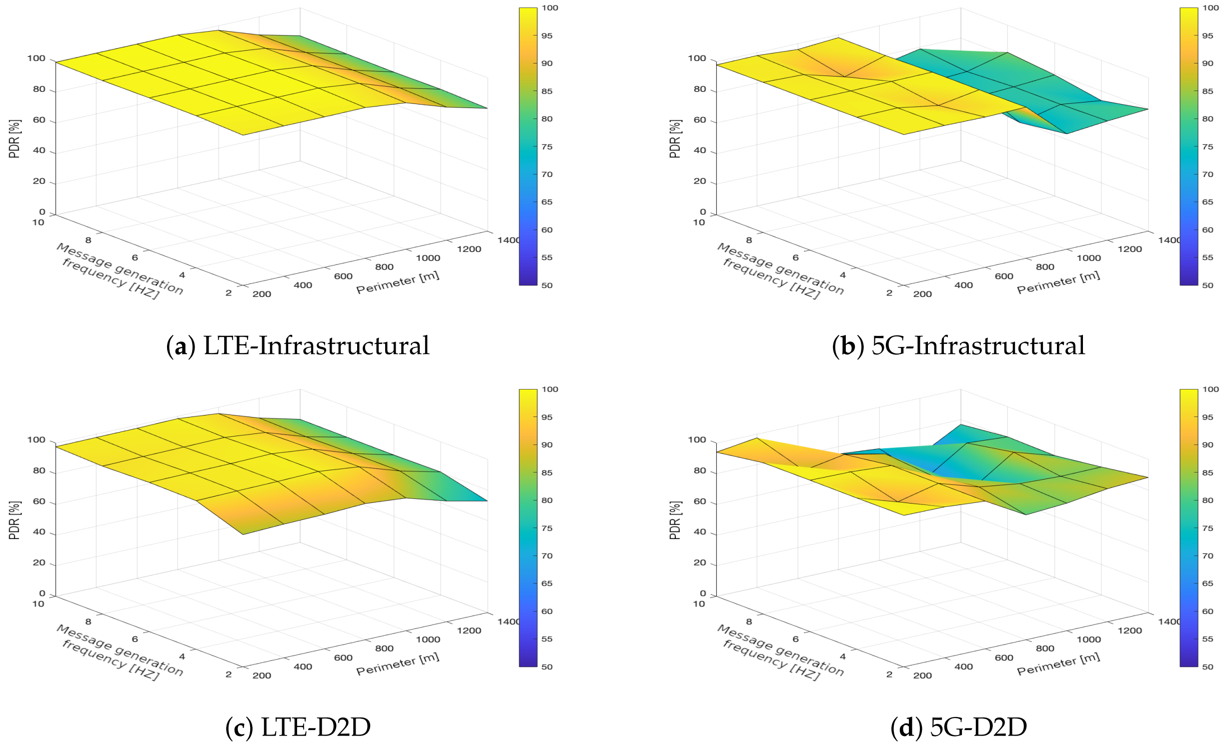
Figure 2. Packet Delivery Ratio (PDR) simulated for all the investigated modes of the 4G-based and 5G-based C-V2X technologies and traffic intensity of 250 vehicles per hour.



(**a**) LTE-Infrastructural (**b**) 5G-Infrastructural

(**c**) LTE-D2D (**d**) 5G-D2D

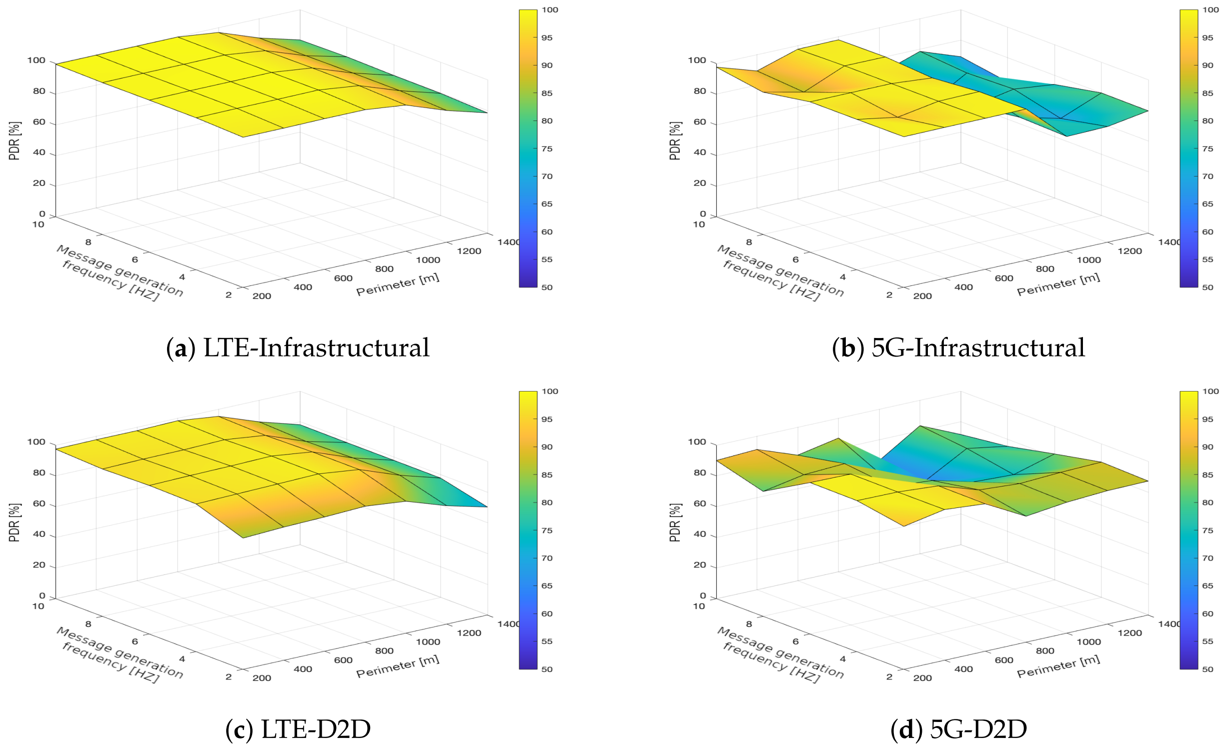
Figure 3. PDR simulated for all the investigated modes of the 4G-based and 5G-based C-V2X technologies and traffic intensity of 5O0 vehicles per hour.



(**a**) LTE-Infrastructural (**b**) 5G-Infrastructural

(**c**) LTE-D2D (**d**) 5G-D2D

Figure 4. PDR simulated for all the investigated modes of the 4G-based and 5G-based C-V2X technologies and traffic intensity of 750 vehicles per hour.



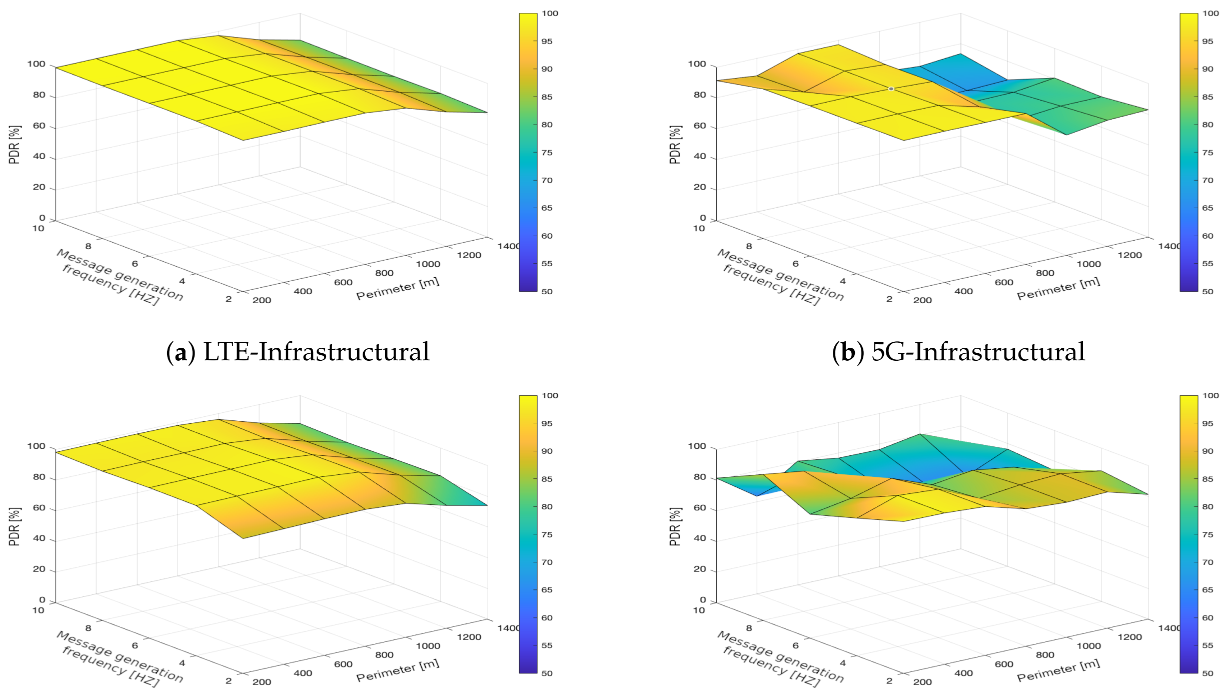
(**a**) LTE-Infrastructural (**b**) 5G-Infrastructural

(**c**) LTE-D2D (**d**) 5G-D2D

Figure 5. PDR simulated for all the investigated modes of the 4G-based and 5G-based C-V2X technologies and traffic intensity of 1000 vehicles per hour.

In both simulated modes of 4G-based C-V2X, no significant impact of the traffic intensity on PDR has been observed, contrary to the results presented in [16]. While in [16], the whole area was served by two cells only, in this study, the same area is divided into four cells, resulting in a better load balancing between the cells. By increasing the traffic intensity in [16], the density of the network nodes, i.e., vehicles, approached the capacity of the cells. The similar phenomenon was not observed in this study thanks to the increased number of the cells and therefore the increased capacity of the network.

The 5G-based C-V2X in the infrastructural mode (Figures 2b, 3b, 4b, 5b, 6b and 7b) has achieved very high PDR values (up to 98.8%) for the communication perimeters below 800 m. The PDR has dropped significantly beyond 800 m and remained relatively stable, reaching values around 75% for the perimeters of up to 1400 m. This seems to be caused by an insufficient signal strength due to the rather long communication link. A slight impact of the traffic intensity can be seen in the case of the 5G-based C-V2X in the infrastructural mode, where the minimum achieved PDR decreases with the increasing traffic intensity. No significant impact of the message generation frequency on PDR was observed when using the 5G-based C-V2X in the infrastructural mode for V2I communication in the simulated urban scenario.

