This document is a preprint of: W. Anwar, N. Franchi and G. Fettweis, “Physical Layer Evaluation of V2X Communications Technologies: 5G NR-V2X, LTE-V2X, IEEE 802.11bd, and IEEE 802.11p,” in Proceedings of IEEE Vehicular Technology Conference (VTC Fall 2019), Honolulu, Hawaii, USA, Sep 2019. DOI:10.1109/VTCFall.2019.8891313

Physical Layer Evaluation of V2X Communications Technologies: 5G NR-V2X, LTE-V2X, IEEE 802.11bd, and IEEE 802.11p

Waqar Anwar, Norman Franchi, and Gerhard Fettweis
Vodafone Chair Mobile Communications Systems, Technische Universität Dresden, Germany
{waqar.anwar, norman.franchi, gerhard.fettweis}@tu-dresden.de

***Abstract*—Vehicular communications have an eminence potential to improve the road safety by exchange of information with their surrounding. To enable vehicular communications, IEEE 802.11p and LTE-V2X are the state of the art technologies. A number of studies and field trials are carried out to evaluate their performance in various vehicle-to-everything (V2X) communications scenarios. On the one hand, 3GPP (3rd Generation Partnership Project) is working on the next generation V2X technology (i.e., 5G NR-V2X) to address new use cases and improve the performance. On the other hand, an IEEE 802.11 study group NGV (next generation V2X) is identifying new use cases and requirements, to define a possible amendment named IEEE 802.11bd. In this paper, we evaluate and compare the physical layer performance of these upcoming technologies for vehicle-to-vehicle (V2V) communications. The main motivation of this work is to identify which technology is more suitable for V2V communications. Our results show that NR-V2X is expected to outperform all other standards (even IEEE 802.11bd) in terms of reliability, range, latency, and data rates. However, IEEE 802.11bd is expected to be more reliable with improved range and throughput compared to IEEE 802.11p.**

***Index Terms*—IEEE 802.11p, LTE-V2X, 5G NR, NR-V2X, IEEE 802.11 NGV, ITS, IEEE 802.11bd, URLLC, eMBB**

I. INTRODUCTION

In recent years, vehicular-to-everything (V2X) communications gained huge interest because it can reduce traffic jams, increase road safety, provide an alternative emergency communications system in natural disasters, and even enable autonomous driving. Further, it enables many use cases and information sharing capabilities which will improve daily life experience. However, V2X communications demand a variety of performance requirements often defined in terms of latency, reliability, and data rates [1]. If these requirements are not met, safety critical applications will fail to respond in potential dangerous situations. Hence, it is of great interest to have a robust and reliable communications technology. Many standardization organizations have put efforts into specifying V2X communications technologies, especially after the allocation of dedicated spectrum at 5.9 GHz for intelligent transportation system (ITS) in the US (in 1999) and in Europe (in 2008) [2].

The first ever standard for V2X communications, IEEE 802.11p (further refered as 11p), was introduced in 2010 [3]. It was an amendment to the wireless local area network (WLAN) standard IEEE 802.11a. The 11p standard describes a set of protocols required by direct short range communications (DSRC) for information exchange without the need of a basic service set (BSS), as required in traditional 802.11 standards. Since then, the 802.11 standard has evolved with many mature technologies, such as low density parity check (LDPC) codes, Multiple-input and Multiple-output (MIMO), and better handling of Doppler shifts. To fulfill the future needs of V2X communications, 802.11 created a study group named next generation V2X (NGV) to define an amendment IEEE 802.11bd (further refered as 11bd), based on existing and proven WLAN technologies. Motivated by the interest from the automotive community, 3GPP also finalized a cellular based V2X (C-V2X) standard within its Release 14 in 2016 [4], also known as LTE-V2X. Along with the evolutionary development of cellular standards, specifications for the next generation of C-V2X i.e., New Radio V2X (NR-V2X), are expected within Release 16 in June 2019 [5].

Many studies and field trials have been conducted to evaluate the performance and suitability of 11p and LTE-V2X in various V2X communications scenarios [2], [6], [7]. These investigations conclude that both technologies are suitable for enabling basic communications such as exchange of cooperative awareness messages (CAMs). However, these technologies fail to meet the reliability and latency requirements of advanced use cases such as safety critical communications and autonomous driving. The comparison in [8] shows that LTE-V2X has superior performance in terms of data rates and reliability whereas 11p is better in terms of transmission latency. Nevertheless, the main advantage of 11p compared to LTE-V2X is that, it is well tested, fairly reliable and a ready to use technology for vehicular communications. However, the advantage of using LTE-V2X is that similar hardware and software protocols are being used. Even though the upcoming technologies (i.e., IEEE 802.11bd and NR-V2X) are expected to have better performance in terms of reliability and latency; the quantity of improvement compared to each other, and to their predecessors is not studied yet.

The purpose of this study is to evaluate the performance of upcoming V2X technologies and their suitability for different applications. In this paper, we consider two target applications i.e., Ultra Reliable Low Latency Communications (URLLC) and enhanced Mobile Broadband (eMBB). The anayltical calculations of equivalent data rates and transmission latencies for various technologies (as a function of packet size) are presented. We compare technologies based on theoretical calculations of maximum achievable data rates and transmission latencies for URLLC and eMBB applications. We also compare the physical layer performance in terms of packet error rates (PER), packet reception ratios (PRR), net data rates, and packet inter arrival times through simulations.

