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On the Reliability of NR-V2X and IEEE 802.11bd

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***Abstract*—Ultra-reliable communications enable various advanced use cases, such as autonomous driving and safety critical applications. However, state-of-the-art vehicular communications technologies, such as IEEE 802.11p and LTE-V2X, cannot meet the reliability requirement of all time-critical use cases. Therefore, the next generation of these technologies are being developed to enhance vehicular support for ultra-reliable use cases. In this paper, the reliability of these upcoming vehicular communications technologies (i.e., IEEE 802.11bd and NR-V2X) is analyzed. Even though physical layer standardizations are not yet available, proposed candidate settings are used for investigations. We use Monte Carlo simulations to evaluate the physical layer performance of these technologies in various vehicle-to-vehicle (V2V) scenarios. High Doppler shifts in V2V scenarios is one of the main challenges to enable ultra-reliable communications. It is shown that NR-V2X can be expected to outperform IEEE 802.11bd in terms of reliability due to better handling of Doppler shifts. In case of IEEE 802.11bd, high Doppler shifts cause packet errors even at high signal-to-noise ratios (SNRs). Therefore, different measures to improve the performance of IEEE 802.11bd are discussed and evaluated.**

***Index Terms*—IEEE 802.11p, IEEE 802.11bd, LTE-V2X, NR-V2X, ultra-reliable communications**

I. INTRODUCTION

Nowadays vehicles are heavily equipped with sensors to assist their driver in various situations to increase road safety. Sensors can overcome some human fallibility, since they are not prone to fatigue, deflection or emotion. However, they have limited sight as humans. Establishing communications among road users and infrastructure known as vehicular-to-everything (V2X) will allow information exchange over a much greater distance. Furthermore, V2X enables rapid exchange of information leading to a longer available reaction time in potentially dangerous situations. Especially, in context of autonomous driving, V2X becomes even more important as exchange of information is the key requirement for safe and reliable operation.

The very first V2X standard IEEE 802.11p was introduced in 2010 based on the wireless local area network (WLAN) standard IEEE 802.11a. The amendment 802.11p introduced changes to the physical layer (PHY) and medium access control (MAC) layer of 802.11a to improve the performance of classical WLAN for vehicular applications. An alternative to IEEE 802.11p is the long term evolution (LTE) based cellular V2X standard (LTE-V2X) introduced by the 3rd Generation Partnership Project (3GPP) in 2016. Both technologies are suitable for basic safety use cases, e.g., road work and emergency break warnings, traffic light information and emergency vehicle notifications. To address more advanced use cases, IEEE and 3GPP are both working on the next generations of V2X technologies. A task group called IEEE 802.11 next generation V2X (NGV) was established to create a new amendment IEEE 802.11bd, the successor of 802.11p. It is expected that the next cellular V2X standard based on the fifth generation (5G) of mobile communications system will be finalized till the end of 2019 within Release 16. Since 5G is also known as new radio (NR), the upcoming V2X standard is denoted in the following as NR-V2X.

The state-of-the-art technologies 802.11p and LTE-V2X were recently analyzed in various publications and field trials [1]–[5]. A first performance comparison in terms of expected throughput, latency and reliability of these upcoming technologies (i.e., 802.11bd and NR-V2X) was published in [6]. However, more advanced control applications, e.g., cooperative adaptive cruise control (CACC) or safety critical applications, need to be investigated separately. These applications demand strict requirements towards transmission latency and reliability on the communications system. Achieving reliable communications is especially challenging for vehicular applications due to fast changing nature of the wireless channel which results in a quickly outdated channel estimation. In addition, due to high Doppler shift in V2X scenarios inter-carrier interference (ICI) becomes a bottleneck. As Doppler shift substantially varies from one scenario to another, such as urban line-of-sight (LOS) to highway LOS, hence, a separate evaluation is required for each scenario.