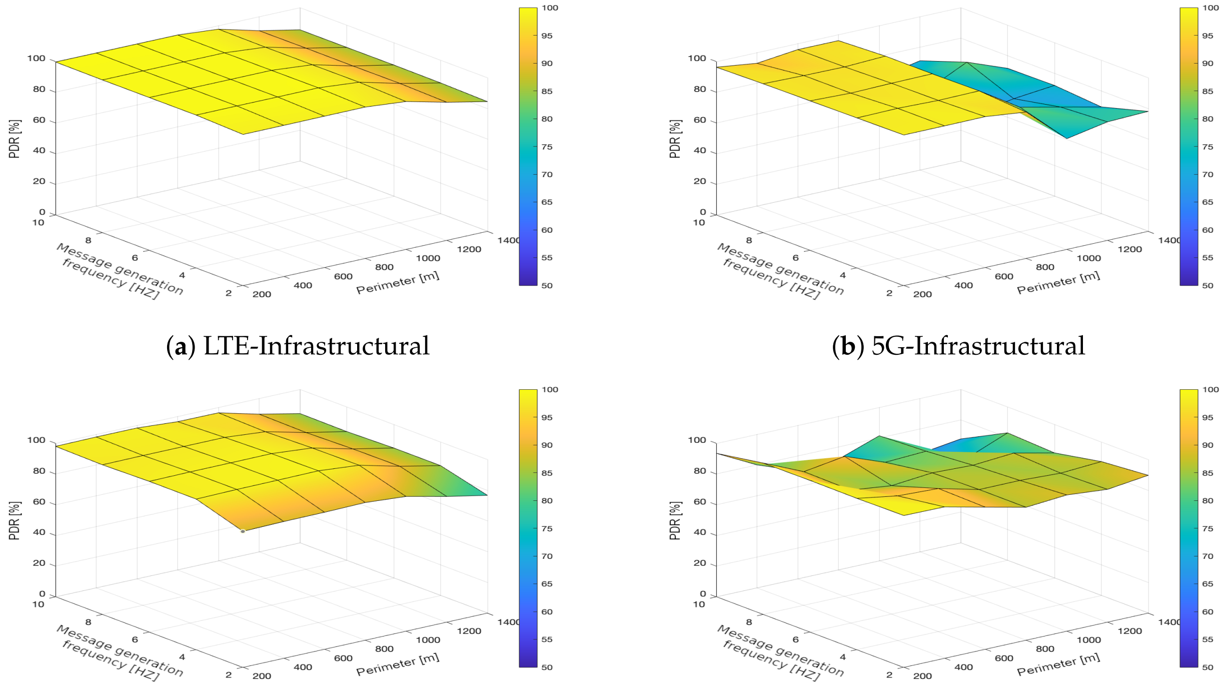


(**a**) LTE-Infrastructural (**b**) 5G-Infrastructural

(**c**) LTE-D2D (**d**) 5G-D2D

Figure 6. PDR simulated for all the investigated modes of the 4G-based and 5G-based C-V2X technologies and traffic intensity of 1250 vehicles per hour.

The 5G in the device-to-device mode 3 (Figures 2d, 3d, 4d, 5d, 6d and 7d) has achieved the lowest performance in terms of PDR from all the investigated technologies. The technology has achieved its peak PDR performance, i.e., 98.8%, in the lowest traffic intensity scenario (Figure 2d) and for the perimeters of up to 400 m. This decrease of PDR is more severe as the traffic intensity increases, as it can be seen in Figures 5d, 6d and 7d.



(**a**) LTE-Infrastructural (**b**) 5G-Infrastructural

(**c**) LTE-D2D (**d**) 5G-D2D

Figure 7. PDR simulated for all the investigated modes of the 4G-based and 5G-based C-V2X technologies and traffic intensity of 1500 vehicles per hour.

3.1.2. Average End-to-End Latency

Compared to the study published in [16], the impact of the communication perimeter is greatly reduced in the case of the 4G-based C-V2X. So, in other words, the impact is negligible in this case. As it can be seen in Figures 8a, 9a, 10a, 11a, 12a and 13a, the average E2E latency of the messages sent by the 4G-based C-V2X in the infrastructural mode remains very low (below 0.5 ms) across all the simulated combinations of the simulation variables, i.e., the message generation frequency, communication perimeter and traffic intensity.

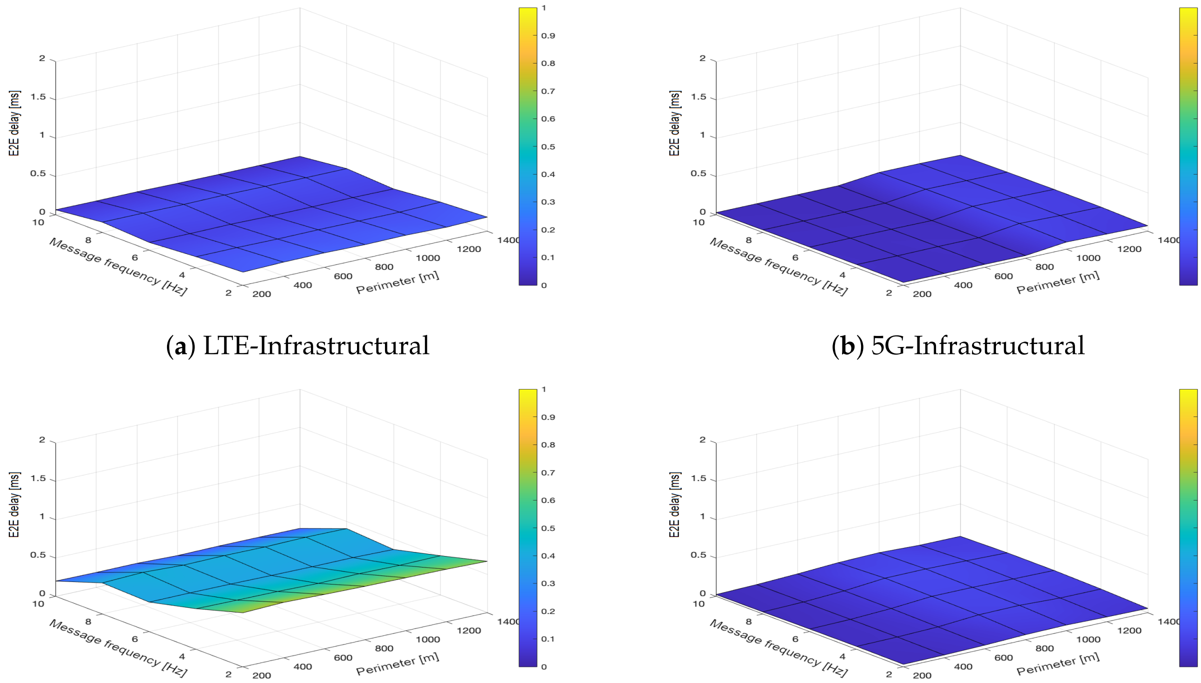
The average E2E latency of the messages sent by the 4G-based C-V2X in the device-to-device mode 3 is also greatly reduced compared to the scenario with 2 cells reported in [16]. Here, a slight impact of the message generation frequency was observed, see Figures 8c, 9c, 10c, 11c, 12c and 13c for more detail, as the latency slightly decreases with the message generation frequency due to the more efficient resource scheduling. While noticeable in the figures, it is worth noting here that this decrease is so small in the absolute values that it has no practical implications.

In the case of the 5G-based C-V2X in the infrastructural mode, a very minor increase of the E2E latency can be seen for the perimeters beyond 800 m, see Figures 8b, 9b, 10b, 11b, 12b and 13b for more detail. Again, the impact is so minimal, considering the scale, that it has no practical implication.

The same can be stated for the 5G-based C-V2X in the device-to-device mode 3, see Figures 8d, 9d, 10d, 11d, 12d and 13d for more detail. The average message E2E latency increases linearly with the communication perimeter, however, the practical impact is essentially negligible.

For both 5G modes, it can be said that the impact of the message generation frequency is practically not present. No noticeable impact of the traffic intensity on the average message E2E latency was observed in the case of both investigated technologies, i.e., 4G-based C-V2X as well as 5G-based C-V2X.

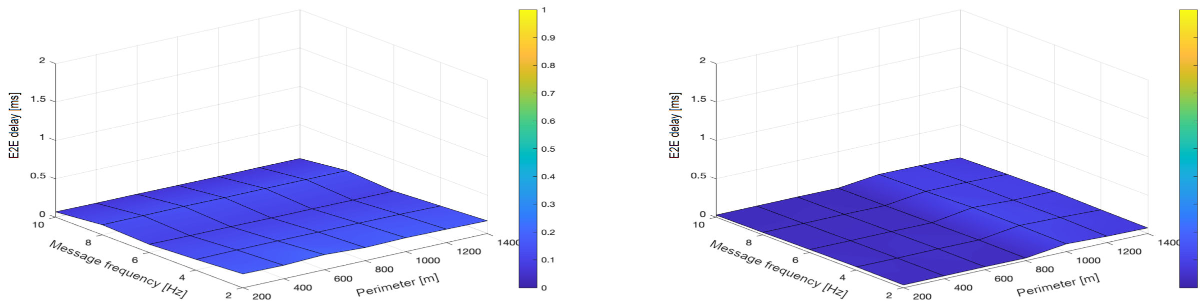
It is worth noting here that increasing the cell deployment density and optimizing their locations have improved the performance of the LTE-based C-V2X for the V2I communication significantly, compared to the results of the study published in [16]. Our findings presented in this section suggest that the LTE-based C-V2X might be, in fact, a viable alternative to the 5G-based C-V2X in the context of the V2I communication when the cell deployment density is comparable to the one of the 5G-based C-V2X.



(**a**) LTE-Infrastructural (**b**) 5G-Infrastructural

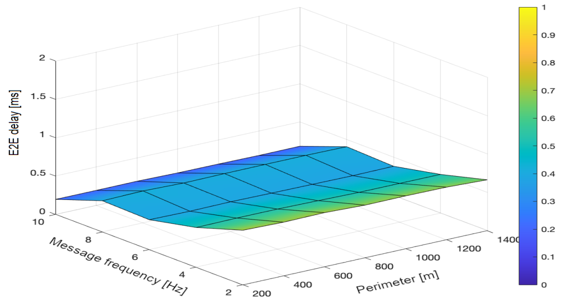
(**c**) LTE-D2D (**d**) 5G-D2D

Figure 8. End-to-End (E2E) latency simulated for all the investigated modes of the 4G-based and 5G-based C-V2X technologies and traffic intensity of 250 vehicles per hour.

