Performance of Radio Access Technologies for Next Generation V2VRU Networks

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***Abstract*—The number of road accidents has remained stable in recent years. By using the latest technologies such as vehicle-to-vehicle communications, it is possible to improve road safety and reduce the number of road fatalities, especially for vulnerable road users (VRUs). There are two existing radio access technologies (RAT) for vehicle-to-everything (V2X) communications, i.e., Wi-Fi -based by IEEE (802.11p and its next-generation standard 802.11bd), and cellular-based by 3GPP (LTE-V2X and 5G NR-V2X). Although many works have evaluated and compared the performance of V2V RAT communications, very little work has been done to compare the performance of these technologies in the context of vehicle-VRU communications. In this paper, we present, to the best of our knowledge, the first work that evaluates the performance of each RAT in the context of vehicle-to-pedestrian (V2P) and vehicle-to-cyclist (V2C) communications. Using four performance metrics, namely packet error rate (PER), packet reception rate (PRR), throughput, and latency, we examined whether each RAT can meet the requirements of safety applications intended for implementation in urban areas. The answer to this question is yes. However, each RAT has its own performance profile. In terms of PER and PRR, 802.11bd has an advantage, while in terms of throughput and latency, 5G NR-V2X performs better.**

***Index Terms*—802.11p, 802.11bd, LTE-V2X, 5G NR-V2X, V2VRU**

I. Introduction

Road traffic injuries are becoming the eighth leading cause of death, where 54% of the fatally injured are vulnerable road users (VRU) (i.e., pedestrians, cyclists, and motorcyclists). The significant improvements in road safety that have been observed in recent years have been based primarily on improving vehicle safety. Only a few technologies have focused on the protection of VRUs, even though the percentage of road fatalities for VRU is over 50%. The development of technologies, such as vehicle communications, that has been going on for many years now [1]–[19], can support the deployment of Intelligent Transportation Systems (ITS), where the ability of vehicles to communicate with vulnerable road users (V2VRUs) offers new opportunities to reduce road fatalities [11] .

There are two existing radio access technologies (RAT) for V2X communications, i.e., Wi-Fi-based by IEEE [20]–[23] and Cellular-based by 3GPP [24]–[28]. Many works have been reported in the literature where the performance of V2V and vehicle-to-infrastructure (V2I) communications have been evaluated for different scenarios [29]–[31]. However, work on performance evaluation of V2VRU communications is scarce. In this paper, we investigate the performance of each RAT (802.11p, 802.11bd, LTE-V2X and 5G NR-V2X) for V2VRU communication. We considered vehicle-to-pedestrian (V2P) and vehicle-to-cyclist (V2C) communications. For V2P communication, we addressed the three main scenarios proposed by recent work [32], i.e., a) the vehicle to static pedestrian, b) the vehicle to moving pedestrian, and c) the vehicle to pedestrians with crowd shadowing scenarios. For V2C, we used the scenario of a vehicle to cyclist communication in an urban environment as proposed in recent work [33]. For each one of these scenarios, we used the corresponding accurate channel model, and we assessed V2VRU performance in terms of packet error rate (PER), packet reception ratio (PRR), throughput, and latency. The first objective of the work was to investigate whether each RAT can answer the requirements for safety applications intended for the protection of the VRU. A second objective was to compare the performance of each one of these technologies based on the aforementioned metrics.

The contributions of this paper are as follows:

- We addressed the main scenarios of road-safety V2C and V2P communications, and we implemented an accurate channel model for these scenarios.
- We assessed the performance of 802.11p and its next generation standard 802.11bd, as well as LTE-V2X and 5G NR-V2X for V2VRU communications.
- We investigated whether each RAT can meet the requirements for safety applications intended to the protection of the VRU.
- We compared the performance of each RAT technology in the context of V2VRU communications and explained the gaps found in the results.