This document is a preprint of: W. Anwar, N. Franchi and G. Fettweis, “Physical Layer Evaluation of V2X Communications Technologies: 5G NR-V2X, LTE-V2X, IEEE 802.11bd, and IEEE 802.11p,” in Proceedings of IEEE Vehicular Technology Conference (VTC Fall 2019), Honolulu, Hawaii, USA, Sep 2019. DOI:10.1109/VTCFall.2019.8891313

TABLE I
802.11: MCS OPTIONS, THEORETICAL DATA RATES (Mbps), AND TRANSMISSION LATENCIES (ms)

MCS	IEEE 802.11p						IEEE 802.11bd					
			100 bytes		1500 bytes				100 bytes		1500 bytes	
index	Modulation	R^{11p}	$\mathit{\Gamma}^{11p}$	T_{tx}^{11p}	$\mathit{\Gamma}^{11p}$	T_{tx}^{11p}	Modulation	R^{11bd}	$\mathit{\Gamma}^{11bd}/\mathit{\Gamma}^{11bd^{DC}}$	$T^{11bd}/T_{tx}^{11bd^{DC}}$	$\mathit{\Gamma}^{11bd}/\mathit{\Gamma}^{11bd^{DC}}$	$T^{11bd}/T_{tx}^{11bd^{DC}}$
0	BPSK	1/2	2.32	0.344	2.94	4.08	BPSK	1/2	2.38 /1.33	0.336 / 0.600	3.02 / 1.52	3.98 / 7.88
1	BPSK	3/4	3.12	0.256	4.37	2.74	QPSK	1/2	3.85 / 2.35	0.208 / 0.340	5.93 / 3.02	2.02 / 3.98
2	QPSK	1/2	3.85	0.208	5.77	2.08	QPSK	3/4	4.76	0.168	8.72	1.38
3	QPSK	3/4	4.76	0.168	8.52	1.41	16-QAM	1/2	5.71 / 3.77	0.140 / 0.212	11.41 / 5.92	1.05 / 2.03
4	16-QAM	1/2	5.55	0.144	11.19	1.07	16-QAM	3/4	6.45	0.124	16.57	0.724
5	16-QAM	3/4	6.67	0.120	16.13	0.744	64-QAM	2/3	7.41	0.108	20.13	0.596
6	64-QAM	2/3	7.14	0.112	20.83	0.576	64-QAM	3/4	7.41	0.108	22.22	0.540
7	64-QAM	3/4	7.69	0.104	23.08	0.520	64-QAM	5/6	7.41	0.108	24.19	0.496
8	-	-	-	-	-	-	256-QAM	3/4	8.00	0.100	28.30	0.424
9	-	-	-	-	-	-	256-QAM	5/6	8.00	0.100	30.92	0.388

II. OVERVIEW OF TECHNOLOGIES

This section provides a brief overview of currently available and upcoming V2X communications technologies.

A. IEEE 802.11p

The physical layer of 11p is based on OFDM similar to most 802.11 standards. The main difference as compared to IEEE 802.11a is that carrier spacing and bandwidth are reduced by a factor of two which result in two times longer symbol duration. The cyclic prefix (CP) duration is also doubled, which allows to compensate larger delay spreads and makes it more suitable for outdoor environments. The possible modulation and coding schemes (MCS) are defined in [9, Table 17.4]. The MAC layer of 11p uses an enhanced distributed channel access (EDCA) method which uses carrier sense multiple access with collision avoidance (CSMA/CA).

Transmission Latency: The transmission latency (T_{tx}^{11p}) is defined here as the time required to transmit a packet on the wireless medium. For a given payload (P_b), the transmission latency is obtained as

$$T_{tx}^{11p} = t_{pre} + t_{AIFS} + t_{sym} \times n_{sym}, \qquad (1)$$

where t_{pre} is the preamble duration (40 μs for 802.11p), t_{AIFS} is arbitrary inter-frame space which is the waiting time for nodes after medium is sensed free (32 μs for priority data), t_{sym} is the OFDM symbol duration (8 μs), and n_{sym} denotes the number of OFDM symbols required to transmit a certain payload (including MAC header, service, and tails bits).

Data Rates: The analytical data rates ($\mathit{\Gamma}^{11p}$) is the ratio of the total number of data bits transmitted in T_{tx}^{11p} and is given as

$$\mathit{\Gamma}^{11p} = \frac{P_b \times 8}{T_{tx}^{11p}}. \qquad (2)$$

The calculations of T_{tx}^{11p} and $\mathit{\Gamma}^{11p}$ for all MCS are provided in Table I for packet sizes (P_b) of 100 and 1500 bytes.

B. IEEE 802.11bd

The specifications of IEEE 802.11bd are currently being developed by 802.11 task group (TGbd). According to the project authorization report (PAR) [10], following are the main design goals.

- Backward compatible and interoperable with 11p
- Two times higher throughput measured at MAC
- Higher reliability by reducing packet collisions and improving performance under high Doppler shifts
- Target speed of 250 Km/h
- Range improvement by a factor of two

Higher data rates can be achieved by adopting some of the existing PHY technologies such as LDPC, MIMO, 256 QAM modulation, and 20 MHz bandwidth. In order to improve the range, dual carrier modulation (DCM) and range extension modes can be adopted from 802.11ax. According to [11], following are the candidate settings of 11bd PHY.

- Carrier modulation scheme: OFDM
- Tone spacing: 156.25 kHz / 78.125 kHz
- CP duration: 1.6 μs / 3.2 μs
- Channel coding: LDPC
- Lowest rate: MCS0 (1/2 BPSK)
- Highest rate: MCS9 (5/6 256-QAM)
- Doppler recovery method: high frequency midambles
- Bandwidth: 10 MHz / 20 MHz

The analytical data rates and latency values for 11bd can be obtained following the same steps as used in 11p. For transmission latency calculations, an additional 4 μs 11bd header for normal packet and 8 μs for extended range format are considered. In addition, after every 9th OFDM symbol a midamble is inserted for MCS0 to MCS4 and after every 4th OFDM symbols otherwise. In this paper, two different modes of 11bd are considered.

- **11bd:** 2 times downclock of 802.11ac with midambles
- **$\mathbf{11bd^{DC}}$:** 11bd with DCM and range extension mode enabled for MCS0, MCS1, and MCS3

Table I provides MCS options, analytical data rates ($\mathit{\Gamma}^{11bd}$), and latencies (T_{tx}^{11bd}) for payload sizes of 100 and 1500 bytes.