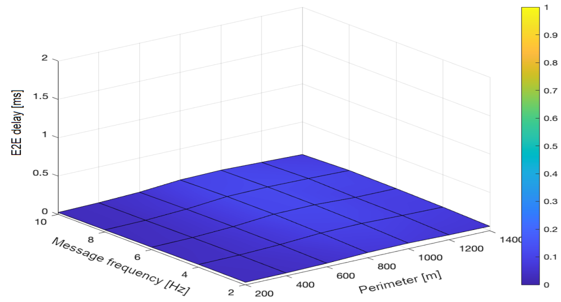


(**a**) LTE-Infrastructural (**b**) 5G-Infrastructural

Figure 9. *Cont.*

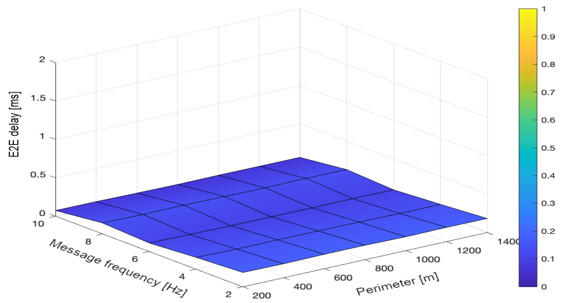


(**c**) LTE-D2D

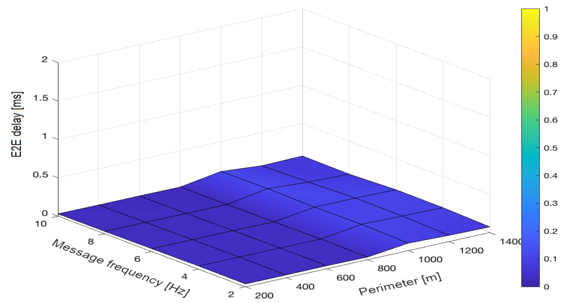


(**d**) 5G-D2D

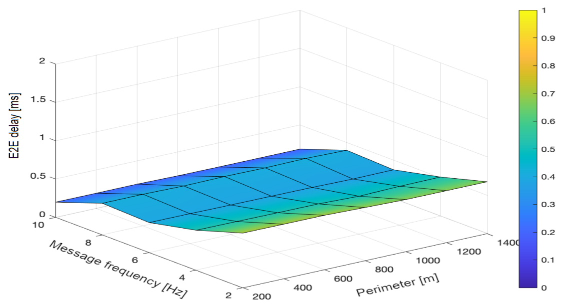
Figure 9. E2E latency simulated for all the investigated modes of the 4G-based and 5G-based C-V2X technologies and traffic intensity of 500 vehicles per hour.



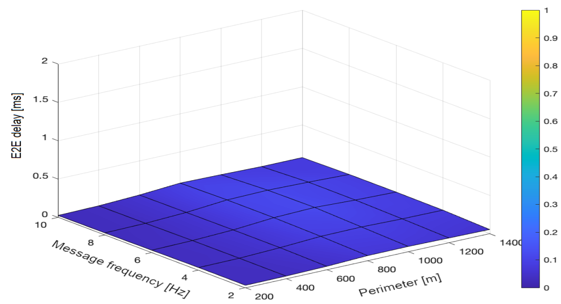
(**a**) LTE-Infrastructural



(**b**) 5G-Infrastructural

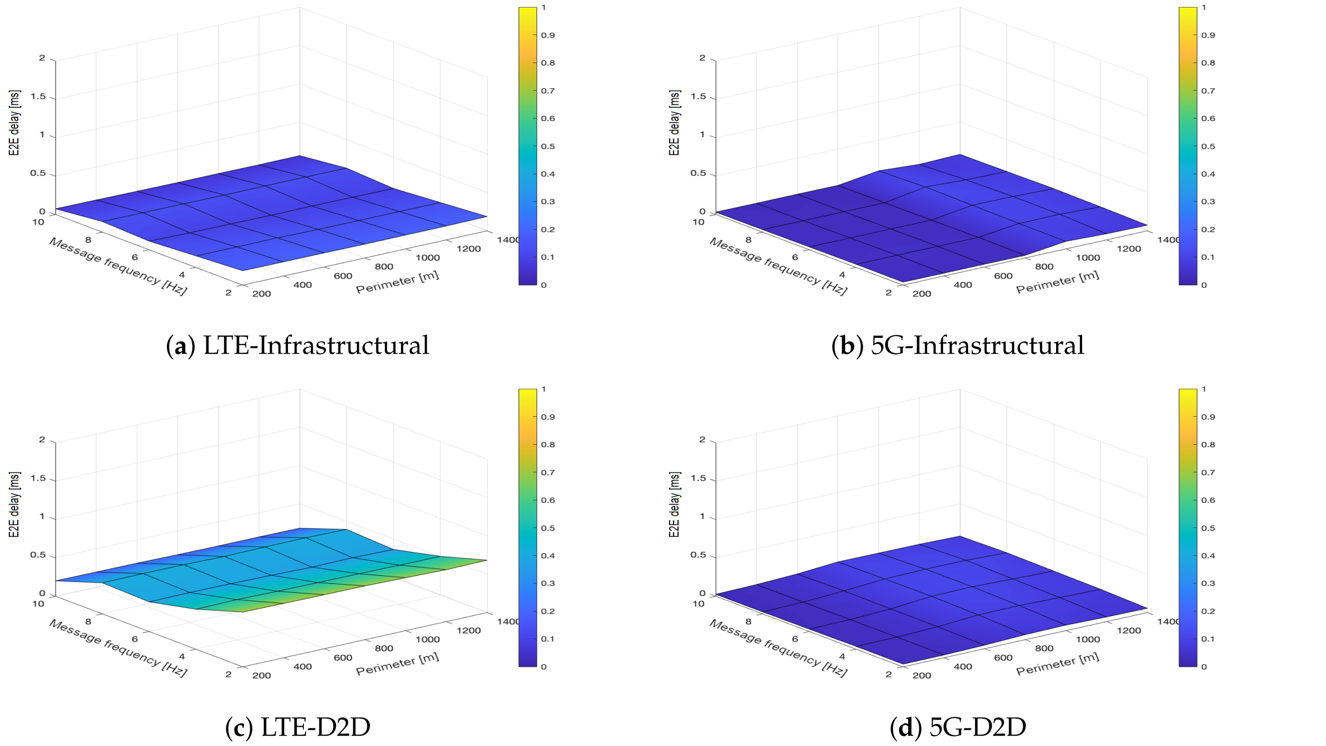


(**c**) LTE-D2D



(**d**) 5G-D2D

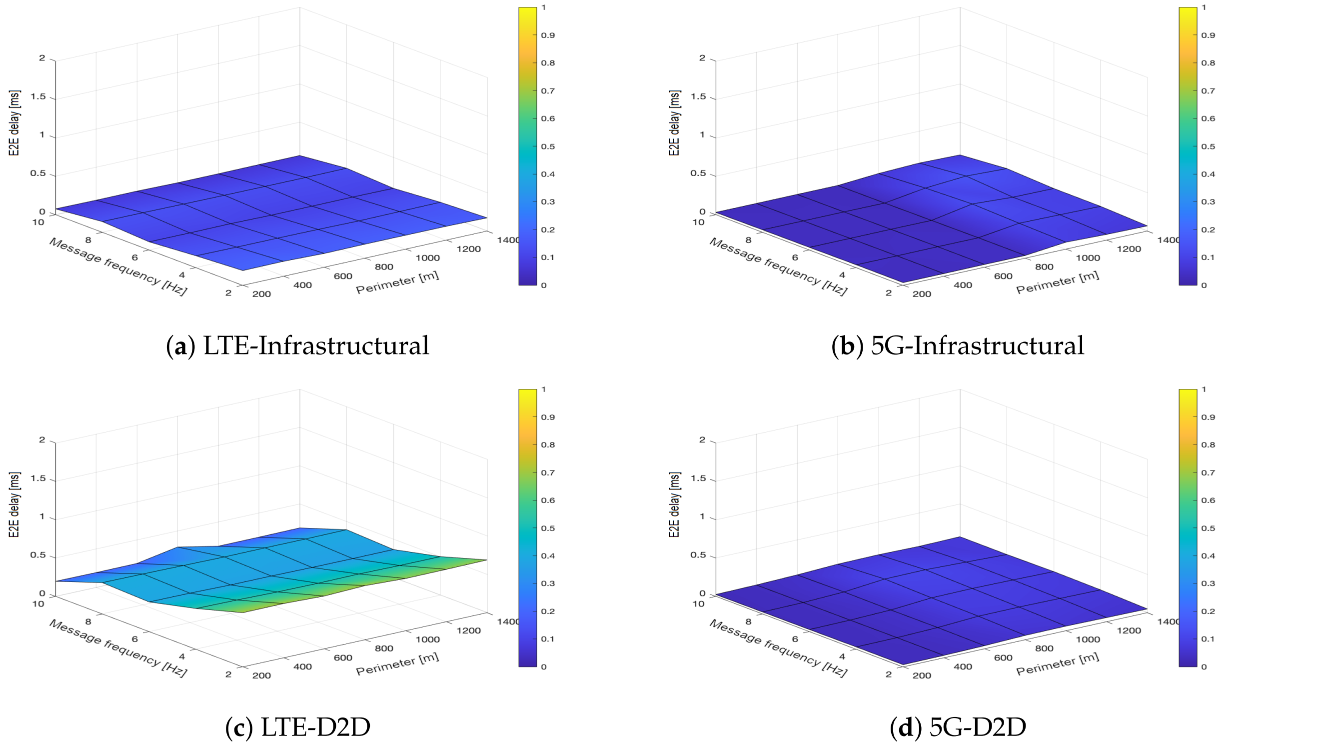
Figure 10. E2E latency simulated for all the investigated modes of the 4G-based and 5G-based C-V2X technologies and traffic intensity of 750 vehicles per hour.