In this paper, we evaluate the PHY performance of upcoming V2X communications technologies (i.e., 802.11bd and NR-V2X) in terms of packet error rates (PERs). The PER is commonly used to characterize receiver performance in terms of reliability. Moreover, in low latency applications reliability can play an important role, as in such applications retransmissions cannot be used due to strict latency requirements. In this work, it is shown that in the case of 802.11bd high Doppler shifts can lead to packet errors, even at high signal-to-noise ratios (SNRs). This is caused by outdated channel estimations in combination with deep fades. To improve the channel estimation, midambles are utilized to prevent saturation effects. It is shown that the periodicity of mi-

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TABLE I

MCS OPTIONS, ACHIEVABLE DATA RATES, AND LATENCIES FOR A PACKET SIZE OF 300 BYTES

IEEE 802.11bd					NR-V2X					
MCS	Modulation	Code rate	Data rate	Latency	MCS	Modulation	Code rate	N_{PRB}	Data rate	Latency
0	BPSK	1/2	3.05 Mbps	0.788 ms	0	QPSK	0.117	69	1.41 Mbps	1.75 ms
1	QPSK	1/2	5.71 Mbps	0.420 ms	7	QPSK	0.514	17	6.07 Mbps	0.50 ms
2	QPSK	3/4	8.22 Mbps	0.292 ms	10	16-QAM	0.332	12	8.10 Mbps	0.50 ms
3	16-QAM	1/2	10.17 Mbps	0.236 ms	13	16-QAM	0.478	9	10.79 Mbps	0.25 ms
4	16-QAM	3/4	13.95 Mbps	0.172 ms	16	16-QAM	0.643	7	13.88 Mbps	0.25 ms
5	64-QAM	2/3	17.14 Mbps	0.140 ms	21	64-QAM	0.650	5	19.43 Mbps	0.25 ms
6	64-QAM	3/4	18.18 Mbps	0.132 ms	23	64-QAM	0.754	4	24.29 Mbps	0.25 ms
7	64-QAM	5/6	19.35 Mbps	0.124 ms	24	64-QAM	0.803	4	24.29 Mbps	0.25 ms
8	256-QAM	3/4	22.22 Mbps	0.108 ms	26	64-QAM	0.889	3	32.38 Mbps	0.25 ms
9	256-QAM	5/6	24.00 Mbps	0.100 ms	27	64-QAM	0.926	3	32.38 Mbps	0.25 ms

dambles needs to be adapted according to the vehicular speed. To further improve the performance of 802.11bd in low SNR regions, we propose to adopt IEEE 802.11ax defined features, such as an extended range preamble and dual carrier modulation (DCM). Finally, the performance gain of 802.11bd after utilizing these options is evaluated and compared against NR-V2X.

II. TECHNOLOGY OVERVIEW

In this section, the most likely PHY enhancements of the upcoming V2X standards (i.e., 802.11bd and NR-V2X) as compared to their predecessors are discussed.

A. *IEEE 802.11bd*

IEEE 802.11p, introduced in 2010, is an amendment to the IEEE 802.11a standard. Since then a variety of PHY options were made available for WLAN systems, which need to be adopted for V2X communications. It can be expected that the upcoming V2X standard 802.11bd will be based on existing and proven WLAN technologies e.g., IEEE 802.11ac, utilizing available PHY options [7].

In recent 802.11 standards PHY throughput was mainly enhanced by enabling higher order modulation and coding schemes (MCSs), more bandwidth options using carrier aggregation, multiple input multiple output (MIMO) transmissions and low density parity check (LDPC) codes, which are more efficient at larger payloads in terms of data rates and reliability. Reliability was further enhanced by introducing diversity options such as space time block coding (STBC) or DCM. STBC is an antenna diversity option enabling two signal branches on transmitter side, whereas DCM is a frequency diversity option utilizing two signal branches. In case of DCM, the bandwidth of one user is split in two halves which are then used for redundant data transmissions, a useful technique in frequency selective channels (coherence bandwidth $\ll$ channel bandwidth). Multiple cyclic prefix (CP) options enable scenario specific selection for inter symbol interference prevention and therefore make 802.11 standards more suitable for outdoor environments. A higher periodicity of channel estimation using midambles is now possible and allows better handling of high Doppler shifts. Furthermore, an extended range option is available, which boosts the power of synchronization and channel estimation fields and repeats certain signaling fields of the preamble to achieve higher range and reliability.