The article is organized as follows, in section II, a background of RAT for V2VRU communications, V2X applications requirements and related works are presented. Section III describes the performance analysis of each RAT. Section IV discusses the simulation-based results, and the last part of the paper is dedicated to the conclusions.

II. Background

A. Radio Access Technologies for V2X

There are two existing radio access technologies (RAT) for V2X communications, i.e., Wi-Fi-based, and Cellular based [27], [34]–[36] technologies. The Wi-Fi-based V2X communication is standardized by the Institute of Electrical and Electronics Engineers (IEEE). Its first V2X standard was published in 2010 and is called 802.11p. Is is also refered to as dedicated short-range communication (DSRC) or ITS-G5. This technology supports V2V and V2I direct communications, and many automotive industries have already adopted DSRC into their market products. The new task group, TGbd, was formed recently by IEEE, with the purpose to explore the future roadmap for V2X, and work toward a new standard called next-generation V2X (NGV). This new standard has been expected to be published in 2021-2022 and is called 802.11bd. 802.11bd is the amendment of the 802.11p that defines modifications to both the Medium Access Control (MAC) and PHY layers for V2X communications in the 5.9 GHz band, and; optionally in the 60 GHz frequency band (57 to 71 GHz) or mm-wave.

A V2X specification was also issued in 2016 by the 3rd Generation Partnership Project (3GPP). It is based on cellular communication using 4G Long-Term Evolution (LTE) under the umbrella of LTE release 14 and is referred to as Cellular-V2X (C-V2X) or LTE-V2X. It employs two complementary transmission modes, i.e., direct communications (using V2V, V2I, or V2P) and network communications (using conventional mobile cellular networks or V2N). In the context of the next generation C-V2X communication, 3GPP recently finalized the 5G NR-V2X specifications in release 15 [16]. It uses two frequency ranges, i.e., the sub 6 GHz one (FR1:450MHz to 6GHz) and the mm-wave one (FR2: 24.25 to 52.6GHz).

B. V2X Safety Applications for VRU

The wide variety of V2X applications can be classified based on their purpose and minimum requirements, but generally, V2X applications can be viewed as belonging to four major categories, i.e., traffic safety, traffic efficiency, cooperative driving, and infotainment [36]. Use case examples of traffic safety applications include pre-sense crash warnings and vulnerable road-user warnings. These use cases have requirements of 20-100 ms latency and 0.5-700 Mbps throughput. These values can therefore be considered as the thresholds based upon which a RAT technology can be said to meet the requirements of VRU protection applications. According to 5GAA [37], there are three main scenarios for vehicular communications for VRU safety: 1) VRU in high-risk zones, where vehicles are delivered warnings when they enter a high-risk area where there is a likely presence of many VRUs, 2) interactive communications between VRU and vehicles, where there is a negotiation between the VRU's device and a vehicle, and 3) VRU safety messages and algorithms, where VRUs' devices and vehicles send messages and risk assessment is continuously performed by the vehicle and/or infrastructure.

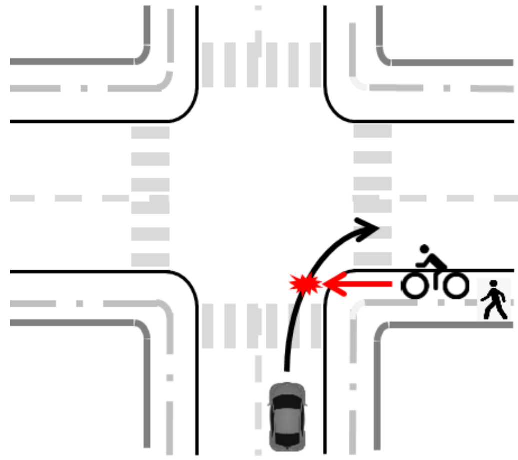

Fig. 1. An accident scenario, modified from [33], where VRU (pedestrian or cyclist) is crossing the road with approaching vehicle in the urban intersection.

