

Design of V2X Communications Based on 5G NR: a Physical Layer Perspective^{*}

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Abstract. The call for high performance vehicular-to-everything (V2X) connectivity for automotive applications has spurred the considerable development of several standards, where the 5G New Radio (NR) is playing definitely an essential role. In this paper, after briefly reviewing the basics of the NR physical layer, we first evaluate by simulation the performance of NR-based V2X communication links for the NR modulation and coding scheme (MCS) options, and then, such outcomes are exploited to perform the link design for realistic wireless scenarios. Our results show considerable performance gains when the proper MCS is adopted, thus motivating the need for suitable resource allocation algorithms.

Keywords: 5G NR · NR-V2X · Packet error rate performance evaluation · Link design.

1 Introduction

Future networks will have to provide broadband every-where and every-time connectivity to support a diverse range of services and applications including everything from voice, 3D video, virtual and augmented reality, safety, emergency, factory automation, self-driving cars, smart city. The demand for high performance connectivity has gained a considerable ever increasing interest also from the automotive area about what is called as Vehicular-to-Everything (V2X) communications. In the recent years, indeed, this has motivated the development of several yet different standards, such as IEEE 802.11p, 802.11bd, LTE-V2X [1]. However, the stringent requirements for advanced V2X applications has brought to give a significative emphasis to the newer standard based on 5G New Radio (NR), also known as NR-V2X [2]. 5G NR fully satisfies the required demanding features of the automotive applications, its components being designed to enable flexibility, ultra-lean factor, backward and forward compatibility, low-latency, ultra-reliability, greater coverage, low error performance, high data rates and the exploitation of new higher frequency bands such as millimeter wave (mm-Wave) [3].

Contributions.

1. A brief overview of 5G NR PHY layer to emphasize some key features, as frequency bands, modulation and channel coding, multiple numerology, and time-frequency domain signalling, which are useful in the following sections.
2. The evaluation of the packet error rate (PER) performance for the Infrastructure to Vehicular (I2V) and Vehicular to Infrastructure (V2I) communication links employing

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the NR modulation and coding scheme (MCS) options, based on the simulation of the overall communication system over realistic wireless scenarios.

3. The design of the I2V and V2I links through combining the link budget equation with the PER performance obtained by the simulation runs, from which it can be deduced the need of adaptive resource allocation matched to the time-varying mobile environment.

2 Overview of 5G NR PHY Technology

According to the 3GPP specifications defined in Release 16, the design of the 5G NR physical layer (PHY) is based on up-to-date key techniques, [4], [5], such as: *i*) efficient channel coding, *ii*) hybrid-ARQ (HARQ) soft combining, *iii*) error detection and signalling to the upper layers, *iv*) rate matching to the channel available resources, *v*) multicarrier modulation, *vi*) Multiple-Input Multiple-Output (MIMO) antennas, with the aim of enabling high system performance, notable flexibility and both backward and forward compatibility. Next, brief insights into some of the main PHY features are detailed.

RF Frequency Bands. The 5G spectrum can be basically classified into two ranges, the Frequency Range 1 (FR1) covering all the frequency bands lower than 6 GHz, and the Frequency Range 2 (FR2) including the new frequencies from 24.25 to 52.6 GHz, the so-called millimeter wave (mm-Wave).

Specifically, the low-frequency bands are the ones up to 2 GHz, which were previously used for the LTE transmissions. They offer wide coverage areas and 20 MHz wide bandwidths. The medium-frequency bands are in the range 3–6 GHz, with larger bandwidths till 100 MHz, thus allowing higher levels of capacity and data rates. The high-frequency bands are above 24 GHz with bandwidths up to 400 MHz. In view of the adverse propagation properties incurred in such frequency interval, however, they can not be used for wide coverage but only for ultra-small cells (hotspots), though giving remarkable throughput performance.

OFDM Modulation and Channel Coding. In order to enhance the spectral efficiency and the ease of implementation, Orthogonal Frequency Division Multiplexing (OFDM) is adopted as standard modulation format for both downlink (DL) and uplink (UL) transmissions, using either Time Division Duplexing (TDD) or Frequency Division Duplexing (FDD). Herein, the data stream is mapped onto different subcarriers belonging to the available bandwidth, with QPSK, 16-QAM, 64-QAM, and 256-QAM as possible modulation schemes. As alternative choice to the cyclic-prefix (CP) based OFDM, the DFT-spread-OFDM (DFT-s-OFDM) may be employed in the UL to reduce the peak-to-average power ratio (PAPR), which is useful when power efficiency is required.