(**a**) LTE-Infrastructural (**b**) 5G-Infrastructural

(**c**) LTE-D2D (**d**) 5G-D2D

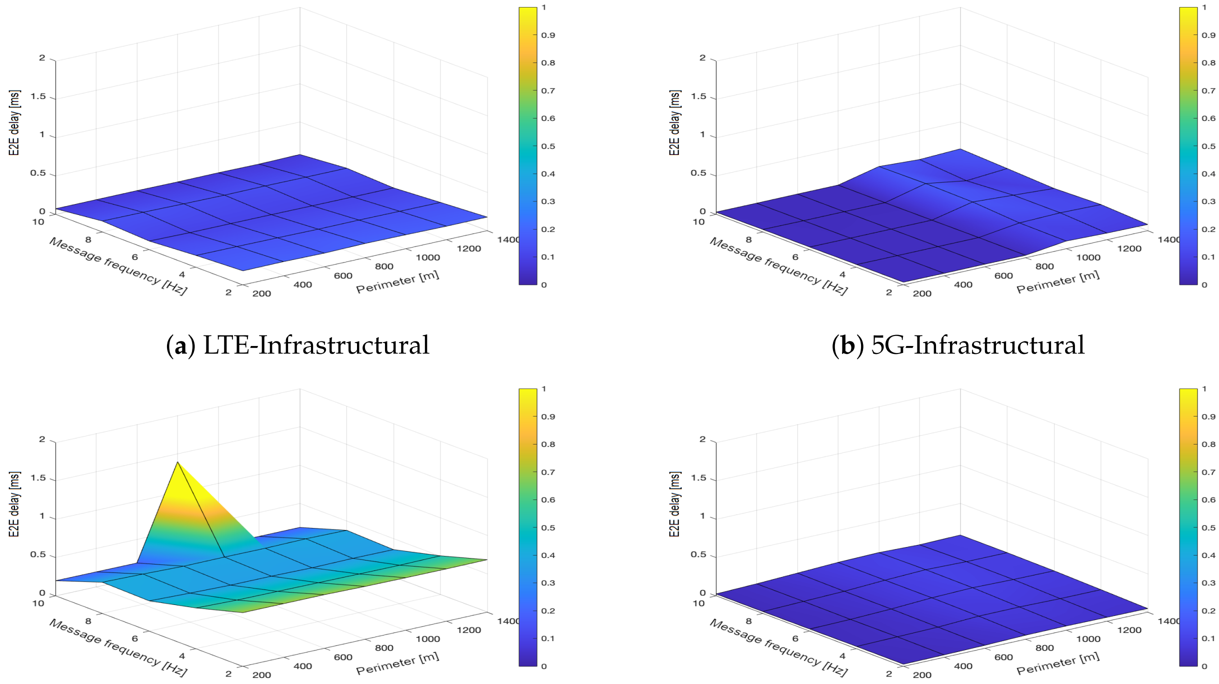
Figure 11. E2E latency simulated for all the investigated modes of the 4G-based and 5G-based C-V2X technologies and traffic intensity of 1000 vehicles per hour.



(**a**) LTE-Infrastructural (**b**) 5G-Infrastructural

(**c**) LTE-D2D (**d**) 5G-D2D

Figure 12. E2E latency simulated for all the investigated modes of the 4G-based and 5G-based C-V2X technologies and traffic intensity of 1250 vehicles per hour.



(**a**) LTE-Infrastructural (**b**) 5G-Infrastructural

(**c**) LTE-D2D (**d**) 5G-D2D

Figure 13. E2E latency simulated for all the investigated modes of the 4G-based and 5G-based C-V2X technologies and traffic intensity of 1500 vehicles per hour.

The obtained simulation results presented above in Figures 2–13 were put into the context of the communication requirements of the most popular V2I C-ITS services from the E2E latency and PDR perspective, coming from the renowned literature [39], which is based on [40–42]. So, this is to say that the obtained results were mapped to the above mentioned communication requirements to show whether the corresponding communication technologies fulfill those requirements in the context of the investigated V2I C-ITS services. This should help transport engineers to correctly deploy the corresponding technologies in reality.

The experimental results indicate that all the investigated C-V2X technologies are able to fulfill the communication requirements of the most popular V2I C-ITS services, under assumption of sufficient infrastructure deployment in an urban scenario (see Table 4).

Table 4. Communication requirements of common Cooperative Intelligent Transport Systems (C-ITS) services and their fulfillment by the investigated communication technologies in the investigated context. Adapted from [39] and updated.

C-ITS Service	LTE-Infrastructural	LTE-D2D	5G-Infrastructural	5G-D2D
Low frequency (1–2 Hz), low latency (<100 milliseconds) services				
Slow and stationary vehicle warning	✓	✓	✓	✓
Weather conditions warning	✓	✓	✓	✓
Intersection management	✓	✓	✓	✓
Low frequency (1–2 Hz), high latency (<500 milliseconds) services				
Point of interest notification	✓	✓	✓	✓
Local electronic commerce	✓	✓	✓	✓
Media upload	✓	✓	✓	✓
Map updates	✓	✓	✓	✓
Cooperative flexible lane change	✓	✓	✓	✓
High frequency (10 Hz), low latency (<100 milliseconds) services				
Electronic emergency break light	✓	✓	✓	✓
Emergency vehicle approaching	✓	✓	✓	✓

3.2. Varying Infrastructure Density Scenario

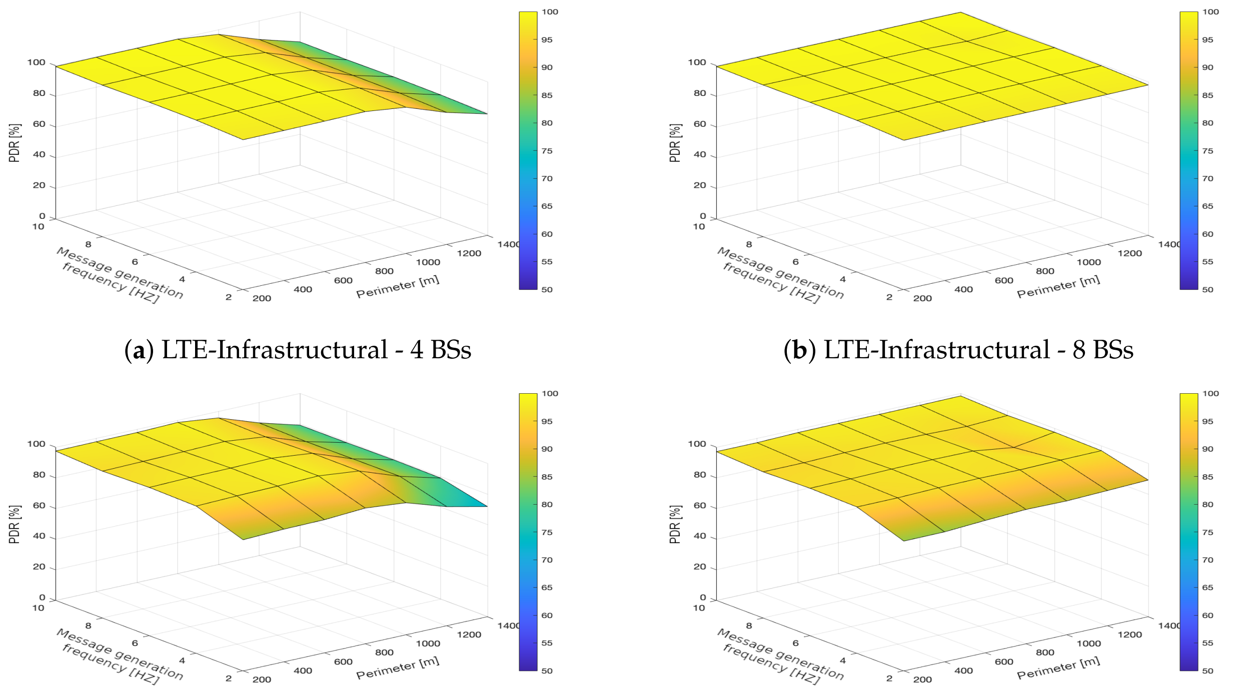
A comparison of the results presented in the previous subsection with the results of the study published in [16] has indicated that the infrastructure density might have a rather remarkable impact on the performance of C-V2X technologies, especially the 4G-based one, in the investigated context. Therefore, we present here the simulation results obtained using the same traffic scenario and communication technology-specific settings as applied in the previous section, i.e., the fixed infrastructure density scenario, but with a variable number of cells, i.e., 4 and 8, in order to shed light on this issue. Due to space constraints, the results obtained for the lowest and highest simulated value of the traffic intensity, i.e., 250 vehicles per hour and 1500 vehicles per hour, are only reported in the following subsections. Regardless, the trends remain the same across all the traffic intensity values.

3.2.1. Packet Delivery Ratio

Figure 14a–d depict an impact of the infrastructure density deployment on the packet delivery ratio for the traffic intensity of 250 vehicles per hour and both investigated modes of the 4G-based C-V2X technology, i.e., the infrastructural mode and D2D mode (mode 3), respectively. As it can be clearly seen from Figure 14a,b, the impact is rather severe when it comes to the communication perimeter above 1000 m, as the reported PDR has increased from 85–90% to 100% by deploying 8 BSs. Moreover, there is no impact of the message generation frequency in this case. On the other hand, this impact is nicely visible for the D2D mode when it comes to the lowest message generation frequencies, i.e., 2 and 4, and a communication perimeter above 1000 m, see Figure 14c,d for more details. It is worth noting here that the longer communication perimeter above 1000 m has also played a role in the case of the remaining message generation frequencies. In other words, PDR has increased from 80–85% to 85–100% when 8 BSs were deployed. When it comes to the impact of the highest traffic intensity, i.e., 1500 vehicles per hour, and the infrastructural mode, the trend remains the same, but the PDR was slightly improved for the communication perimeter above 1000 m and less dense infrastructure deployment, i.e., 4 BSs, see Figure 15a,b for more details. The same is true also for the D2D mode, see Figure 15c,d for more details.