Each scenario has its scope and use-case categories. For example, in the first scenario, one use-case is when pedestrians are in a crosswalk at an intersection and send alerts to vehicles as illustrated in Fig. 1. This scenario has been chosen in this work for evaluating the performance of different RAT.

C. Related Works

In a previous work [31], the performance of PHY layer enhancement of the 802.11bd compared to 802.11p standard for the NGV communication was investigated, where the results show better PER and throughput of all techniques in 802.11bd compared to the 802.11p legacy standard. Other works evaluated the performance of all RAT (802.11p, 802.11bd, LTE-V2X and 5G NR-V2X) for V2V communications [30]. Furthermore, in [29], the authors proposed the modeling and analysis for each RAT using PHY layer abstraction (PLA) techniques for an urban crossing environment. In this work, we adopt the same PLA technique as in [36] and use it for our V2VRU communication system model.

As stated in the introduction, we used two-channel modeling, one for V2P and another for V2C, for V2VRU communication. We used the V2P channel to assess communication performances in three scenarios, i.e., vehicle to static pedestrian, vehicle to moving pedestrian, and vehicle to pedestrian with crowd shadowing. Previous works [32] proposed V2P channel characterization and had the result of a wideband measurement campaign based on the scenarios above. Other works [33] proposed the large-scale fading characteristic for V2C channel in an urban environment at 5GHz with a dual-slope path loss model. In this paper, we used the characterization of the VRU channel in terms of path loss and path loss exponent based on both the results obtained in [32] and [33] as summarized in Table. I.

This paper investigates the performance of each RAT for V2VRU communication using four performance metrics, i.e., the PER based on signal to noise ratio (SNR) of the transmitted signal, and also PRR, throughput, and latency based on the

TABLE I
LOG-DISTANCE PATH LOSS PARAMETERS IN V2VRU BASED ON LITERATURE [32] AND [33]

V2VRU Scenario	Parameters	Values
V2P scenario 1 (static pedestrian)	Path loss Path loss exponent Shadow fading	46.77 dB 2.03 3.20 dB
V2P scenario 2 (moving pedestrian)	Path loss Path loss exponent Shadow fading	40 dB 2.44 5.47 dB
V2P scenario 3 (crowded pedestrian)	Path loss Path loss exponent Shadow fading	67 dB 1.26 3.35 dB
V2C scenario	Reference distance Breakpoint distance Path loss at reference Path loss exponent at reference Path loss exponent at breakpoint Shadow fading	1 m 32 m 46 dB 2.7 5.7 3.9 dB

distance between vehicles and the VRU. The performance analysis of each metric will be described in the next section.

III. PERFORMANCE ANALYSIS

Based on [32], the calculation of the propagation loss in different V2P scenarios using the log-distance path loss model is expressed by:

$$P_L(d) = P_L(d_0) + 10nlog_{10}\left(\frac{d}{d_0}\right) + X \tag{1}$$

where $P_L(d)$ is the path loss between vehicle and VRU with the distance d, $P_L(d_0)$ is the path loss at the reference distance d_0, n is the path loss exponent for each scenario, and X is the value of shadow fading. While for the V2C channel, based on [33], the total propagation loss between a vehicle and VRU is calculated using the dual-slope log-distance path loss model expressed by:

$$P_{Ltot} = \overline{P_L(d)} + X, \tag{2}$$

$$\overline{P_L(d)} = \begin{cases} P_{L0} + 10n_1 log_{10}\left(\frac{d}{d_0}\right), \\ P_{L0} + 10n_2 log_{10}\left(\frac{d_c}{d_0}\right) + 10n_2 log_{10}\left(\frac{d}{d_c}\right), \end{cases} \tag{3}$$

where d_0 is the reference distance, d_c is the break point distance where the second slope begin, d is the distance between vehicle and VRU, n_1 and n_2 are the path loss exponent for the first and second slope.