According to the 802.11bd project authorization report [7], following PHY parameters and enhancements are in consideration:

- carrier modulation scheme: orthogonal frequency-division multiplexing (OFDM)
- subcarrier spacing: $156.25\,\text{kHz}$ and $78.125\,\text{kHz}$
- CP durations: $1.6\,\mu\text{s}$ and $3.2\,\mu\text{s}$
- channel coding: LDPC
- lowest rate: MCS0 (1/2 BPSK) possibly utilizing range extension mode
- highest rate: MCS9 (5/6 256-QAM)
- target speed: $250\,\text{km/h}$
- Doppler recovery method: high density midambles
- DCM: diversity option to improve performance

In Table I, MCS options of the expected 802.11bd standard are listed. In addition, achievable data rates and transmission latencies are provided for a packet size of 300 bytes. The procedure of calculating these values is described in [6].

B. *NR-V2X*

The first cellular V2X standard (i.e., LTE-V2X) was completed by 3GPP in 2016 with Release 14 [8]. Since then enhancements are being made with each further release. Major changes are expected with the upcoming 5G NR standard in which new V2X use cases and requirements are already identified [9]. 3GPP specifications for NR-V2X are expected to be finalized at the end of 2019 with Release 16. However, based on the candidate settings of the PHY [10], it is expected that NR-V2X will be oriented on the NR uplink (Release 15). As NR uplink specifications are already available, a simulation framework for NR-V2X can be designed.

The main enhancement on the PHY layer of NR uplink compared to LTE is that both DFT-spread-OFDM (DFT-s-OFDM) and OFDM can be used for data transmission. OFDM provides higher throughput efficiency for wide-bandwidth operations with lower implementation complexity and hence is more suitable for high

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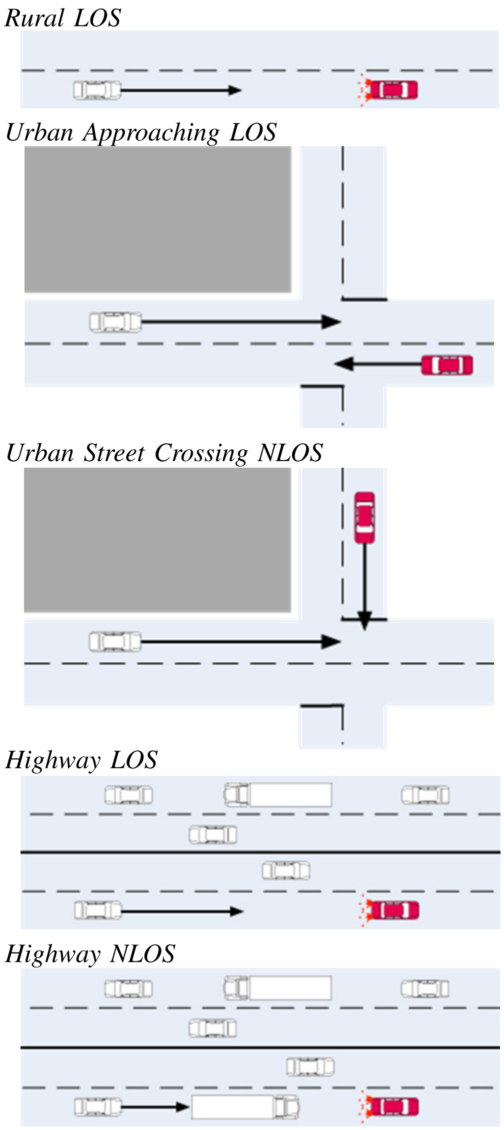
throughput applications. However, in the case of low budget devices where high power efficiency is required, DFT-s-OFDM is a better choice due to its low peak-to-average power ratio (PAPR). Another enhancement introduced in NR is scalable OFDM numerologies, allowing to choose between different subcarrier spacings from 15 kHz up to 480 kHz. In conjunction to these numerologies, the slot duration also varies from 1 ms down to 0.031 ms. Contrary to LTE, the minimum transmission time interval (TTI) in NR is equal to one slot duration. In addition, for low latency communications a mini-slot option is provided to transmit data using just 2, 4, or 7 OFDM symbols without any slot boundaries. Scalable numerologies, along with variable CP durations in NR, provide the required application and environment specific adaptability.