C. LTE-V2X

Long term evolution (LTE) with its versatile communication options and ubiquitous coverage is emerged as a new option for V2X services. Unlike 802.11p, LTE-V2X uses DFT spread OFDM (DFT-s-OFDM) as a carrier modulation technique for better power efficiency. The symbol duration of LTE-V2X is 10 times larger than the symbol duration of 11p which provides robustness against multi-path and reduces

This document is a preprint of: W. Anwar, N. Franchi and G. Fettweis, "Physical Layer Evaluation of V2X Communications Technologies: 5G NR-V2X, LTE-V2X, IEEE 802.11bd, and IEEE 802.11p," in Proceedings of IEEE Vehicular Technology Conference (VTC Fall 2019), Honolulu, Hawaii, USA, Sep 2019. DOI:10.1109/VTCFall.2019.8891313

TABLE II
C-V2X: MCS OPTIONS, TEORATICAL DATA RATES (Mbps), AND TRANSMISSION LATENCIES (ms)

MCS index	LTE-V2X								5G NR-V2X								
		Code	100 bytes			1500 bytes				Code		100 bytes			1500 bytes		
	Modulation	Rate	$n_{\text{RB}}^{\text{LTE}}$	Γ^{LTE}	$T_{\text{tx}}^{\text{LTE}}$	$n_{\text{RB}}^{\text{LTE}}$	Γ^{LTE}	$T_{\text{tx}}^{\text{LTE}}$	Modulation	Rate	$n_{\text{nbpm}}^{\text{NR}}$	$n_{\text{RB}}^{\text{NR}}$	Γ^{NR^2}	$T_{\text{tx}}^{\text{NR}^2}$	$n_{\text{RB}}^{\text{NR}}$	Γ^{NR^0}	$T_{\text{tx}}^{\text{NR}^0}$
0	QPSK	0.13	30	1.09	1	434	1.13	11	QPSK	0.12	0.23	23	1.41	0.75	337	1.70	8
6	QPSK	0.47	8	4.08	1	116	4.22	3	QPSK	0.44	0.87	7	4.63	0.25	91	6.31	2
7	QPSK	0.55	7	4.66	1	99	4.94	3	QPSK	0.51	1.03	6	5.40	0.25	78	7.36	2
10	QPSK	0.81	5	6.53	1	69	7.09	2	16-QAM	0.33	1.33	4	8.10	0.25	60	9.57	2
13	16-QAM	0.52	4	8.16	1	53	9.24	2	16-QAM	0.48	1.91	3	10.79	0.25	42	13.67	1
17	16-QAM	0.75	3	10.88	1	38	12.88	1	64-QAM	0.45	2.73	2	16.19	0.25	29	19.80	1
21	64-QAM	0.65	2	16.32	1	28	17.49	1	64-QAM	0.65	3.90	2	16.19	0.25	21	27.34	1
27	64-QAM	0.93	2	16.32	1	19	25.77	1	64-QAM	0.92	5.55	1	32.38	0.25	15	38.27	1

inter symbol interference (ISI). However, sensitivity to carrier frequency offset and phase noise increases. Further, LTE-V2X provides multiple bandwidth options such as 1.4 MHz, 5 MHz, 10 MHz, and 20 MHz. Users are assigned with variable number of resource blocks (RB) depending upon the payload size and MCS, which means that assigned bandwidth can be shared among users. LTE-V2X provides continuous variations of MCS combinations [12, Table 8.6.1-1] with a more advanced channel coding scheme (Turbo codes) as compared to convolutional codes used in 11p. Transmissions in LTE consist of frames each with a duration (t_{fr}) of 10 ms. Frames are divided into subframes ($t_{\text{sub-fr}}^{\text{LTE}}$) of 1 ms which are further subdivided into time slots of 0.5 ms. The minimum transmission time interval (TTI) is equal to one subframe.

Transmission Latency: The transmission latency $T_{\text{tx}}^{\text{LTE}}$ is the number of subframe required to transmit P_{b} computed as

$$T_{\text{tx}}^{\text{LTE}} = \left\lceil \frac{n_{\text{RB}}^{\text{LTE}}}{n_{\text{RB-fr}}^{\text{LTE}}/20} \right\rceil \times t_{\text{sub-fr}}^{\text{LTE}}, \tag{3}$$

where $n_{\text{RB}}^{\text{LTE}}$ denotes the number of RBs required to transmit P_{b} obtained from [12, Table 7.1.7.2.1-1], and $n_{\text{RB-fr}}^{\text{LTE}}$ is the total number of RBs available in a frame for data transmission (i.e. 816 for 10 MHz [13, Table 2]).

Data Rates: Given the payload size (P_{b}), the analytical data rates (Γ^{LTE}) are calculated as:

$$\Gamma^{\text{LTE}} = \frac{P_{\text{b}} \times 8 \times n_{\text{RB-fr}}^{\text{LTE}}/20}{n_{\text{RB}}^{\text{LTE}} \times t_{\text{sub-fr}}^{\text{LTE}}}. \tag{4}$$

Code Rate: The code rate in LTE-V2X can be obtained as

$$\text{Code Rate} = \frac{n_{\text{bits-RB}}^{\text{LTE}}}{n_{\text{RB}}^{\text{LTE}} \times n_{\text{d-sym}}^{\text{LTE}} \times n_{\text{sc}}^{\text{LTE}} \times n_{\text{bps}}}, \tag{5}$$

where $n_{\text{bits-RB}}^{\text{LTE}}$ is the number of bits carried by $n_{\text{RB}}^{\text{LTE}}$ resource blocks, $n_{\text{d-sym}}^{\text{LTE}}$ is the number of data symbols in one subframe (= 9 [2]), $n_{\text{sc}}^{\text{LTE}}$ is the number of subcarriers in one RB (= 12), and n_{bps} is the number of bits carried by modulation scheme.

Table II provides examplary calculations of $T_{\text{tx}}^{\text{LTE}}$, Γ^{LTE}, and the code rate for payloads of 100 and 1500 bytes.

D. 5G NR-V2X

The 3GPP has recently finalized specifications for 5G NR with Release 15 (Phase 1). The study of new V2X use cases and requirements for NR-V2X is already completed and specifications are expected to be finalized until the end of 2019 with Release 16 (Phase 2) [14]. Even though, the NR-V2X specifications are not available yet but it can be easily stated what is expected, as most PHY features will be adopted from the 5G NR uplink.