A. PER

The PER is chosen as a performance metric of the RAT by calculating the ratio between the error of the received packets and the total number of the transmitted packets. Based on [29], the power of the received signal with the distance d, can be calculated as follows:

$$P_{Rx} = \frac{P_{Tx} \cdot G_{Tx} \cdot G_{Rx}}{P_{L0} \cdot d^n \cdot NF}, \tag{4}$$

where P_{Tx} and P_{Rx} are the power of the transmitted and received signal respectively, G_{Tx} and G_{Rx} are the gain from transmitted and received antennas respectively, and NF is the noise figure. To model the effective signal to interference plus noise ratio (SINR) of transmitted OFDM symbol under the influence of the inter-carrier interference (ICI), we calculate the power of the ICI based on the subcarrier spacing and Doppler frequency (f_D). The received SINR is calculated based on the function of the frequency response of the channel, the received signal power at the distance d, and the ICI power. And then, the effective SINR is computed using the enhanced-exponential effective SINR mapping (eEESM) by considering the specific fading channel condition. Finally, the PER performance in the link level, will use the PLA technique to map the effective SINR to the value of the pre-calculated PER.

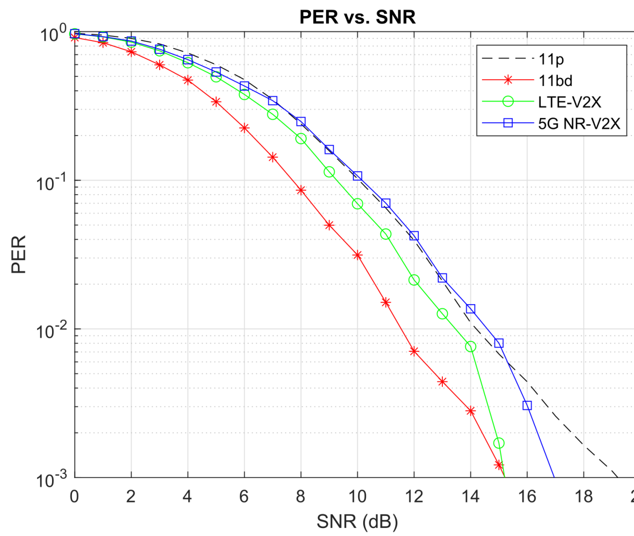

Fig. 2. PER performance of each RAT based on SNR of the transmitted signal using PLA technic.

The typical safety applications for V2X communication use QPSK with a code rate of $1/2$. The value of the MCS of the RAT is different, where MCS value of 2, 1, and 21 are the MCS of the 802.11p, 802.11bd and LTE-V2X/5G NR-V2X respectively.

Fig. 2 shows the PER performance of each RAT depending on SNR using the MCS of QPSK $1/2$. The PER of 802.11bd is better compared to LTE-V2X and 5G NR-V2X due to the lower ICI values. It is also better compared to 802.11p due to the use of the LDPC channel coding technique. This result is consistent the results found in [29]. For the reliability of 90%, 802.11bd gained around 1-2 dB compared to the other RAT, while for 99% reliability, it gained around 2-3 dB.

B. PRR

The PRR is the probability of a successful transmission, where the received OFDM symbols are the same as the transmitted symbols. The PRR metric is indeed the inverse value of the PER metric. Using the same MCS for the safety application (QPSK $1/2$) and also the path loss equation for each V2P and V2C channel model, we calculate the performance of PRR for different distances and also the value of the PER. The PRR

TABLE II
SIMULATIONS PARAMETERS

Parameter	Value			
	802.11p	*802.11bd*	*LTE-V2X*	*5G NR-V2X*
Carrier spacing	156.25 kHz		15 kHz	60 kHz
Transmission power	23 dBm			
Tx/Rx antenna gain	0 dBm			
Noise power	-104 dB (at 10 MHz)			
Noise figure	9 dB			
Distance	0-1000 m			
Packet size	300 Bytes dBm			
Environment	Urban crossing			

metric is used to know the performance in terms of reliability and also the communication range of each RAT.