NR also provides various de-modulation reference signals (DMRSs) configuration options for better channel recovery under frequency and time selective channels. As channel coding has significant impact on transmission reliability and throughput of a wireless technology, more efficient and reliable coding techniques are adopted, i.e., LTE turbo codes are replaced by LDPC codes for data channels and LTE convolutional codes are replaced by cyclic redudency check (CRC) aided polar codes for the control channel. Moreover, NR is capable of utilizing the millimeter wave spectrum with frequencies above 24 GHz as well as frequencies below 6 GHz. The maximum bandwidth available to a user in NR is 100 MHz for the sub 6 GHz band, and 400 MHz for the millimeter wave spectrum, which is much higher than the bandwidth of 20 MHz available in LTE. Due to the large available bandwidth, higher peak data rates will be possible to achieve or higher number of users will be accommodated. All above described features make NR more reliable, flexible, and throughput efficient compared to LTE.

The available MCS options for NR uplink are provided in [11, Table 6.1.4.1-1]. Achievable data rates and transmission latency values for a packet size of 300 bytes are provided for selected MCS options in Table I. Calculation of these values are described in [6].

III. V2V SCENARIOS AND CHANNEL MODELS

A set of vehicle-to-vehicle (V2V) channel models are introduced by the 802.11 dedicated short range communications (DSRC) group for performance evaluation and testing [12]. The channel models are derived based on three measurement campaigns carried out by different organizations in five common V2V scenarios, shown in Fig. 1. These channel models are used by the 802.11bd study group for performance evaluation and as a base reference for further enhancements. The measured RMS delay profile and Doppler of these channel models are summarized in Table II.


Rural LOS

Urban Approaching LOS

Urban Street Crossing NLOS

Highway LOS

Highway NLOS

Fig. 1. IEEE 802.11 DSRC group defined V2V senarios [12]

A. Rural LOS

This channel model realizes the communications between two vehicles in an open environment. As in rural areas line of sight (LOS) communications is generally possible due to the absence of other vehicles, large fences, and buildings. Therefore, the obtained delay profile shows a strong LOS component with a few weak multi-path components and a maximum Doppler shift of 490 Hz.

B. Urban Approaching LOS

In this channel model communications between two approaching cars in an urban street is modeled. Due to buildings and a high density of vehicles strong reflections and multi-path fading can be observed. From measurements, it can be seen that reflected components with higher power are available as compared to the rural LOS scenario.

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TABLE II
IEEE 802.11 DSRC GROUP DEFINED CHANNEL MODEL PARAMETERS

V2V Scenario	Power (dB)	Delay (ns)	Doppler (Hz)
Rural LOS	[0 -14 -17]	[0 83 183]	[0 492 -295]
Urban Approaching LOS	[0 -8 -10 -15]	[0 117 183 333]	[0 236 -157 492]
Urban Crossing NLOS	[0 -3 -5 -10]	[0 267 400 533]	[0 295 -98 591]
Highway LOS	[0 -10 -15 -20]	[0 100 167 500]	[0 689 -492 886]
Highway NLOS	[0 -2 -5 -7]	[0 200 433 700]	[0 689 -492 886]

C. Urban Street Crossing NLOS

Communications between two vehicles approaching an urban blind street crossing with other traffic present is realized here. Buildings and fences are expected to be present at all corners which will lead to reflections and a strong multi-path components. Due to the absences of a dominant LOS component and very small power difference among reflected multi-path components strong fading is expected.

D. Highway LOS

This scenario mimics the communications between two vehicles following each other on multilane inter-region roadways such as motorways. Even though high density traffic, signs, hill sides and overpasses are present, LOS communications is still possible. However, a higher Doppler shift compared to previous scenarios can be expected due to high differential speeds between approaching vehicles.

E. Highway NLOS

This scenario is similar to the highway LOS case except that a truck is in between communicating vehicles and blocking the LOS path. As no strong reflecting objects are available for longer periods, due to high vehicular speeds, strong degradation and variations in link quality can occur. It is the most challenging scenario among all above discussed scenarios, due to NLOS communications, strong multi-path components, and fast fading due to high Doppler.