5G NR supports both OFDM (for high throughput efficiency) and DFT-s-OFDM (for low link budget devices) for uplink transmissions. Two frequency ranges (FR) are defined which are sub-6 GHz (FR1: 450 MHz - 6 GHz) and millimeter wave (FR2: 24.25 GHz - 52.6 GHz). The maximum single user bandwidths in FR1 and FR2 are 100 MHz and 400 MHz respectively, much larger than the maximum LTE bandwidth of 20 MHz. Scalable OFDM numerology μ ($2^{\mu} \times 15$ kHz where $\mu = 0, 1 \ldots 5$) are defined to cover a wide range of scenarios and to meet use case specific requirements. In addition to other enhancements, 5G NR supports advanced coding schemes such as LDPC codes for the data channel and a cyclic redundancy check (CRC) assisted polar codes for the control channel. Another important enhancement is the frame structure. In 5G NR a subframe is divided into 2^{μ} slots each consisting of 14 OFDM symbols. Resources are assigned per slot unlike LTE, where the minimum TTI is equal to one subframe. In order to further reduce latency, 5G NR also provides a *mini-slot* option to transmit data using just 2, 4 or 7 OFDM symbols without any slot boundaries.

In this paper, we use two different modes of NR-V2X in sub-6 GHz band with 10 MHz bandwidth which are:

- **NR^0 (15 kHz)** for 1500 bytes packet using OFDM to achieve high throughput efficiency
- **NR^2 (60 kHz)** for 100 bytes packet using DFT-s-OFDM to achieve high reliability

Number of RBs: In order to calculate the analytical data rate (Γ^{NR}) for 5G NR-V2X, we need to compute the required number of RBs ($n_{\text{RB}}^{\text{NR}}$) first. An RB consists of 168 resource elements (RE) i.e., 12 subcarriers in frequency domain and 14 OFDM symbols in time domain. Due to the fast changing channel conditions, 16 REs (mapping type = A with 3 additional symbols) are used for a high density demodulation reference signal (DMRS). Therefore, the number of REs available for data transmission ($n_{\text{d-RE}}^{\text{NR}}$) are reduced to 152. The required number of RBs ($n_{\text{RB}}^{\text{NR}}$) for a given payload size (P_{b}) are calculated as

$$n_{\text{RB}}^{\text{NR}} = \left\lceil \frac{P_{\text{b}} \times 8}{n_{\text{d-RE}}^{\text{NR}} \times n_{\text{nbpm}}^{\text{NR}}} \right\rceil, \tag{6}$$

This document is a preprint of: W. Anwar, N. Franchi and G. Fettweis, "Physical Layer Evaluation of V2X Communications Technologies: 5G NR-V2X, LTE-V2X, IEEE 802.11bd, and IEEE 802.11p," in Proceedings of IEEE Vehicular Technology Conference (VTC Fall 2019), Honolulu, Hawaii, USA, Sep 2019. DOI:10.1109/VTCFall.2019.8891313

where $n^{\mathrm{NR}}_{\mathrm{nbpm}}$ is the spectral efficiency of a given MCS obtained from [15, Table 6.1.4.1-1].

Transmission Latency: The transmission latency ($T^{\mathrm{NR}}_{\mathrm{tx}}$) for 5G NR is the number of time slots required to transmit a payload of P_{b} multiplied with the slot duration ($t^{\mathrm{NR}}_{\mathrm{slot}}$).

$$T^{\mathrm{NR}}_{\mathrm{tx}} = \left\lceil \frac{n^{\mathrm{NR}}_{\mathrm{RB}}}{n^{\mathrm{NR}}_{\mathrm{RB\text{-}slot}} \times (1 - \mathrm{OH})} \right\rceil \times t^{\mathrm{NR}}_{\mathrm{slot}}, \qquad (7)$$

where ($n^{\mathrm{NR}}_{\mathrm{RB\text{-}slot}}$) is the number of RBs available to a user in a certain bandwidth [16, Table 5.3.2-1] and OH is the uplink overhead (=8% [17, Sec. 4.1.2]).

Data Rates: The data rates ($\mathit{\Gamma}^{\mathrm{NR}}$) are computed as

$$\mathit{\Gamma}^{\mathrm{NR}} = \frac{P_{\mathrm{b}} \times 8 \times n^{\mathrm{NR}}_{\mathrm{RB\text{-}slot}} \times (1 - \mathrm{OH})}{n^{\mathrm{NR}}_{\mathrm{RB}} \times t^{\mathrm{NR}}_{\mathrm{slot}}}. \qquad (8)$$

Code Rate: The code rate for NR can be obtained from [15, Table 6.1.4.1-1].

An exemplary calculation of $n^{\mathrm{NR}}_{\mathrm{RB}}$, $T^{\mathrm{NR}}_{\mathrm{tx}}$, and $\mathit{\Gamma}^{\mathrm{NR}}$ are provided in Table II for payloads of 100 and 1500 bytes.

III. Discussion on Theoretical Evaluation

In the previous section, we calculated the transmission latencies and data rates for different technologies. In this section, the performance of technologies is evaluated based on analytical calculations to give an impression what could be expected in best case scenarios.

Transmission Latency: Transmission latency is defined as the time required by PHY to transmit a packet to air interface, which can have a significant influence on the end-to-end latency. Starting with 802.11 based variants, the transmission latency decreases with increasing MCS order. This is due to the fact that less OFDM symbols are required to transmit the data. There is no significant difference in transmission latency among 802.11 variants except the 11bd$^{\mathrm{DC}}$ which requires double time compared to 11bd due to DCM. However, the transmission latency in the case of 11bd is less compared to 11p which is due to the use of higher order MCS and the fact that 4 more data carriers are available. For the considered packet sizes of 100 bytes and 1500 bytes, the lowest latencies achieved by 11bd are 0.1 ms and 0.388 ms respectively. Compared to NR-V2X, the minimum latencies are 0.25 ms (100 bytes) and 1 ms (1500 bytes) which are almost two times higher than 11bd. Nevertheless, NR-V2X is much better than LTE-V2X in terms of latency where the minimum latency can not be less than 1 ms. In addition, we do not consider the mini slot option provided by NR-V2X, which can further reduce latency by a factor of 7 (even better than 11bd). Finally, considering same modulation and code rate such as 1/2 QPSK, there is no significant difference in terms of latency between 11bd and NR-V2X.