C. Latency

The transmission latency is the time needed to transmit PHY frame for each RAT. In this work, we assessed the packet arrival time as a function of distance, which is derived from the log-distance path loss model. According to [36], the safety application has a requirement of 20-100 ms in terms of latency. Therefore, we evaluated the latency of each RAT and compared the result with the requirements.

D. Throughput

Using the OFDM numerology defined in the standard of each RAT, the theoretical data rates for each MCS can be calculated as follows:

$$DataRate = \frac{N_{SD} * N_{BPSCS} * R * N_{SS}}{T_{sym} + T_{GI}}, \quad (5)$$

where N_{SD} to be the number of data sub-carriers, N_{BPSCS} is the number of coded bits per sub-carriers per stream, R is the coding rate, N_{SS} is the number of spatial streams, T_{sym} is OFDM symbol duration, and T_{GI} is guard interval duration.

The throughput metric used in this paper is the effective value of the achievable data rates for each RAT, which is calculated using the multiplication between the PRR and the theoretical data rates.

In this paper, we used the performance metrics in [29], because we adopted the PLA technic for modeling and analyzing the V2VRU networks. Please refer to [29] for the detailed PLA technique, its application in the system-level simulation and also the calculation of the performance metrics of each RAT

IV. SIMULATION RESULTS

We used three performance metrics, i.e., the PRR, latency in terms of packet inter-arrival time, and throughput in terms of the effective data rate as function of the distance. We performed 1000 channel simulations and calculated the average of each metric. The latency metric is taken from the average value of the minimum packet inter arrival-time, while the throughput is taken from the average value of the maximum effective data rates. Table II summarizes all the parameters and values used in the simulation.

A. V2P with Static Pedestrian

Fig. 3 shows the performance of each RAT in the V2P channel model for the static pedestrian at the urban crossing environment. Based on the safety application requirements, i.e., having 20-100 ms latency and 0.5-700 Mbps throughput, each RAT meets this requirement.

In the PRR of 95%, 802.11bd gains a longer communication range, around 150-200 m, due to better PER. However, 5G NR-V2X gave superior throughput and latency performances compared to the other RATs. It achieves data rates of 6-20 Mbps and latencies of 0.2-0.6 ms for distances up to 1000 m.

B. V2P with Moving Pedestrian

Fig. 4 shows the performance of each RAT in the V2P channel model for the moving pedestrian at the urban crossing environment. In this scenario, each RAT also can answer the safety application requirement for latency and throughput.

With the PRR of 90%, 802.11bd gains a longer communication range, and has a communication range of up to 500 m, while other RAT have around 380-400 m. In terms of throughput and delay performances, 5G NR-V2X still gave better throughput and latency performances compared to the other RATs. However, the latency performances of 5G NR-V2X is better in the close communication range ($<$ 600 m), and has almost the same latency performance for the communication range of more than 600 m.

If we compare the performance metrics with the previous scenario, V2P with static fading, we can see that the performance for moving pedestrians is worst due to the higher value of the shadow fading.

C. V2P with Crowded Pedestrian

Fig. 5 shows the performance of each RAT in the V2P channel model for the crowd pedestrian at the urban crossing environment. Each RAT also can answer the requirements of the safety applications, which are having 20-100 ms latency and 0.5-700 Mbps throughput.

For the PRR of 98%, 802.11bd gains a longer communication range, around 200-250 m. The 5G NR-V2X gives superior throughput and latency performances compared to the other RATs. It achieves data rates of 8-20 Mbps and the latencies of 0.2-0.4 ms for distances up to 1000m.