As for the channel coding, the low density parity check (LDPC) and the cyclic redundancy check (CRC) aided polar codes are proposed for the data channel and the control channel, respectively. The LDPC code covers a wide range of coding rates and block sizes, and supports incremental redundancy (IR) HARQ techniques as well. On the other side, polar coding has been shown as the best performed short code with low algorithmic decoding complexity.

Numerology and Subcarrier Spacing. One of the key aspect of the 5G NR is the selection of a multiple numerology for the subcarrier spacing Δf , as given by

$$\Delta f = 2^\mu \cdot 15 \text{ kHz}, \quad \mu = 0, \dots, 4, \quad (1)$$

that allows the flexibility of addressing different spectrum, bandwidth, scenarios and services with varying requirements. Hence, the minimum spacing amounts to 15 kHz, the one employed for LTE, to ensure backward compatibility. According to the adopted NR numerology, each value of subcarrier spacing defined in (1) corresponds to a given duration of the CP and the useful symbol interval as shown in Sect. (3). Further, (1) is such that the duration in the time domain of one OFDM symbol includes a number of OFDM symbols at higher spacing obtained as a power of two.

Structure in Time and Frequency Domain. The transmission of NR physical signals in the time domain is based on 10 ms long frames, which are divided into ten 1 ms long subframes. The flexibility is reached by dividing each subframe into a variable number of slots depending on μ in (1), while each slot contains a fixed number of 14 OFDM symbols. To achieve flexibility also in the frequency domain, the NR standard introduces the resource element as the smallest physical resource, one OFDM symbol upon one subcarrier, the resource block, 12 consecutive subcarriers upon one OFDM symbol, and the resource grids, each consisting (depending on μ) of a multiple of 12 consecutive subcarriers and some OFDM symbols.

3 V2X Communication Model

3.1 System Model

In the V2X communication system we are dealing with, a *packet*, usually corresponding to an IP packet or a layer 3 control signalling message, is taken as the basic information to be transmitted over the radio interface. At the transmitter side, packet-processing is first performed, then followed by frame processing. The packet-processing is based on: *i*) one-to-one mapping of each input packet to a radio link control (RLC) sub-layer protocol data unit (PDU), including a CRC sequence for error detection and the payload received from upper layers¹, *ii*) coding each RLC PDU according to the schemes illustrated in Sect. 2 depending on the logical channel to be delivered, *iii*) rate matching by puncturing to select a specific set of encoded bits suitable to the available channel resources, and *iv*) proper interleaving. The frame processing section performs the mapping of the coded and interleaved sequence to the symbols of the adopted QAM constellation and the IFFT-based OFDM modulation. Hence, for each input packet, a frame of OFDM symbols is obtained which conveys the information for the end-user. The resulting OFDM frame signal is thus transmitted over a mobile frequency-selective time-varying multipath channel. Then, the received signal undergoes OFDM demodulation, zero-forcing equalization, soft demapping, deinterleaving and eventually is decoded.

¹ If the input bit sequence is larger than the maximum LDPC block size (8448 or 3840), segmentation is performed and an additional CRC is attached to each block.

Table 1. MCS options and data rates for LDPC and Polar coding.

MCS	Modulation	Code rate	LDPC Code data rate (Mbps)	Polar Code data rate (Mbps)
6	QPSK	0.44	6.31	4.63
7	QPSK	0.51	7.36	5.40
10	16-QAM	0.33	9.57	8.10
13	16-QAM	0.48	13.67	10.79
21	64-QAM	0.65	27.34	16.19
27	64-QAM	0.92	38.27	32.38

Table 2. Channel model parameters.

Scenario	Power profile (dB)	Delay profile (ns)
Urban LOS	[0 -8 -10 -15]	[0 117 183 333]
Urban NLOS	[0 -3 -5 -10]	[0 267 400 533]

3.2 Simulation Setup

In accordance with the 5G NR Release 16 standard [4], [5], we consider the following V2X communication systems, having carrier frequency of 5.9 GHz (sub-6 GHz) and bandwidth of 10 MHz.

1. **Infrastructure to Vehicular (I2V) for DL.** LDPC coding is employed to allow high throughput efficiency, the input packet being $12 \cdot 10^3$ bits long. The decoding is based on the suboptimal Normalized Min-Sum Algorithm, which reduces the computational complexity of the best known Belief Propagation Algorithm. As for the mobile multipath channel, it is assumed to be time-correlated according to the speed of the vehicle, which is taken as 13.8 m/s.
2. **Vehicular to Infrastructure (V2I) for UL.** Polar coding is employed to achieve high reliability for URLLC applications, the input packet being 300 bits long. The decoding is based on the CRC-Aided Successive Cancellation List Decoding (CA-SCL), whereas the mobile multipath channel is time-invariant within the frame interval, but randomly independent across consecutive frames (block fading).