IV. PERFORMANCE EVALUATION

Theoretical calculations given in Table I can be used to compare the considered technologies in terms of maximum achievable data rates and transmission latencies for a packet size of 300 byte. The procedure to obtain these values is explained in [6]. From calculations, it can be concluded that NR-V2X is superior in terms of peak data rates (a difference of 8 Mbps can be observed). Considering transmission latency, IEEE 802.11bd is better compared to NR-V2X due to its shorter packet duration. However, these values are obtained considering that all packets are delivered successfully, which is not the case in reality. The actual throughput and latency can be obtained by scaling these values with the probability of successful transmission, which is a function of receive SNR, MCS, and channel conditions. In this section performance is evaluated in terms of PERs (inverse of probability of success) in above defined V2V channel models. As high reliability is an essential requirement for V2X applications, it is important to know which technology is more reliable under different channel conditions. Moreover, low latency applications also need to be highly reliable, as retransmission of data cannot be supported. Although, NR defines hybrid automatic repeat request (HARQ) procedure to improve reliability, it is not considered here due to strict latency requirements.

In order to compute the PER, complete PHY layer functional blocks are implemented in MATLAB for respective technologies. The fast fading and multi-path effects (in addition to additive white Gaussian noise (AWGN)) for V2V channel models defined in Section III are realized using Rician distribution. In case of NR-V2X, DMRS mapping type A with 3 additional reference symbol is used with a maximum length of 1 [13]. Using the given scheme, 24 DMRS symbols are used inside a time slot (on every 3rd OFDM symbol in time and on alternative subcarrier in frequency). Due to the high density of DMRS, better channel estimation is possible. The other relevant simulation parameters are summarized in Table III.

Two combinations of modulation and coding rate are used for comparison. We compare the lowest available MCS option (MCS0) in both standards (i.e., QPSK with 0.12 code rate in NR-V2X and 1/2 BPSK in 802.11bd) which also defines the range of a technology. For the sake of fair comparison, we also compare them for 1/2 16QAM which corresponds to MCS13 in NR-V2X and MCS3 in 802.11bd. The point to be noted here is that both technologies use an adoptive MCS procedure to find the appropriate MCS option according to the channel conditions. However, to analyze all MCS options is beyond the scope of this paper, as both metrics reliability and throughput efficiency are required to be considered. Therefore, we limit our analysis to only two MCS options which are more relevant to achieve ultra-reliable communications. Furthermore, in case of ultra-reliable communications, a PER $< 10^{-5}$ (10^{7} packet transmissions) is required to be evaluated, which is difficult to achieve through PHY simulations in a limited time. Therefore, our evaluation is limited to PER $= 10^{-3}$ (10^{5} packet transmissions). However, lower PER values can be predicted by extrapolating the available curves.

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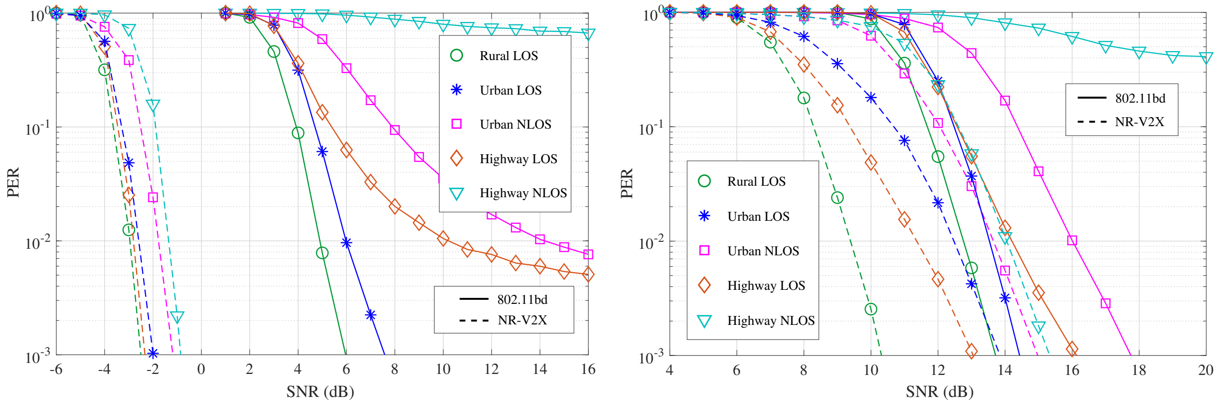