Data Rates: Analytical data rates are defined as the number of data bits transmitted in a given time interval. It directly indicates how many users can be accommodated with a given data rate requirement. In this paper, we consider that a single user is continuously transmitting data. In the case of multi-user operation, data rates can be sub-divided among users. The peak data rates of 802.11 based V2X are highly dependent on the packet size due to the fixed preamble overhead. In case of 100 bytes packet transmissions, the preamble overhead is more significant compared to 1500 bytes packet transmissions. This results in a peak data rate difference of ≈15 Mbps for 11p and ≈23 Mbps for 11bd. Nevertheless, 11bd improves the peak data rate compared to 11p by ≈0.3 Mbps for 100 bytes packet and ≈8 Mbps for 1500 bytes packet. In case of C-V2X, the data rates are less effected by the packet size due to separation of control and data channels. NR-V2X significantly improves the data rate compared to LTE-V2X (≈16 Mbps for 100 bytes packet and ≈13 Mbps for 1500 bytes packet) due to smaller control overhead and higher bandwidth efficiency. Furthermore, NR-V2X is superior in terms of data rates compared to 11bd, four times higher for 100 bytes packet and 7 Mbps higher for 1500 bytes packet.

Summarizing the above discussion, it can be concluded that NR-V2X is expected to be better than 11bd in terms of transmission latency and data rates.

TABLE III
Introduction of Variables and Simulation Parameters

Parameter	**LTE / NR^0**	**NR^2**	**11p / 11bd**
Carrier Spacing	15 kHz	60 kHz	156.25 kHz
Symbol duration	66.7 μs	16.7 μs	6.4 μs
Cyclic prefix	4.69 μs	1.17 μs	1.6 μs
no. of useful sub-carriers	600 / 624	132	52 / 56
Transmit power (P_{tx})	23 dBm		
RX antenna gain (G_{rx})	3 dBm		
TX antenna gain (G_{tx})	3 dBm		
Path loss (L_0)	47.86 dB (at 1 m and 5.9 GHz)		
Loss exponent (α)	2.75		
Noise power (P_n)	-104 dB (over 10 MHz)		
Noise Figure (NF)	9 dB		
Payload size (P_b)	100 bytes (URLLC), 1500 bytes (eMBB)		
Channel model	Urban NLOS [18]		

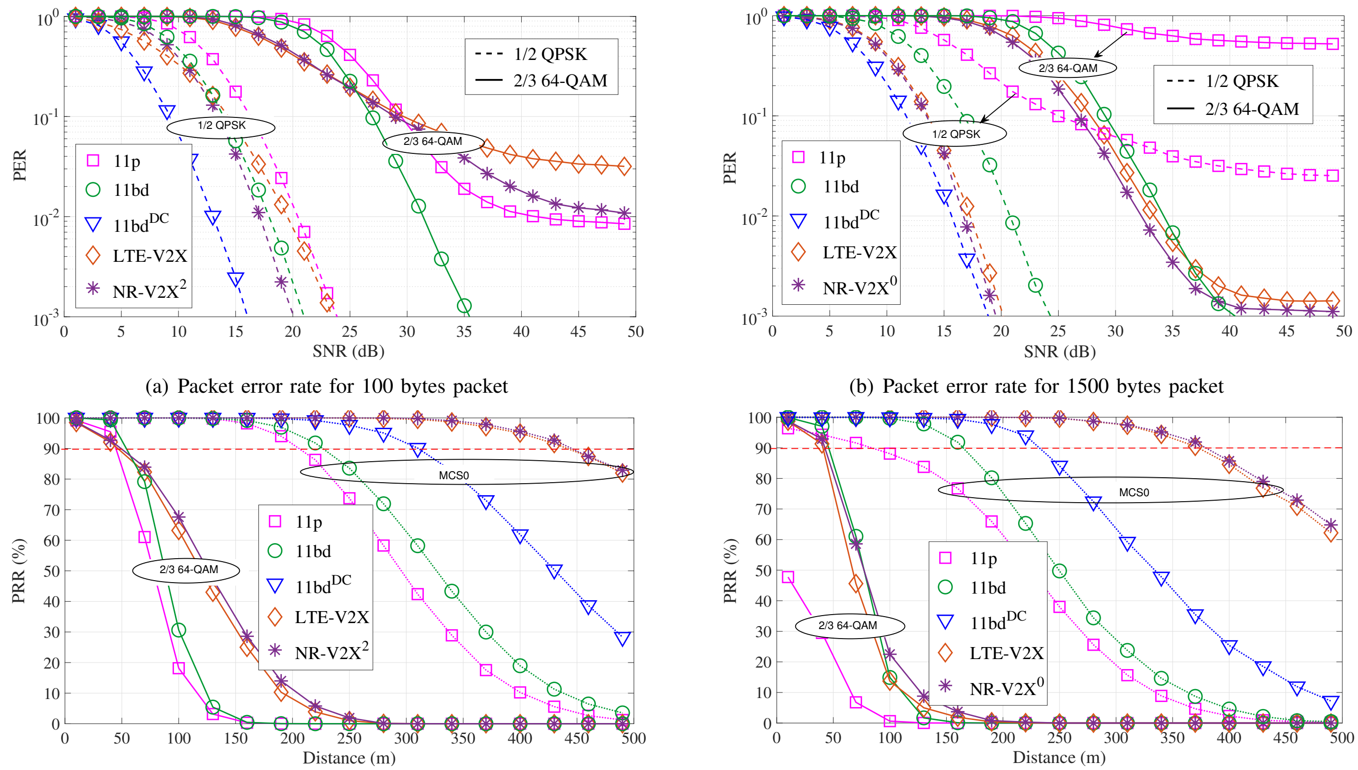
IV. Simulation-based Evaluation

In this section, we evaluate the performance of V2X technologies by modeling their complete PHY features in a MATLAB based simulation framework. The purpose is to obtain realistic performance measurements closer to the real world scenarios. It is worth noticing that no packet re-transmissions or hybrid automatic repeat request (HARQ) techniques are considered. The simulation parameters are summarized in Table III. Existing technologies such as 11p and LTE-V2X are modeled according to the specification provided in the respective standard. The 11bd is modeled based on IEEE 802.11ac standard with 2 times downclock of 20 MHz PHY. Some additional features are also adopted from IEEE 802.11ax such as DCM, extended range, and midambels. The NR-V2X is modeled using the specification provided for NR uplink communications (Release 15). Communications between two vehicles (V2V) are modeled in an urban NLOS street crossing scenario, as described in [18]. The path loss is defined as:

$$\mathrm{PL}(d) = \mathrm{PL}(d_0) + \alpha \cdot 10 \log(\frac{d}{d_0}), \qquad (9)$$

where $\mathrm{PL}(d_0)$ is the reference path loss at 1 m, d is the distance (in meters) between vehicles, and α is the path loss exponent.