Regarding the results obtained for the 5G-based C-V2X, they are reported in Figure 16a–d for the traffic intensity of 250 vehicles per hour and both modes of the 5G-based C-V2X technology, respectively. As we can clearly see from Figure 16a,b, the trend obtained for the infrastructural mode remains the same as that reported above for the 4G-based C-V2X, but the influence of the communication perimeter was slightly broadened. To be more precise, it is starting to play a role from 800 m. It should be noted here that the PDR values reported for the communication perimeter above 800 m are a bit lower than those reported for the 4G-based

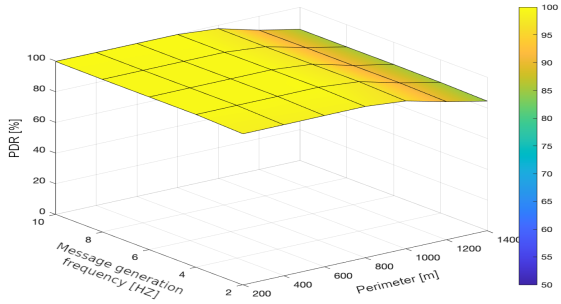
C-V2X in the case of the both infrastructure density deployments. The difference is much more pronounced for the more dense infrastructure deployment, i.e., 8 BSs. Regardless, the gain of the increased infrastructure deployment is still nicely visible, see Figure 16a,b for more details. Regarding the D2D mode of 5G-based C-V2X, the trend is similar to that reported above for the 4G-based C-V2X besides the fact that there is mostly negligible impact when it comes to the frequency of message generation. The impact of the communication perimeter was again broadened, becoming important from 600 m. The reported values are again a bit lower as in the 4G case. Surprisingly, the impact of the infrastructure density deployment seems to be minor, even for the longer communication perimeters, see Figure 16c,d for more details. When it comes to the traffic intensity of 1500 vehicles per hour and infrastructure mode, the behavior for the less dense infrastructure deployment is more or less the same as that reported for the traffic intensity of 250 vehicles per hour. On the other hand, it seems not to be so beneficial to apply the more dense infrastructure deployment for the shorter communication perimeter (below 600 m), as it is detrimental, see Figure 17a,b for more detail. For the D2D mode, the behavior is more or less the same as that reported for the lowest traffic intensity, with the lower values reported for the lower communication perimeters, i.e., below 600 m, see Figure 17c for more detail. Moreover, it can be clearly seen from Figure 17d that the impact of the more dense infrastructure deployment is very rarely beneficial; if so, the benefit is rather small.



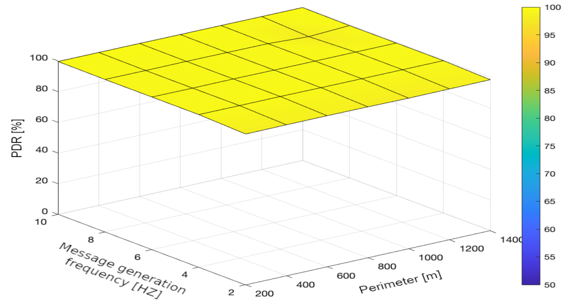
(**a**) LTE-Infrastructural - 4 BSs (**b**) LTE-Infrastructural - 8 BSs

(**c**) LTE-D2D - 4 BSs (**d**) LTE-D2D - 8 BSs

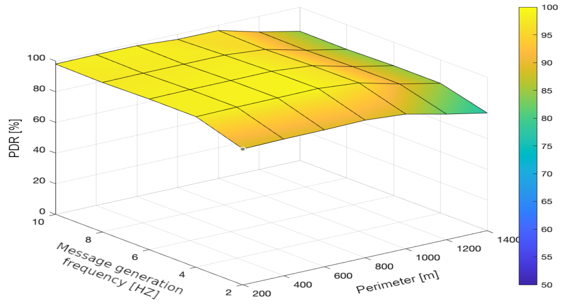
Figure 14. PDR simulated for the both modes of the 4G-based C-V2X technology, both infrastructure density deployments and traffic intensity of 250 vehicles per hour.



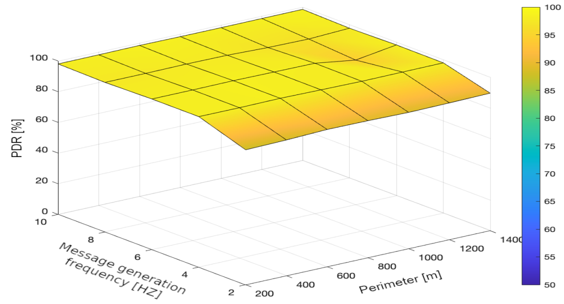
(**a**) LTE-Infrastructural - 4 BSs



(**b**) LTE-Infrastructural - 8 BSs

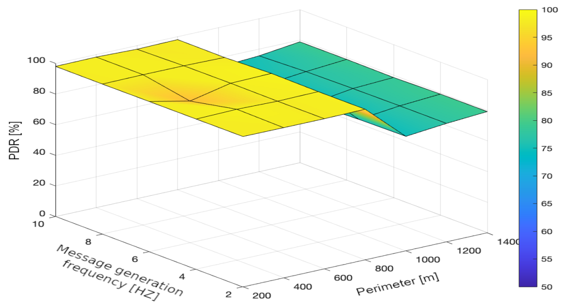


(**c**) LTE-D2D - 4 BSs

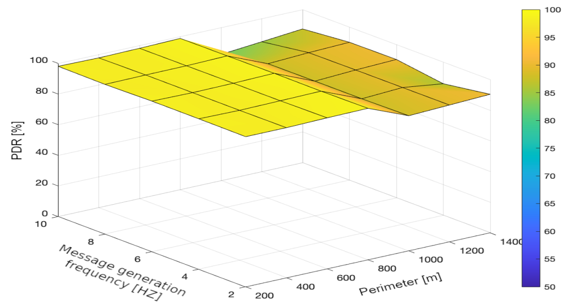


(**d**) LTE-D2D - 8 BSs

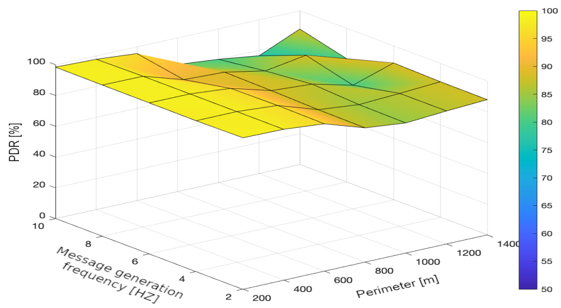
Figure 15. PDR simulated for the both modes of the 4G-based C-V2X technology, both infrastructure density deployments and traffic intensity of 1500 vehicles per hour.



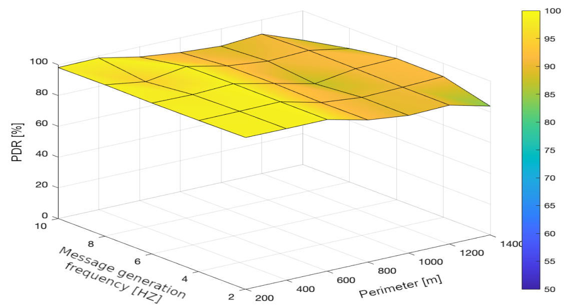
(**a**) 5G-Infrastructural - 4 BSs



(**b**) 5G-Infrastructural - 8 BSs

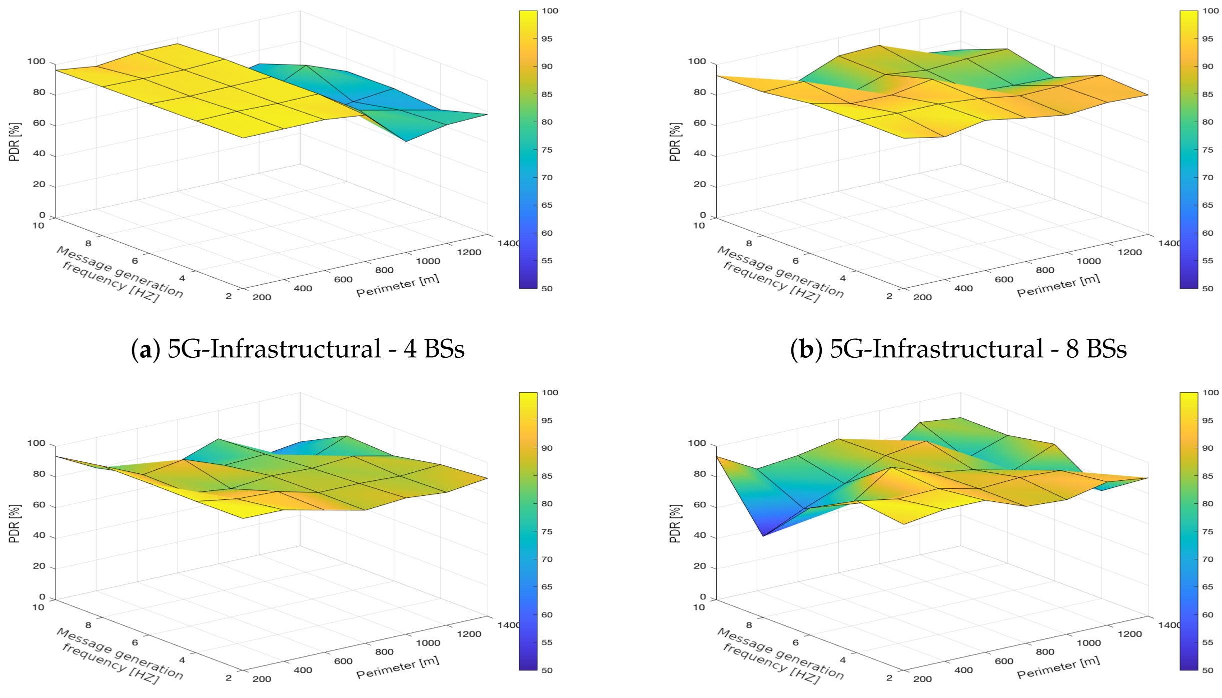


(**c**) 5G-D2D - 4 BSs



(**d**) 5G-D2D - 8 BSs

Figure 16. PDR simulated for the both modes of the 5G-based C-V2X technology, both infrastructure density deployments and traffic intensity of 250 vehicles per hour.



(**a**) 5G-Infrastructural - 4 BSs
(**b**) 5G-Infrastructural - 8 BSs
(**c**) 5G-D2D - 4 BSs
(**d**) 5G-D2D - 8 BSs

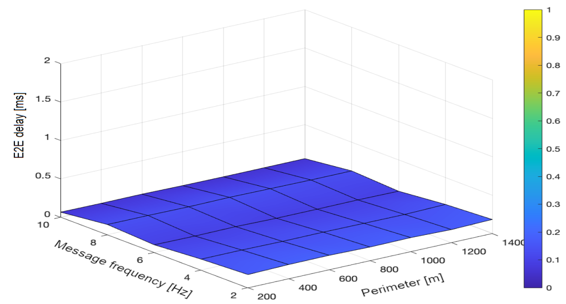
Figure 17. PDR simulated for the both modes of the 5G-based C-V2X technology, both infrastructure density deployments and traffic intensity of 1500 vehicles per hour.