(a) PER performance with MCS0

(b) PER performance with 1/2 16QAM

Fig. 2. Comparison of technologies in various V2V scenarios

TABLE III
VARIABLES AND SIMULATION PARAMETERS

Parameter	NR-V2X	802.11bd
waveform	DFT-s-OFDM	OFDM
carrier Spacing	60 kHz	156.25 kHz
symbol duration	16.7 µs	6.4 µs
cyclic prefix	1.17 µs	1.6 µs
no. of useful sub-carriers	132	56
used MCS options	MCS0, MCS13	MCS0, MCS3
equalization method	MMSE	
payload size (P_b)	300 Byte	
channel bandwidth	10 MHz	
carrier frequency	5.9 GHz	
Doppler shift (f_d)	variable (0 - 1000 Hz)	

A. PER comparison with lowest MCS

Fig. 2(a) plots the PER for the lowest MCS (i.e., MCS0) of both technologies in above described V2X channel models. It is worth to be noted that as both technologies define different combinations of modulation and coding rate, the maximum achievable data rates will be different as provided in Table I.

From results, it is observed that NR-V2X performs equally well in all V2V channel models and its PER is marginally effected by different delay profiles and Doppler shifts. However, the PER in case of 802.11bd varies much depending on the channel type. NR-V2X has ≈ 9 dB gain compared to 802.11bd in case of the rural LOS scenario and ≈ 10 dB in case of the urban approaching LOS scenario. For all other investigated scenarios PER of 802.11bd gets saturated since the channel estimation gets outdated over the course of a packet. This saturation occurs when the ratio between packet duration and coherence time is larger or close to one. In other words, if the packet duration is larger than the coherence time of the channel, the channel estimation is not valid for symbols at the end of the packet anymore. The influence of this outdated channel estimation depends on the current fading depth. If no deep fade occurs a small absolute deviation of the channel estimation from its ideal value can be observed. However, in combination with a deep fade this absolute deviation results in a big relative error which then causes a packet error. To improve the performance in fast varying channels, midambles can be utilized which are investigated later in this section. Furthermore, other techniques to reduce the probability of deep fades, e.g., diversity can be used.

Contrary to 802.11bd, DMRSs are embedded inside the data for channel estimation in NR-V2X. Furthermore, NR-V2X provides various configurations of DMRSs depending on the time and frequency selectivity of the channel which leads to better channel estimation. Another reason behind the excellent performance of NR-V2X is its lower code rate of 0.12 as compared to 0.5 in case of 802.11bd. Overall, it can be concluded that NR-V2X is expected to achieve higher transmission range and reliability compared to 802.11bd in the case of MCS0.

B. PER comparison with 1/2 16QAM

In order to have a fair comparison between technologies, equal modulation and coding rate is applied here. Fig. 2(b) shows the PER achieved by technologies with 1/2 16QAM in different V2V channel models. Even though the difference between NR-V2X and 802.11bd is reduced considerably compared to MCS0, NR-V2X still outperforms 802.11bd for all scenarios. NR-V2X has a gain of ≈ 3 dB compared to 802.11bd for the rural LOS, highway LOS and urban crossing NLOS scenario. However, the gain in case of the urban approaching LOS channel model is just ≈ 1 dB and when using the highway NLOS channel model the PER of 802.11bd gets saturated due to a bad channel estimation as explained earlier. Nevertheless, the performance of 802.11bd with 1/2 16QAM is much better compared to MCS0 for the highway LOS, highway NLOS and Urban crossing NLOS channel models. The reason behind this improvement is the reduced packet duration by a factor of four as peak data rates are four times higher when using 1/2 16QAM compared to MCS0 (1/2 BPSK). The reduced packet duration leads to a better performance in 802.11bd preamble based channel estimations as the