D. V2C

Finally, Fig. 6 shows the performance of each RAT in the V2C channel model at the urban crossing environment. The requirement of the safety application is also fulfilled. However, we can see from the figure that the communication range in this V2C channel model is limited to around 600 m.

For the PRR of 90%, 802.11bd gains a longer communication range, of around 30-40 m. 5G NR-V2X gives superior throughput and latency performances in the communication ranges up to 500 m compared to the other RATs. It gives data rates of 0.9-20 Mbps for the distances up to 700 m, and latencies of 0.2-1 ms for distances up to 500 m.

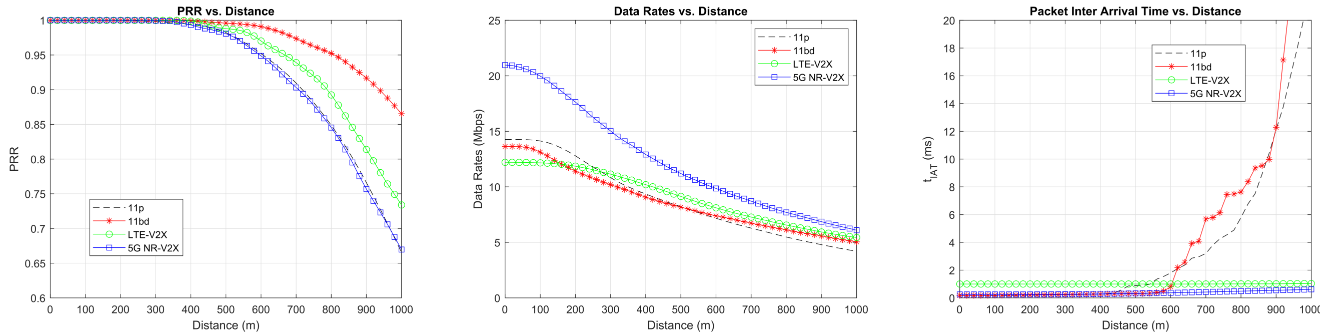

Fig. 3. RAT performance in V2P of the scenario 1 (with static pedestrian) at the urban crossing environments.

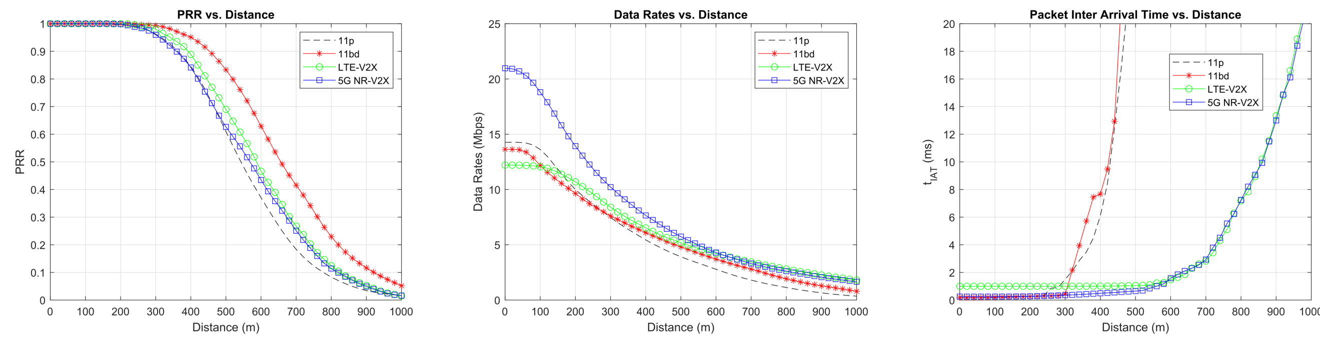

Fig. 4. RAT performance in V2P of the scenario 2 (with moving pedestrian) at the urban crossing environments.