3.2.2. Average End-to-End Latency

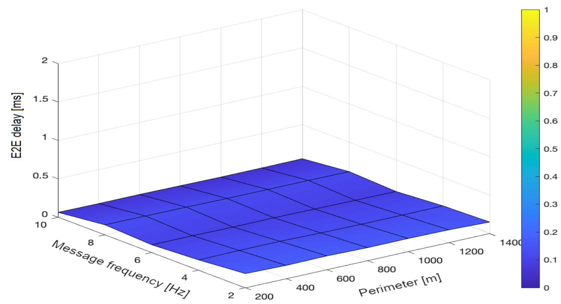
The influence of the infrastructure deployment on the E2E latency reported for traffic intensity of 250 vehicles per hour is shown in Figure 18a–d for both investigated modes of the 4G-based C-V2X, respectively. We can clearly see from Figure 18a,b that the impact of the infrastructure density deployment in terms of latency is negligible for the infrastructural mode. Moreover, neither the message generation frequency nor the communication perimeter play a role in this case. The former is also true for the D2D mode. On the other hand, only the message generation frequency has a significant impact on the E2E latency in the D2D mode and for both infrastructure densities, see Figure 18c,d for more details. When it comes to the highest traffic intensity, i.e., 1500 vehicles per hour, and the infrastructural mode, no change in comparison to the traffic intensity of 250 vehicles per hour was observed, see Figure 19a,b for more detail. For the D2D mode, as it can be seen from Figure 19c,d, the behavior has remained the same, but some spikes have appeared.

When it comes to the 5G-based C-V2X, we can clearly see in Figure 20a–d that the impact of the more dense infrastructure deployment is negligible for both modes, similarly as in the LTE case. Moreover, both the message generation frequency and communication perimeter have no impact on the reported E2E latency values, even for the D2D mode. Regarding the higher traffic intensity, i.e., 1500 vehicles per hour, the behavior is completely the same as reported above for the traffic intensity of 250 vehicles per hour, see Figure 21a–d for more detail. It should be noted here that slightly higher values are reported for the infrastructural mode deploying 4BSs, i.e., the less dense infrastructure deployment, and longer communication perimeter above 1000 m in comparison to the lowest traffic intensity, see Figures 20a and 21a for more detail.

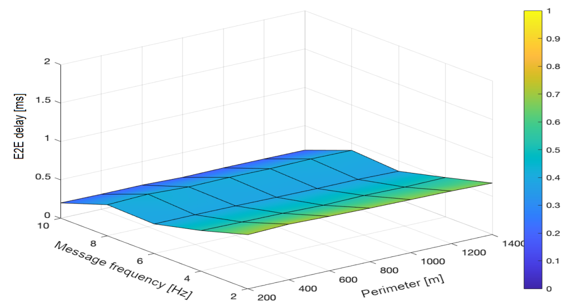
Similarly to the fixed infrastructure density scenario, see Section 3.1 for more detail, we have put the obtained results into a context of communication requirements of the most popular V2I C-ITS services, see [39] for more detail. Regarding the 4G-based C-V2X as well as the infrastructural mode, we can see from Table 5 that more dense infrastructure deployment is very beneficial in the context of all the considered types of the V2I services, i.e., the low-frequency and low-latency services, low-frequency and high-latency services and high-frequency and low-latency services. To be more precise, when at least 4 BSs are deployed, no limitations when it comes to the communication perimeter and traffic intensity (the low-frequency and low-latency services) or the communication perimeter (the low-frequency and high-latency services) are present in the case of all the considered services. Moreover, a great improvement, i.e., from no service support to a full support without the limitations, is achieved for the high-frequency and low-latency services. The similar situation, i.e., the transition from no service support to the full support without the limitations, is also obtained in the D2D mode 3 of the 4G-based C-V2X for all the services when more than 4 BSs are deployed, see Table 6 for more detail. Regarding the 5G-based C-V2X and the infrastructural mode, the transition is even more perceived for all the considered services, in comparison to the LTE case, as the transition from no coverage to the full support without the limitations can be seen here when the more dense infrastructure deployments, i.e., 4 and 8 BSs, are applied, see Table 7 for more detail. The same behavior, see Table 8 for more detail, was reported for the D2D mode 3 of the 5G-based C-V2X. It should be noted in this context that no coverage is meant here as no coverage for resource scheduling, not for transmitting the data packets. To sum up, the simulation results suggest that for the both investigated C-V2X technologies and their modes, the more dense infrastructure deployment is very beneficial. In particular, the upgrade from 2 BSs to 4 BSs brings the major improvement in the context of all the considered V2I services. The gain was higher for the 5G-based C-V2X as the transition from no coverage to the full support without the limitations is obtained for this technology and its both modes. Moreover, it is worth noting here that the density infrastructure increase from 4BSs to 8 BSs does not provide any further benefit in any of the investigated cases. So, also taking into account the economical feasibility of this deployment, we can conclude that this deployment is not beneficial from the technical as well as economical perspective.



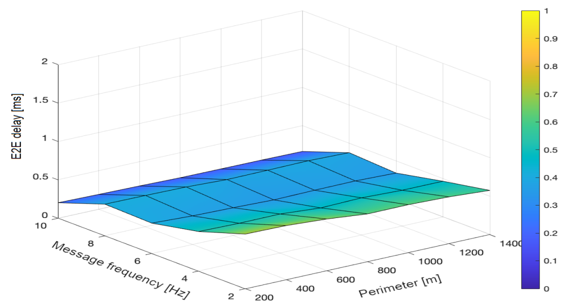
(**a**) LTE-Infrastructural - 4 BSs



(**b**) LTE-Infrastructural - 8 BSs

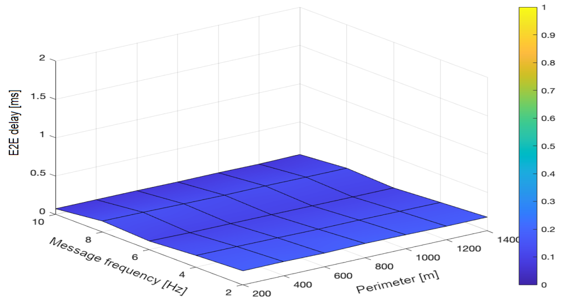


(**c**) LTE-D2D - 4 BSs

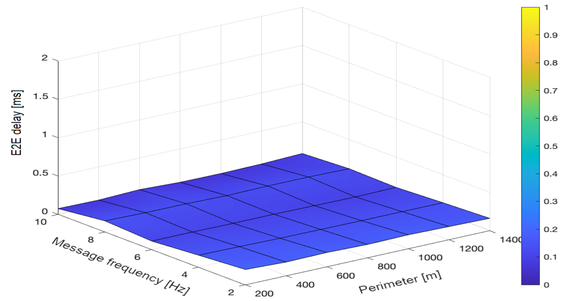


(**d**) LTE-D2D - 8 BSs

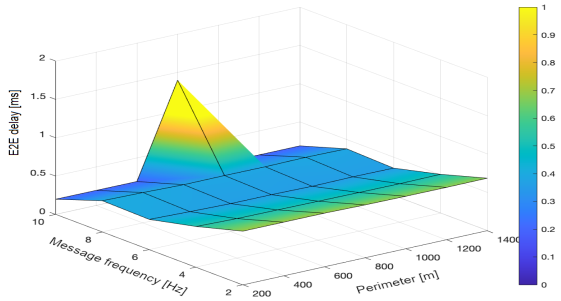
Figure 18. E2E latency simulated for the both modes of the 4G-based C-V2X technology, both infrastructure density deployments and traffic intensity of 250 vehicles per hour.



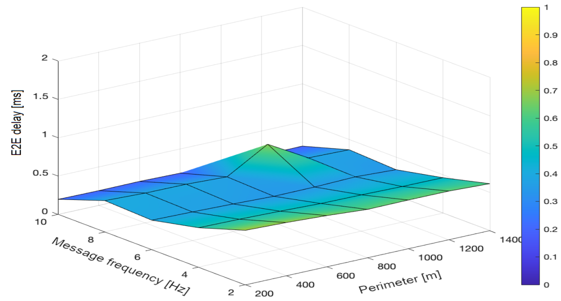
(**a**) LTE-Infrastructural - 4 BSs



(**b**) LTE-Infrastructural - 8 BSs

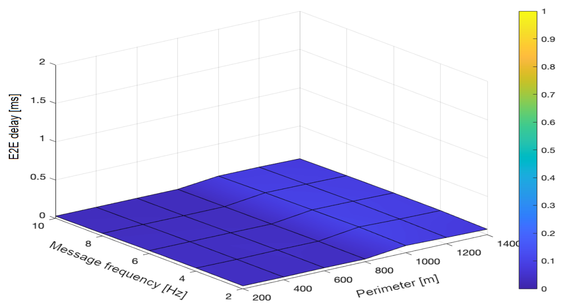


(**c**) LTE-D2D - 4 BSs

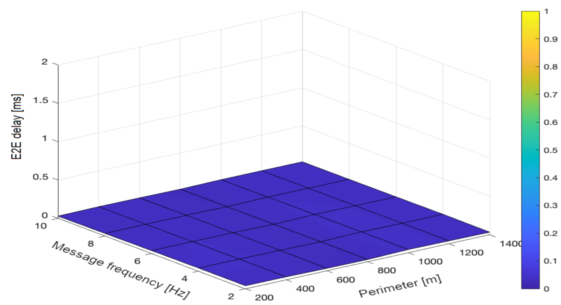


(**d**) LTE-D2D - 8 BSs

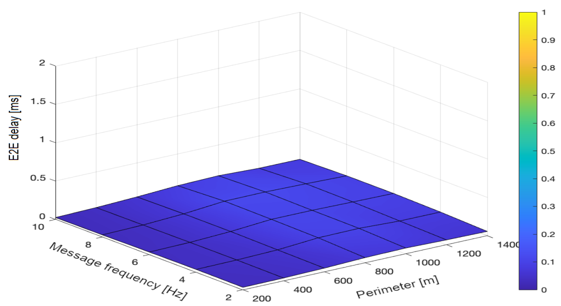
Figure 19. E2E latency simulated for the both modes of the 4G-based C-V2X technology, both infrastructure density deployments and traffic intensity of 1500 vehicles per hour.