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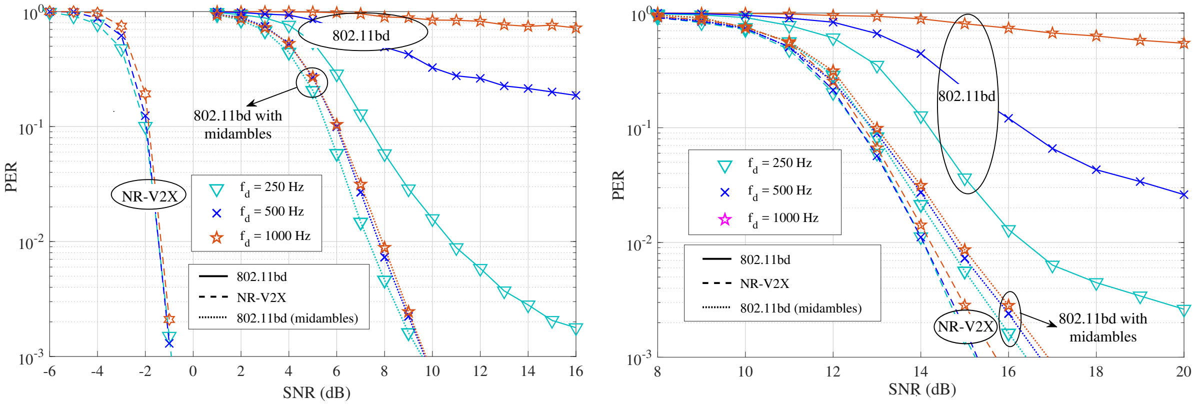

(a) PER comparison with lowest MCS (MCS0)

(b) PER comparison with 1/2 16QAM

Fig. 3. Performance of technologies with variable Doppler shift (f_d)

ratio between packet duration and coherence time is reduced. If this ratio is $<< 1$, no saturation will occur due to channel estimation. For the highway NLOS scenario this ratio is higher than 1 as 50% coherence time (often approximated as $\frac{9}{16\pi * f_d}$) [14] is 202 µs which is less than the packet duration of 236 µs.

The reasons behind the better performance of NR-V2X for the same constellation and code rate are again better channel estimation and the use of DFT-s-OFDM. DFT-s-OFDM provides better PER performance compared to OFDM under frequency selective fading, since the symbol energy is spread over the whole bandwidth.

C. Channel estimation under varying Doppler shifts

In previous subsections, it is observed that the 802.11bd performance is strongly effected by Doppler shift in conjunction with preamble based channel estimations. Therefore, to improve the performance midambles are being considered, where channel estimation symbol (known as midamble) are repeated inside data to obtain current channel estimation, as shown in Fig. 4. The periodicity of midambles need to be adapted according to the differential speed of the communicating vehicles. As a low frequency of midambles will lead to channel estimation errors and a high frequency of midambles will increase the packet duration (inversely related to the data rates). In order to evaluate technologies under varying Doppler shifts, we selected the highway NLOS scenario which is also the worst case scenario. The Doppler profile of the channel is scaled for three maximum Doppler shift values, which are 250 Hz, 500 Hz and 1000 Hz. In the case of 802.11bd two settings are assumed, one without midambles and another with adaptive midambles. The periodicity of midamble is 10, 5 and 3 OFDM symbols for 250 Hz, 500 Hz and 1000 Hz respectively. In this way, the midamble periodicity is roughly equal to 90 % of the coherence time for all three Doppler shifts [14].

Fig. 3(a) plots the PER when using MCS0 under various Doppler shifts. It is observed that NR-V2X is very robust against Doppler shifts due to better channel estimation and a very low code rate. The better channel estimation in NR-V2X is achieved through high density DMRS along with moving average channel estimation window to overcome channel estimation errors. Although high Doppler shifts induce ICI but for lower SNR values noise is more dominant. Hence, ICI is not relevant for considered MCS. As indicated earlier, the 802.11bd performance deteriorates with increasing Doppler shifts due to outdated channel estimations. The use of adaptive midambles greatly improves the performance of 802.11bd and helps to overcome the channel estimation error floor. Given that the periodicity of midambles is sufficiently large compared to the coherence time of the channel. Even though midambles help to avoid PER saturation in 802.11bd, still a 10 dB difference can be observed compared to NR-V2X.