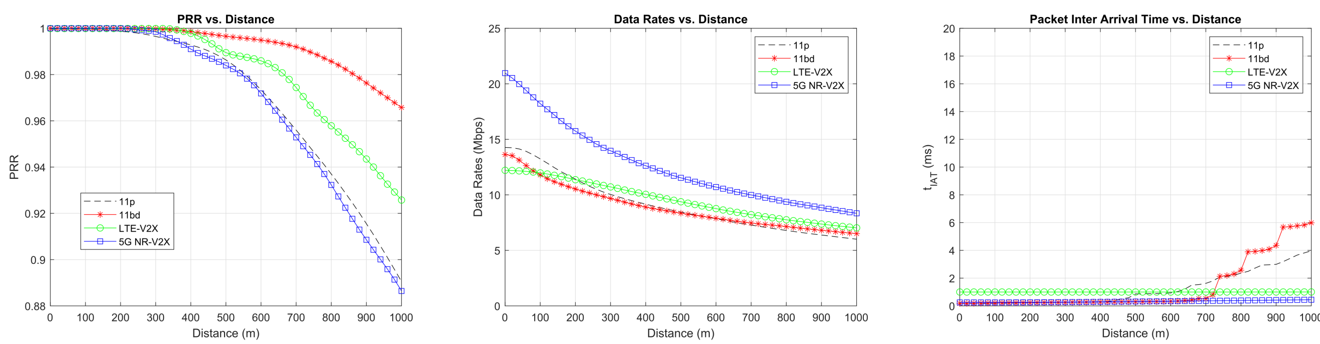

Fig. 5. RAT performance in V2P of the scenario 3 (with crowd pedestrian) in the urban crossing environments.

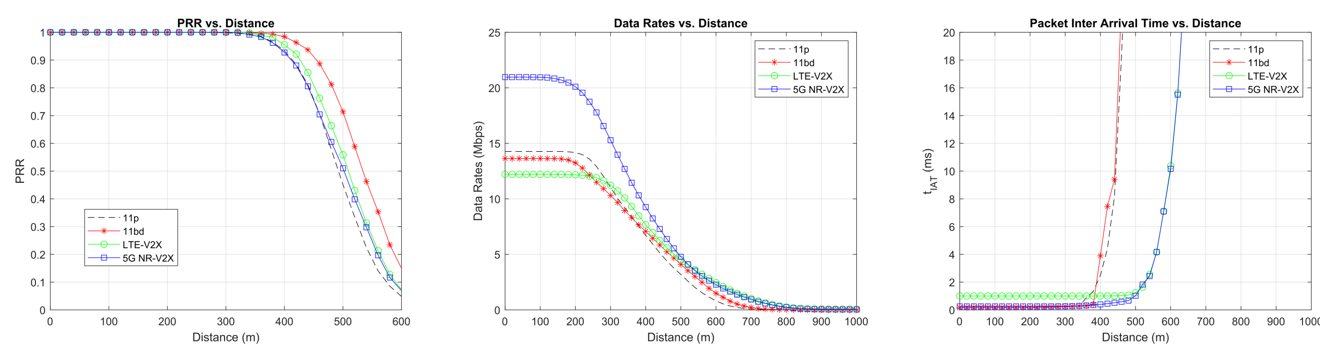

Fig. 6. RAT performance in V2C at the urban crossing environments.

V. Conclusions

In this paper, we assess the performance of each RAT for V2VRU networks. Using the performance metrics of PER, PRR, latency and throughput, the PLA technic, and also V2C and V2P channel model characteristics we can compare the performance of 802.11p, 802.11bd, LTE-V2X, and 5G NR-V2X. From the simulation results, we can conclude that each RAT can answered all the safety applications requirements, which are having 20-100 ms latency and 0.5-700 Mbps throughput. In terms of PER and PRR, 802.11bd has a good performance due to the small ICI value and the use of a more advanced channel coding technique, i.e., LDPC. While in terms of data rate and latency, 5G NR-V2X has a better performance.

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