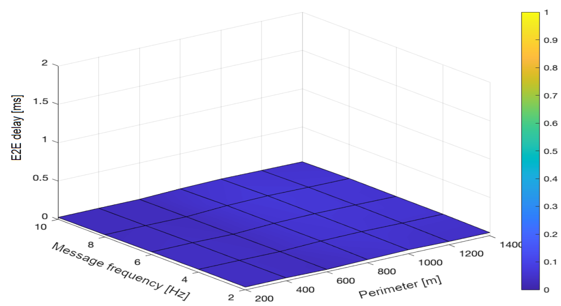
(**a**) 5G-Infrastructural - 4 BSs



(**b**) 5G-Infrastructural - 8 BSs

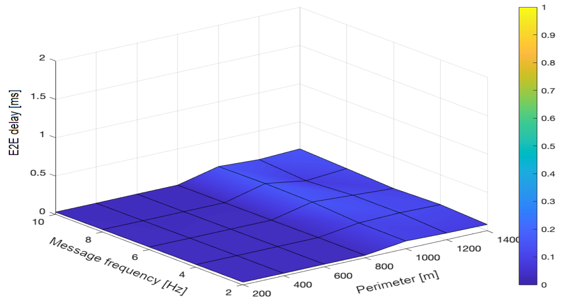


(**c**) 5G-D2D - 4 BSs

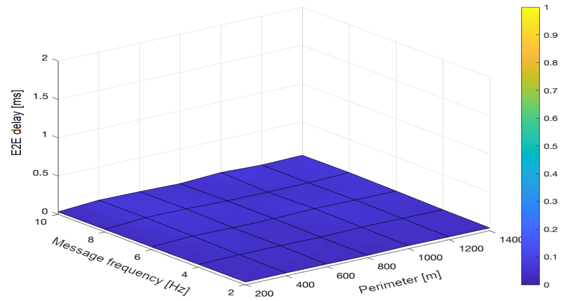


(**d**) 5G-D2D - 8 BSs

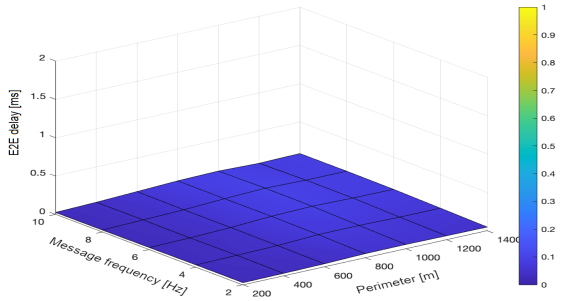
Figure 20. E2E latency simulated for the both modes of the 5G-based C-V2X technology, both infrastructure density deployments and traffic intensity of 250 vehicles per hour.



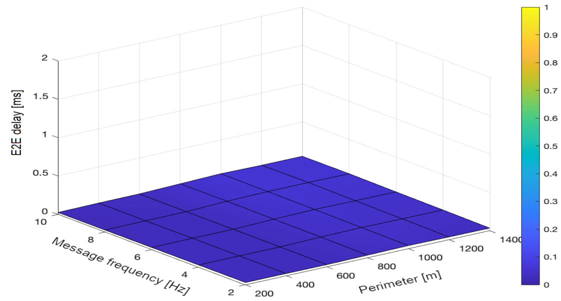
(**a**) 5G-Infrastructural - 4 BSs



(**b**) 5G-Infrastructural - 8 BSs



(**c**) 5G-D2D - 4 BSs



(**d**) 5G-D2D - 8 BSs

Figure 21. E2E latency simulated for the both modes of the 5G-based C-V2X technology, both infrastructure density deployments and traffic intensity of 1500 vehicles per hour.

Table 5. Communication requirements of common C-ITS services and their fulfillment by LTE-based C-V2X in the infrastructural mode and investigated context. Adapted and updated from [16,39].

C-ITS Service	2 Base Stations	4 Base Stations	8 Base Stations
Low-frequency (1–2 Hz), low-latency (<100 milliseconds) services			
Slow and stationary vehicle warning	✓< 600 m and 1000 vehicles per hour	✓	✓
Weather condition warnings	✓< 600 m and 1000 vehicles per hour	✓	✓
Intersection management	✓< 600 m & 1000 vehicles per hour	✓	✓
Low-frequency (1–2 Hz), high-latency (<500 milliseconds) services			
Point of interest notification	✓< 600 m	✓	✓
Local electronic commerce	✓< 600 m	✓	✓
Media upload	✓< 600 m	✓	✓
Map updates	✓< 600 m	✓	✓
Cooperative flexible lane change	✓< 600 m	✓	✓
High-frequency (10 Hz), low-latency (<100 milliseconds) services			
Electronic emergency brake light	✗	✓	✓
Emergency vehicle approaching	✗	✓	✓

Table 6. Communication requirements of common C-ITS services and their fulfillment by LTE-based C-V2X in the D2D mode 3 and investigated context. Adapted and updated from [16,39].

C-ITS Service	2 Base Stations	4 Base Stations	8 Base Stations
Low-frequency (1–2 Hz), low-latency (<100 milliseconds) services			
Slow and stationary vehicle warning	✗	✓	✓
Weather condition warnings	✗	✓	✓
Intersection management	✗	✓	✓
Low-frequency (1–2 Hz), high-latency (<500 milliseconds) services			
Point of interest notification	✗	✓	✓
Local electronic commerce	✗	✓	✓
Media upload	✗	✓	✓
Map updates	✗	✓	✓
Cooperative flexible lane change	✗	✓	✓
High-frequency (10 Hz), low-latency (<100 milliseconds) services			
Electronic emergency brake light	✗	✓	✓
Emergency vehicle approaching	✗	✓	✓

Table 7. Communication requirements of common C-ITS services and their fulfillment by 5G-based C-V2X in the infrastructural mode and investigated context. Adapted and updated from [39].

C-ITS Service	2 Base Stations	4 Base Stations	8 Base Stations
Low-frequency (1–2 Hz), low-latency (<100 milliseconds) services			
Slow and stationary vehicle warning	No coverage	✓	✓
Weather condition warnings	No coverage	✓	✓
Intersection management	No coverage	✓	✓
Low-frequency (1–2 Hz), high-latency (<500 milliseconds) services			
Point of interest notification	No coverage	✓	✓
Local electronic commerce	No coverage	✓	✓
Media upload	No coverage	✓	✓
Map updates	No coverage	✓	✓
Cooperative flexible lane change	No coverage	✓	✓
High-frequency (10 Hz), low-latency (<100 milliseconds) services			
Electronic emergency brake light	No coverage	✓	✓
Emergency vehicle approaching	No coverage	✓	✓

Table 8. Communication requirements of common C-ITS services and their fulfillment by 5G-based C-V2X in the D2D mode 3 and investigated context. Adapted and updated from [39].

C-ITS Service	2 Base Stations	4 Base Stations	8 Base Stations
Low-frequency (1–2 Hz), low-latency (<100 milliseconds) services			
Slow and stationary vehicle warning	No coverage for resource scheduling	✓	✓
Weather condition warnings	No coverage for resource scheduling	✓	✓
Intersection management	No coverage for resource scheduling	✓	✓
Low-frequency (1–2 Hz), high-latency (<500 milliseconds) services			
Point of interest notification	No coverage for resource scheduling	✓	✓
Local electronic commerce	No coverage for resource scheduling	✓	✓
Media upload	No coverage for resource scheduling	✓	✓
Map updates	No coverage for resource scheduling	✓	✓
Cooperative flexible lane change	No coverage for resource scheduling	✓	✓
High-frequency (10 Hz), low-latency (<100 milliseconds) services			
Electronic emergency brake light	No coverage for resource scheduling	✓	✓
Emergency vehicle approaching	No coverage for resource scheduling	✓	✓

4. Conclusions

In this paper, we have benchmarked the performance of the 4G-based and 5G-based C-V2X in the V2I communication and urban scenarios context from the communication perimeter, traffic intensity and frequency of message generation perspective and in terms of the PDR and E2E latency. In both cases, the infrastructural mode and device-to-device mode 3 were considered. The obtained results were put into a context of the communication requirements of the popular V2I C-ITS services from the E2E latency and PDR perspective. The results clearly indicate that both C-V2X technologies are capable to support all the considered V2I services with no limitations in terms of the communication perimeter as well as traffic intensity. Moreover, the impact of the infrastructure density was also investigated in the above-mentioned context. The results show that the more dense infrastructure deployment is very beneficial for the both investigated technologies and their modes. To be more precise, the upgrade from 2 BSs to 4 BSs offers the remarkable improvement for all the considered V2I services as well as C-V2X technologies and their modes. The benefit is higher for the 5G-based C-V2X as the transition from no coverage to the full support without the limitations is obtained for this technology and both its modes. On the other hand, there is no further benefit of the upgrade from four BSs to eight BSs for any of the investigated cases. Considering also its economic feasibility, we can simply conclude that it is not beneficial at all.

As this study presumes that the channels purely dedicated for C-ITS services in 4G-based and 5G-based C-V2X will be deployed in the real implementations as is foreseen in the literature [31,32], background traffic seems not to play any role here. Regardless, when this will not be the case, i.e., the deployment of the channels purely dedicated for C-ITS services in 4G-based and 5G-based C-V2X, an investigation of the background traffic impact might be relevant. Moreover, 5G network slicing, as one of the very promising features of 5G networks to cope with an increasing traffic load, could be also considered in a further extension of this work.

Author Contributions: Conceptualization, T.P. and P.P.; methodology, T.P., P.P. and T.K.; software, T.P.; validation, T.P. and P.P.; formal analysis, T.P. and P.P.; investigation, T.P. and P.P.; resources, T.P. and P.P.; data curation, T.P.; writing—original draft preparation, T.P., P.P. and T.K.; writing—review and editing, T.P., P.P. and T.K.; visualization, T.P.; supervision, P.P.; project administration, T.K.; funding acquisition, T.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 101007019. This work was supported by the Slovak Research and Development Agency under the contract no. SK-IL-RD-18-005 ICT and the Smart Cars for Efficient Emergency Response and Traffic Management (SENECA) program.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The models and simulation data are available upon request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. European Environment Agency: Passenger and Freight Transport Demand in EUROPE. Available online: https://www.eea.europa.eu/data-and-maps/indicators/passenger-and-freight-transport-demand/assessment-1 (accessed on 9 September 2022).
2. Kenney, J.B. Dedicated short-range communications (DSRC) standards in the United States. *Proc. IEEE* **2011**, *99*, 1162–1182. [CrossRef]
3. Seo, H.; Lee, K.D.; Yasukawa, S.; Peng, Y.; Sartori, P. LTE evolution for vehicle-to-everything services. *IEEE Commun. Mag.* **2016**, *54*, 22–28. [CrossRef]
4. Barranco, A.C.; Gálvez, J.A.Y.; Armijo, J.A.; Aguayo-Torres, M.C.; Sicilia, J.C.R.; Gómez, G. Overview of LTE for Vehicular Communications. *Wirel. Pers. Commun.* **2020**, *113*, 1471–1494. [CrossRef]