This document is a preprint of: W. Anwar, N. Franchi and G. Fettweis, "Physical Layer Evaluation of V2X Communications Technologies: 5G NR-V2X, LTE-V2X, IEEE 802.11bd, and IEEE 802.11p," in Proceedings of IEEE Vehicular Technology Conference (VTC Fall 2019), Honolulu, Hawaii, USA, Sep 2019. DOI:10.1109/VTCFall.2019.8891313



(a) Packet error rate for 100 bytes packet

(b) Packet error rate for 1500 bytes packet

(c) Packet reception ratio for 100 bytes packet

(d) Packet reception ratio for 1500 bytes packet

Fig. 1. PER and PRR of various technologies in Urban NLOS scenario

Packet Error Rate: The packet error rate (PER) is defined as the ratio between erroneously received packets and total transmitted packets. It is the most common metric to evaluate the performance of a receiver in terms of reliability. For ultra-reliable communications a PER $< 10^{-5}$ [19] is required which is conveniently evaluated using PER vs SNR curves.

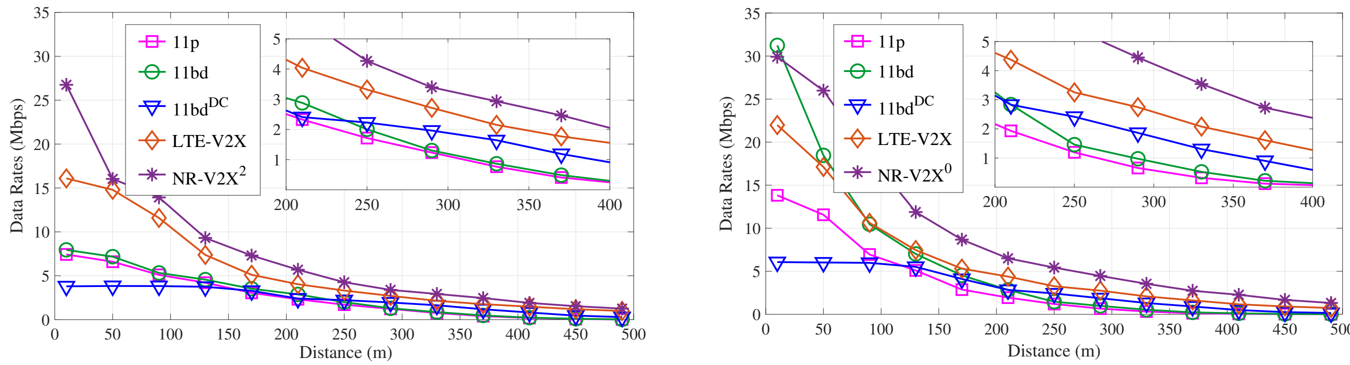
Fig. 1(a) compares PERs of different technologies for a payload of 100 bytes. In case of 1/2 QPSK, the 11p has the worst PER performance followed by LTE-V2X. The 11bd has a $\approx$3dB gain compared to both LTE-V2X and 11p, whereas NR-V2X has a $\approx$0.5 dB gain compared to 11bd. Nevertheless, 11bd^{DC} outperforms all other technologies because of its extended range option ($\approx$3 dB gain) and its diversity gain in frequency selective channels, a $\approx$5 dB gain compared to 11bd and an 8 dB gain compared to 11p. In case of 2/3 64QAM, LTE-V2X has a worse PER due to the fact that the channel estimation at high Doppler shifts becomes outdated. Even though it uses two additional reference symbols compared to LTE-V2X. However, NR-V2X has a slightly better PER performance due to its four times lower subcarrier spacing compared to LTE-V2X, and its better performing LDPC codes compared to Turbo codes. The 11p also suffers as a reason of its preamble based channel estimation. Nevertheless, 11bd outperforms all other technologies due to the use of midambles for channel estimation. Another reason behind bad performance of C-V2X is the flat fading, as only few number of RBs are used for data transmission compared to 11bd which uses whole bandwidth. Therefore, PER curve does not exhibit any error floor and hence best suited for ultra-reliable communications.

The PER for high throughput applications with assumed 1500 bytes packet is plotted in Fig 1(b). It can be observed that the PER performance of 11p is even worse due to its bad channel estimation. Therefore, midambles are used in 11bd where reference symbols are inserted between data symbols for a better channel estimation. The frequency of these midambles depends on the Doppler shift and the chosen MCS. Similar to the 100 bytes case, 11bd^{DC} outperforms all other technologies for 1/2 QPSK and has an almost similar gain over 11bd. However, the difference between the PER performance of LTE-V2X, NR-V2X and 11bd^{DC} is marginal in this case. Furthermore, in case of 2/3 64QAM, 11bd shows a better performance for low PER regions as PER of other technologies geting saturated. One point to be noted is that, both LTE-V2X and NR-V2X perform better for large packet sizes due to the increased error correction capability of both Turbo and LDPC decoders, and frequency diversity due to the use of more RBs.

Packet Reception Ratio: The packet reception ratio (PRR) is defined as the ratio of packets received successfully to the total number of transmitted packets. It is therefore inversely related to PER. The PRR is mostly plotted in a non logarithmic scale and commonly used by vehicular community to evaluate the maximum range of a technology over the distance.

The PRR of different technologies is plotted in Fig. 1(c) for a payload of 100 bytes, using the lowest MCS (MCS0) and 2/3 64QAM. Considering a PRR of 90 % as a threshold,

This document is a preprint of: W. Anwar, N. Franchi and G. Fettweis, "Physical Layer Evaluation of V2X Communications Technologies: 5G NR-V2X, LTE-V2X, IEEE 802.11bd, and IEEE 802.11p," in Proceedings of IEEE Vehicular Technology Conference (VTC Fall 2019), Honolulu, Hawaii, USA, Sep 2019. DOI:10.1109/VTCFall.2019.8891313