A similar comparison is provided in Fig. 3(b) for the case of 1/2 16QAM. Again it is evident from the presented results that high reliability with 802.11bd is only possible with the use of midambles. Even with equivalent modulation and coding rate, NR-V2X has a gain ≥ 1 dB for all Doppler shifts. Furthermore, it is observed that ICI becomes more noticeable at higher SNR values. Hence, PER difference between the technologies increases for different values of Doppler shifts with the increase of SNR.

D. Effects of DCM and extended range option

In the previous subsection, we have shown that the addition of midambles can significantly improve the performance of the assumed 802.11bd standard. It still needs at least 10 dB SNR to achieve a PER of 10^{-3} whereas NR-V2X can achieve the same target with a SNR of less than 0 dB. In order to further improve the performance of 802.11bd in low SNR regions and to meet the goal of two times higher range compared to 802.11p, options such as the range extension mode and DCM can be adopted from 802.11ax. When using the range extension mode a signaling field is repeated twice

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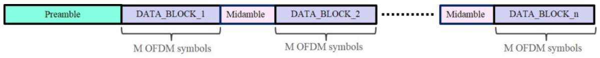

Fig. 4. IEEE 802.11bd packet with midambles

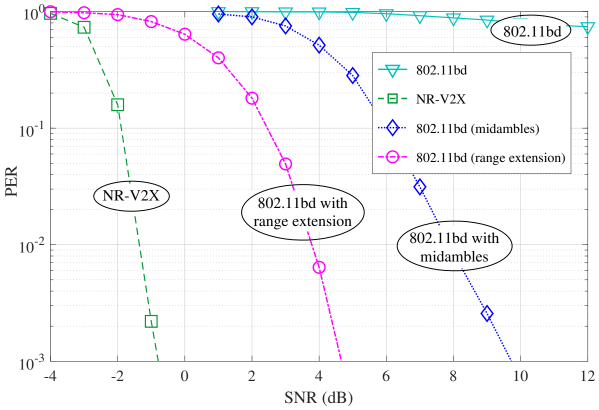

Fig. 5. Performance of 802.11bd with DCM and range extension mode

and the power of certain preamble fields are boosted which improves the receiver sensitivity by 3 dB. When using DCM the data is duplicated on the lower and upper half of the available subcarriers to benefit from frequency diversity in frequency selective channels. IEEE 802.11ax provide these options for lower order MCSs to improve cell edge performance. The performance improvement by enabling these options in 802.11bd is the focus of discussion in this section.

The performance gain of 802.11bd using the range extension mode and DCM is shown in Fig. 5. 802.11bd shows ≈ 5 dB gain after enabling these options. Spectral efficiency of NR-V2X with MCS0 is halved compared to 802.11bd with MCS0. After enabling DCM, spectral efficiency of 802.11bd reduces by a factor of two and becomes equal to NR-V2X MCS0. Although DCM and range extension mode improve the performance of 802.11bd by 5 dB, NR-V2X needs 5 dB less SNR to achieve a similar PER with equal spectral efficiency. As with DCM spectral efficiency reduces by a factor of two. Therefore, other diversity options can be utilized to achieve a similar gain without the expense of a reduced spectral efficiency, such as STBC or receive diversity. When using receive diversity, antennas are placed sufficiently apart so that, received signals at both antennas exhibit uncorrelated fading.

V. CONCLUSIONS

This paper compared the PHY performance of upcoming V2X communications technologies in various V2V scenarios in terms of transmission reliability. The results shows that, the NR-V2X is superior in terms of transmission reliability, whereas 802.11bd is severely effected by Doppler shifts. Furthermore, we showed that midambles significantly improve the performance of 802.11bd under high Doppler shifts given that the midamble periodicity is much lower than the channel coherence time. In addition, we showed that DCM and range extension mode further improve the performance of 802.11bd. Although midambles, extended range preamble and DCM were shown to improve the reliability of 802.11bd, it still cannot outperform NR-V2X. The reasons behind are the better channel estimation technique, lower code rates and DFT-s-OFDM. The future work will focus on designing analytical methods such as PHY abstraction to extend the comparison to other target applications and scenarios.

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