5. Eckermann, F.; Kahlert, M.; Wietfeld, C. Performance analysis of C-V2X mode 4 communication introducing an open-source C-V2X simulator. In Proceedings of the 2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall), Honolulu, HI, USA, 22–25 September 2019; pp. 1–5.
6. Guizar, A.; Mannoni, V.; Poli, F.; Denis, B.; Berg, V. LTE-V2X performance evaluation for cooperative collision avoidance (CoCA) systems. In Proceedings of the 2020 IEEE 92nd Vehicular Technology Conference (VTC2020-Fall), Victoria, BC, Canada, 18 November 2020–16 December 2020; pp. 1–5.
7. Ghodhbane, C.; Kassab, M.; Maaloul, S.; Aniss, H.; Berbineau, M. A Study of LTE-V2X Mode 4 Performances in a Multiapplication Context. *IEEE Access* **2022**, *10*, 63579–63591. [CrossRef]
8. González, E.E.; Garcia-Roger, D.; Monserrat, J.F. LTE/NR V2X Communication Modes and Future Requirements of Intelligent Transportation Systems Based on MR-DC Architectures. *Sustainability* **2022**, *14*, 3879. [CrossRef]
9. Zhao, L.; Fang, J.; Hu, J.; Li, Y.; Lin, L.; Shi, Y.; Li, C. The performance comparison of LTE-V2X and IEEE 802.11 p. In Proceedings of the 2018 IEEE 87th Vehicular Technology Conference (VTC Spring), Porto, Portugal, 3–6 June 2018; pp. 1–5.
10. Bey, T.; Tewolde, G. Evaluation of DSRC and LTE for V2X. In Proceedings of the 2019 IEEE 9th Annual Computing and Communication Workshop and Conference (CCWC), Las Vegas, NV, USA, 7–9 January 2019; pp. 1032–1035.
11. Karoui, M.; Freitas, A.; Chalhoub, G. Performance comparison between LTE-V2X and ITS-G5 under realistic urban scenarios. In Proceedings of the 2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring), Antwerp, Belgium, 25–28 May 2020; pp. 1–7.
12. Nguyen, T.V.; Shailesh, P.; Sudhir, B.; Kapil, G.; Jiang, L.; Wu, Z.; Malladi, D.; Li, J. A comparison of cellular vehicle-to-everything and dedicated short range communication. In Proceedings of the 2017 IEEE Vehicular Networking Conference (VNC), Turin, Italy, 27–29 November 2017; pp. 101–108.
13. Mir, Z.H.; Filali, F. On the performance comparison between IEEE 802.11 p and LTE-based vehicular networks. In Proceedings of the 2014 IEEE 79th Vehicular Technology Conference (VTC Spring), Seoul, Korea, 18–21 May 2014; pp. 1–5.
14. Wang, M.; Winbjork, M.; Zhang, Z.; Blasco, R.; Do, H.; Sorrentino, S.; Belleschi, M.; Zang, Y. Comparison of LTE and DSRC-based connectivity for intelligent transportation systems. In Proceedings of the 2017 IEEE 85th Vehicular Technology Conference (VTC Spring), Sydney, NSW, Australia, 4–7 June 2017; pp. 1–5.
15. Roux, P.; Sesia, S.; Mannoni, V.; Perraud, E. System level analysis for ITS-G5 and LTE-V2X performance comparison. In Proceedings of the 2019 IEEE 16th International Conference on Mobile Ad Hoc and Sensor Systems (MASS), Monterey, CA, USA, 4–7 November 2019; pp. 1–9.
16. Petrov, T.; Sevcik, L.; Pocta, P.; Dado, M. A Performance Benchmark for Dedicated Short-Range Communications and LTE-Based Cellular-V2X in the Context of Vehicle-to-Infrastructure Communication and Urban Scenarios. *Sensors* **2021**, *21*, 5095. [CrossRef] [PubMed]
17. Cecchini, G.; Bazzi, A.; Masini, B.M.; Zanella, A. Performance comparison between IEEE 802.11 p and LTE-V2V in-coverage and out-of-coverage for cooperative awareness. In Proceedings of the 2017 IEEE Vehicular Networking Conference (VNC), Turin, Italy, 27–29 November 2017; pp. 109–114.
18. Mannoni, V.; Berg, V.; Sesia, S.; Perraud, E. A comparison of the V2X communication systems: ITS-G5 and C-V2X. In Proceedings of the 2019 IEEE 89th Vehicular Technology Conference (VTC2019-Spring), Kuala Lumpur, Malaysia, 28 April–1 May 2019; pp. 1–5.
19. Maglogiannis, V.; Naudts, D.; Hadiwardoyo, S.; van den Akker, D.; Marquez-Barja, J.; Moerman, I. Experimental V2X Evaluation for C-V2X and ITS-G5 Technologies in a Real-Life Highway Environment. *IEEE Trans. Netw. Serv. Manag.* **2021**, *19*, 1521–1538. [CrossRef]
20. Zhao, J.; Gai, X.; Luo, X. Performance Comparison of Vehicle Networking Based on DSRC and LTE Technology. In *International Conference on Intelligent Transportation Engineering*; Springer: Singapore, 2022; pp. 722–738.
21. Molina-Masegosa, R.; Gozalvez, J.; Sepulcre, M. Comparison of IEEE 802.11 p and LTE-V2X: An evaluation with periodic and aperiodic messages of constant and variable size. *IEEE Access* **2020**, *8*, 121526–121548. [CrossRef]
22. Sommer, C.; German, R.; Dressler, F. Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis. *IEEE Trans. Mob. Comput. (Tmc)* **2011**, *10*, 3–15. [CrossRef]
23. Sommer, C.; Yao, Z.; German, R.; Dressler, F. Simulating the influence of IVC on road traffic using bidirectionally coupled simulators. In Proceedings of the IEEE INFOCOM Workshops 2008, Phoenix, AZ, USA, 13–18 April 2008; pp. 1–6.
24. Wang, S.Y.; Chou, C.; Chiu, Y.; Tzeng, Y.; Hsu, M.; Cheng, Y.; Liu, W.; Ho, T. NCTUns 4.0: An integrated simulation platform for vehicular traffic, communication, and network researches. In Proceedings of the 2007 IEEE 66th Vehicular Technology Conference, Baltimore, MD, USA, 30 September–3 October 2007; pp. 2081–2085.
25. Petrov, T.; Finkelberg, I.; Zarkhin, N.; Počta, P.; Buzna, L.; Gal-Tzur, A.; Kováčiková, T.; Toledo, T.; Dado, M. A Framework Coupling VISSIM and OMNeT++ to Simulate Future Intelligent Transportation Systems. *Commun.-Sci. Lett. Univ. Zilina* **2021**, *23*, C23–C29. [CrossRef]
26. OMNeT++ Discrete Event Simulator. Available online: https://omnetpp.org/ (accessed on 10 May 2021).
27. Lopez, P.A.; Behrisch, M.; Bieker-Walz, L.; Erdmann, J.; Flötteröd, Y.P.; Hilbrich, R.; Lücken, L.; Rummel, J.; Wagner, P.; Wießner, E. Microscopic Traffic Simulation using SUMO. In Proceedings of the The 21st IEEE International Conference on Intelligent Transportation Systems, Maui, HI, USA, 4–7 November 2018; pp. 2575–2582.

28. Virdis, A.; Stea, G.; Nardini, G. Simulating LTE/LTE-Advanced Networks with SimuLTE. In *Simulation and Modeling Methodologies, Technologies and Applications*; Obaidat, M.S., Ören, T., Kacprzyk, J., Filipe, J., Eds.; Springer International Publishing: Cham, Switzerland, 2015; pp. 83–105.
29. Nardini, G.; Sabella, D.; Stea, G.; Thakkar, P.; Virdis, A. Simu5G–An OMNeT++ Library for End-to-End Performance Evaluation of 5G Networks. *IEEE Access* **2020**, *8*, 181176–181191. [CrossRef]
30. ETSI. *EN 302 637-2 v1.4.1-Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service*; ETSI: Sophia Antipolis, France, 2019.
31. Vukadinovic, V.; Bakowski, K.; Marsch, P.; Garcia, I.D.; Xu, H.; Sybis, M.; Sroka, P.; Wesolowski, K.; Lister, D.; Thibault, I. 3GPP C-V2X and IEEE 802.11 p for Vehicle-to-Vehicle communications in highway platooning scenarios. *Ad Hoc Netw.* **2018**, *74*, 17–29. [CrossRef]
32. Molina-Masegosa, R.; Gozalvez, J.; Sepulcre, M. Configuration of the C-V2X mode 4 sidelink PC5 interface for vehicular communication. In Proceedings of the 2018 14th International Conference on Mobile Ad-Hoc and Sensor Networks (MSN), Shenyang, China, 6–8 December 2018; pp. 43–48.
33. 3rd Generation Partnership Project. *3GPP TS 36.101. Evolved Universal Terrestrial Radio Access (E-UTRA)*; User Equipment (UE) Radio Transmission and Reception. 2021. Available online: https://www.etsi.org/deliver/etsi_ts/136100_136199/136101/16.08.00_60/ts_136101v160800p.pdf (accessed on 24 August 2022).
34. ITU-R. *Report ITU-R M.2292-0-Characteristics of Terrestrial IMT-Advanced Systems for Frequency Sharing/Interference Analyses*; ITU-R: Geneva, Switzerland, 2013.
35. Publications-Veins. Available online: https://veins.car2x.org/publications/ (accessed on 8 September 2022).
36. Nardini, G.; Stea, G.; Virdis, A.; Sabella, D. *Simu5G: A System-Level Simulator for 5G Networks*; SIMULTECH 2020. INSTICC: Lilydale, Australia, 2020; pp. 68–80.
37. SimuLTE: LTE User Plane Simulation Model for INET & OMNeT++ - Related Publications. Available online: https://simulte.com/related.html (accessed on 9 September 2022).
38. Simu5G: 5G New Radio User Plane Simulation Model for INET & OMNeT++ - Related Publications. Available online: http://simu5g.org/related.html (accessed on 9 September 2022).
39. Mueck, M.; Karls, I. *Networking Vehicles to Everything*; De|G Press: Berlin, Germany, 2018. [CrossRef]
40. 3GPP Release 14. Available online: http://www.3gpp.org/release-14 (accessed on 9 September 2022).
41. SAE J2945, Dedicated Short Range Communications (DSRC) Performance Requirements for V2V Safety Awareness. Available online: https://www.sae.org/standards/content/j2945/2_201810/ (accessed on 9 September 2022).
42. ETSI Technical Committee Intelligent Transport Systems. Available online: https://www.etsi.org/technologies/automotive-intelligent-transport (accessed on 9 September 2022).