(a) 100 bytes packet

(b) 1500 bytes packet

Fig. 2. Average data rates of various technologies in Urban NLOS scenario

we can see that both LTE-V2X and NR-V2X can outperform 802.11 based technologies due to their very low coding rate used for MCS0 (≈ 0.1 as compared to 0.5 in case of 802.11). The 11bd$^{\mathrm{DC}}$ significantly improves the range of 11bd ($\approx 80\,\mathrm{m}$) but still fails to meet the goal set by the 11bd study group (2 times higher range over 11p). However, the range of both LTE-V2X and NR-V2X is 2 times higher than 11p and 11bd. In case of 2/3 64QAM, 11bd performs better than other technologies, although the difference is very marginal. Similar comparison is provided among technologies for a payload of 1500 bytes in Fig. 1(d). It is noted that the maximum range of all technologies is decreased by $\approx 60\,\mathrm{m}$ as compared to the 100 bytes packet case, except 11p. The 11p is affected the most as its range decreases from $210\,\mathrm{m}$ to $80\,\mathrm{m}$. The range in the case of 2/3 64QAM is just slightly effected compared to the 100 bytes packet, except 11p which is already in outage. Overall, considering both packet sizes (100 bytes and 1500 bytes) NR-V2X is the most reliable technology reaching higher range. In addition to that, performance of NR-V2X can be further improved by utilizing HARQ process.

Net Data Rates: The net data rates are defined as the number of data bits received in a certain amount of time measured as bits-per-second (bps). The upper limits of achievable data rates using a certain MCS are provided in Table I & II. Due to the change in distance and fading conditions the SNR varies, which requires link adaptation (to select an appropriate MCS) to maximize the received data rates. We assume ideal link adaptation over distance and average data rates are calculated over hundred random channel realizations.

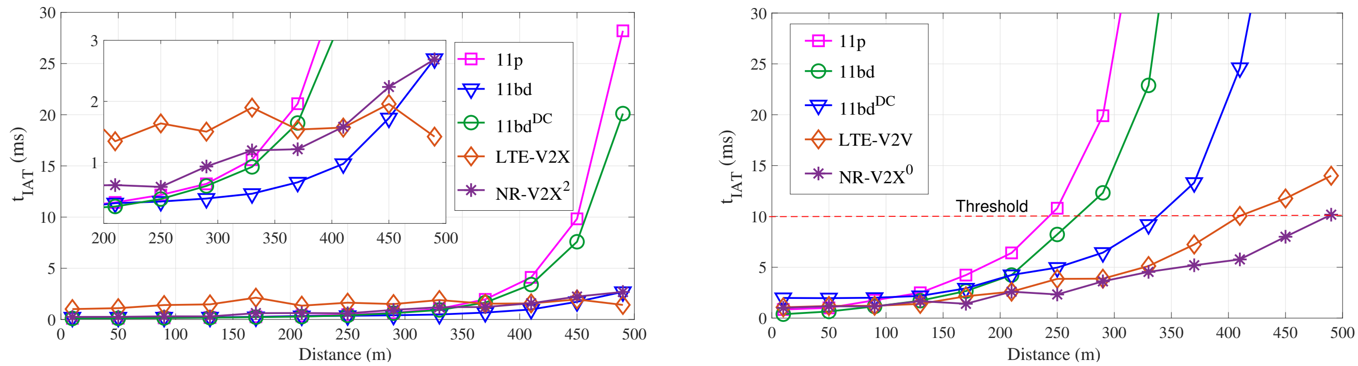
The net data rates over distance are plotted in Fig. 2(a) for a 100 bytes packet. The results show that NR-V2X outperforms all other technologies in terms of throughput followed by LTE-V2X. The throughput improvement of NR-V2X compared to LTE-V2X ($\approx 10\,\mathrm{Mbps}$ at $10\,\mathrm{m}$) is due to its lower overhead and higher reliability. The performance of 802.11 based technologies is greatly effected due to their non neglectable preamble overhead for short packet transmissions. Nevertheless, the 11bd performance is slightly better compared to 11p due to its better channel estimation and channel coding scheme. Furthermore, 11bd$^{\mathrm{DC}}$ outperforms regular 11bd for longer distances ($> 220\,\mathrm{m}$) due to its extended range preamble and frequency diversity mode (DCM). A combination of both can be used for an overall better performance in frequency selective channels, as defined in IEEE 802.11ax (dual carrier and extended range option for lower MCS). Compared to 11bd, NR-V2X has an approx. 3 times higher data rate at $10\,\mathrm{m}$. Further, point to be noted is that C-V2X delivers 1 Mbps even at the range of $500\,\mathrm{m}$ whereas data rates of 802.11 based technologies are already close to zero.

Fig. 2(b) displays data rates for a 1500 bytes packet. Contrary to the previous results, 11bd performance is improved greatly due to a decreased overhead ratio in case of large packet sizes. At a distance of $10\,\mathrm{m}$, 11bd outperforms even NR-V2X but the data rate drops quickly at large distances. The data rates of C-V2X are improved slightly, even though the overhead ratio remains constant. This is due to the use of higher order MCSs, which shows no improvement in data rates for 100 byte packets. Similar to 100 bytes case, the performance of 11bd$^{\mathrm{DC}}$ is better compared to 11bd at large distances due to the same reason as mentioned earlier.

Packet Inter-arrival Time: Packet inter-arrival time (t_{IAT}) is defined as the time between two successive packet arrivals. It is an important measure for closed loop applications which require updates over a regular interval. The packet inter-arrival time depends on the packet transmission time (as described in section II) and on the reliability of the link.

In Fig. 3(a) packet inter-arrival time is plotted for the case of 100 bytes. Results show that for distances $< 350\,\mathrm{m}$, the t_{IAT} of 802.11 based technologies is very small due to their slot-less transmissions and it increases with distance due to the outage. The t_{IAT} in case of LTE-V2X remains between 1-2 ms due to its fixed TTI of 1 ms. However, NR-V2X performs better than LTE-V2X due to its smaller TTI of 0.25 ms and remains close to 11bd$^{\mathrm{DC}}$. It can be concluded that for distances $< 300\,\mathrm{m}$ all technologies can meet 1 ms update interval apart from LTE-V2X. Nevertheless, if the update interval is set to 10 ms then NR-V2X, LTE-V2X, and 11bd$^{\mathrm{DC}}$ can satisfy this requirement up-to a range of 500 m. However, 11bd and 11p can only meet this requirement for distances $< 450\,\mathrm{m}$. The t_{IAT} for a packet size of 1500 bytes is shown in Fig 3(b). Since, this packet size is applicable in case of high throughput applications ultra-low latency is not essential here. Therefore, the target t_{IAT} is set to

This document is a preprint of: W. Anwar, N. Franchi and G. Fettweis, “Physical Layer Evaluation of V2X Communications Technologies: 5G NR-V2X, LTE-V2X, IEEE 802.11bd, and IEEE 802.11p,” in Proceedings of IEEE Vehicular Technology Conference (VTC Fall 2019), Honolulu, Hawaii, USA, Sep 2019. DOI:10.1109/VTCFall.2019.8891313



(a) 100 bytes packet

(b) 1500 bytes packet

Fig. 3. t_{IAT} of various technologies in Urban NLOS scenario

10 ms. Results show that NR-V2X can hold this requirement for distances up-to 490 m, which is 80 m more than LTE-V2X, 150 m more than 11bd$^{\text{DC}}$ and almost double compared to 11p and 11bd. Furthermore, results show that 11bd$^{\text{DC}}$ performs much better than 11bd for higher distances.

Summarizing the above discussions for the 100 bytes packet case, it can be said that 11bd$^{\text{DC}}$ and NR-V2X both can be a good choices for the considered range. In the case of a packet of 1500 bytes, NR-V2X is the only choice for higher range.

V. Conclusions

In this paper, we compared the performance of V2X technologies (i.e., NR-V2X, LTE-V2X, IEEE 802.11bd and IEEE 802.11p) for URLLC and eMBB applications. Based on the theoretical calculations, it can be expected that NR-V2X is superior than IEEE 802.11bd in terms of transmission latency and data rates. Comparisons based on the simulation results show that considering the same modulation and code rate, IEEE 802.11bd performs better than NR-V2X in terms of PER. However, the lowest MCS of NR-V2X is more reliable than the lowest MCS of IEEE 802.11bd. Therefore, NR-V2X can achieve higher range compared to IEEE 802.11bd. Furthermore, NR-V2X outperforms IEEE 802.11bd in terms of net data rates, even though the difference is marginal in the case of eMBB. Finally, NR-V2X is again superior to IEEE 802.11bd in terms of packet inter-arrival time due to more reliable MCS options with lower code rates. Nevertheless, it is shown that IEEE 802.11bd can significantly improve the performance of IEEE 802.11p, specifically in high Doppler scenarios. In addition, the dual carrier modulation and extended range options in IEEE 802.11bd could further improve cell edge performance and range.

Acknowledgment

This work has been supported in part by the Federal Ministry of Education and Research of the Federal Republic of Germany (BMBF) (project 5G NetMobil, funding number 16KIS0688), as well as the Federal State of Saxony and the European Regional Development Fund (ERDF) (project IVS-KOM, funding number 100311749). The authors alone are responsible for the content of the paper.

References

[1] 5G Alliance for Connected Industries and Automation, “5G for connected industries and automation (white paper),” April 2018.

[2] A. Bazzi, B. Masini, A. Zanella, and I. Thibault, “On the performance of IEEE 802.11p and LTE-V2V for the cooperative awareness of connected vehicles,” vol. PP, pp. 1–1, 09 2017.

[3] J. B. Kenney, “Dedicated short-range communications (DSRC) standards in the united states,” *Proceedings of the IEEE*, vol. 99, no. 7, July 2011.

[4] 3GPP: Initial Cellular V2X standard completed, [Accessed on 15th March, 2019]. [Online]. Available: http://www.3gpp.org/news-events//1798v2x_r14

[5] 3GPP: ETSI Work Programme report, [Accessed on 27th February, 2019]. [Online]. Available: http://www.3gpp.org/release-16

[6] S. E. Carpenter and M. L. Sichitiu, “Analysis of packet loss in a large-scale DSRC field operational test,” in *International Conference on Performance Evaluation and Modeling in Wired and Wireless Networks (PEMWN)*, Nov 2016.

[7] X. Huang, D. Zhao, and H. Peng, “Empirical study of DSRC performance based on safety pilot model deployment data,” *IEEE Transactions on Intelligent Transportation Systems*, vol. 18, no. 10, Oct 2017.

[8] W. Anwar, K. Kulkarni, T. R. Augustin, N. Franchi, and G. Fettweis, “PHY abstraction techniques for IEEE 802.11p and LTE-V2V: applications and analysis,” in *IEEE Global Communications Conference (GLOBECOM)*, Abu Dhabi, United Arab Emirates, Dec. 2018.

[9] IEEE 802.11, “IEEE standard - part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications,” *IEEE Std 802.11-2016 (Revision of IEEE Std 802.11-2012)*, pp. 1–3534, Dec 2016.

[10] B. Sun and H. Zhang, “802.11 NGV proposed PAR,” *IEEE 802.11-18/0861r8*, 09 2018.

[11] H. Zhang, R. Cao, Y. Zhang, Y.-L. Chao, and H.-L. Lou, “NGV PHY feasibility discussions,” *IEEE 802.11-18/0860r3*, 05 2018.

[12] 3GPP, “Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures,” 3rd Generation Partnership Project (3GPP), Technical Specification (TS) 36.213, 09 2018, version 15.3.0.

[13] L. Tung and M. Gerla, “LTE resource scheduling for vehicular safety applications,” in *2013 10th Annual Conference on Wireless On-demand Network Systems and Services (WONS)*, March 2013, pp. 116–118.

[14] 3GPP, “Technical specification group services and system aspects; study on enhancement of 3GPP support for 5G V2X services,” 3rd Generation Partnership Project (3GPP), Technical report (TR) 22.886, 09 2018.

[15] 3GPP, “NR; Physical layer procedures for data,” 3rd Generation Partnership Project (3GPP), Technical Specification (TS) 38.214, 09 2018.

[16] 3GPP, “NR; User Equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone,” 3rd Generation Partnership Project (3GPP), Technical Specification (TS) 38.101-1, 09 2018, version 15.3.0.

[17] 3GPP, “NR; User Equipment (UE) radio access capabilities,” 3rd Generation Partnership Project (3GPP), Technical Specification (TS) 38.306, 09 2018, version 15.3.0.

[18] M. Kahn, “V2V radio channel models,” *IEEE 802.11-14/0259r0*, Feb. 2014.

[19] International Telecommunications Union Radiocommunication Sector (ITU-R), “Minimum requirements related to technical performance for imt-2020 radio interface(s),” *Report ITU-R M.2410-0*, 11 2017.