In our simulations, according to the numerology illustrated in Sect. 2, the OFDM parameters are quantified as follows: *i*) subcarrier spacing, 15 kHz (I2V), 60 kHz (V2I); *ii*) symbol duration, $66.7 \mu\text{s}$ (I2V), $16.7 \mu\text{s}$ (V2I); *iii*) cyclic prefix, $4.69 \mu\text{s}$ (I2V), $1.17 \mu\text{s}$ (V2I); *iv*) FFT size, 667 (I2V), 167 (V2I); *v*) useful subcarriers, 624 (I2V), 132 (V2I). Further, the MCS options we address are shown in Table 1, while the communication scenarios of interest are Urban LOS and Urban NLOS [1], as described in Table 2.

4 Performance Evaluation

In this section, the effectiveness of the V2X communication systems we are addressing is numerically tested for the scenarios described in Sect. 3.2. We take as performance metric the PER as a function of the received mean energy per bit-to-noise spectral density ratio E_b/N_0 . The simulation results for the LDPC code are shown

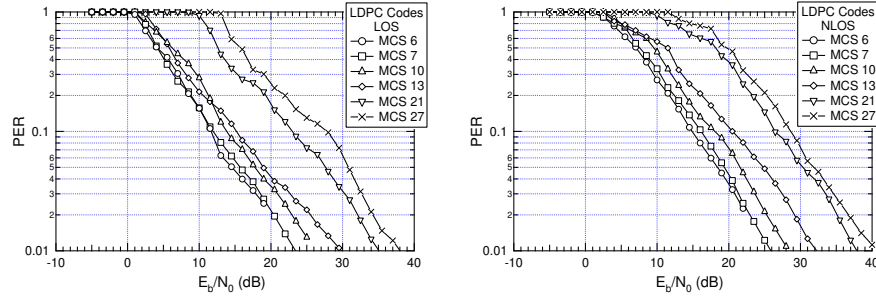


Fig. 1. PER performance for LDPC code in Urban LOS (left) and Urban NLOS (right) channels for various MCSs.

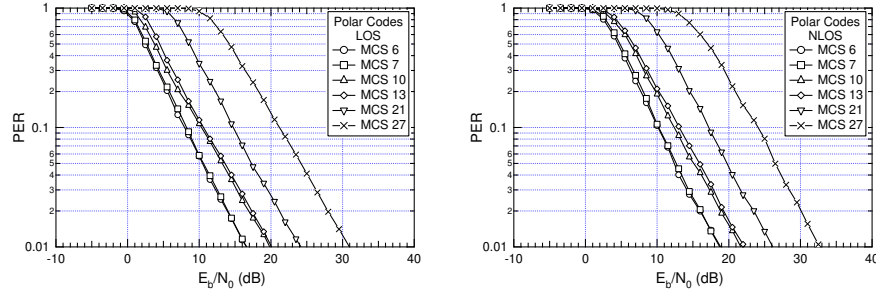


Fig. 2. PER performance for Polar code in Urban LOS (left) and Urban NLOS (right) channels for various MCSs.

in Fig. 1 and for the Polar code in Fig. 2. The figures at the left refer to the Urban LOS channel whereas those at the right to the Urban NLOS channel. As apparent from Figs. 1-2, better PER accuracy is reasonably offered for lower MCS orders, that is to say lower modulation formats and code rates. Additionally, for a given MCS and PER level, moving from the LOS channel to the NLOS one, the Polar codes show a better robustness to performance loss.

5 V2X Link Design and Conclusions

The parameters adopted to design the I2V and V2I communication links are as follows [6]: *i*) carrier frequency f_0 , 5.9 GHz; *ii*) TX power P_T , 23 dBm (mobile), 49 dBm (fixed); *iii*) TX/RX antenna gain G_T , G_R , 0 dBi (mobile), 8 dBi (fixed); *iv*) TX/RX antenna height h_T , h_R , 1.5 m (mobile), 25 m (fixed); *v*) receiver noise figure F , 13 dB (mobile), 7 dB (fixed); *vi*) shadowing loss L_S , 5.2 dB; *vii*) path-loss exponent γ , 3; *viii*) reference distance d_0 , 1 m; *ix*) channel model, Urban NLOS. To the design aim, for a Tx-Rx distance d , the path-loss L_{PL} can be modelled as $(4\pi d/\lambda)^2$ for $d \leq d_0$, and $(4\pi d_0/\lambda)^2 \cdot (d/d_0)^\gamma$ for $d > d_0$, according to [6] and references therein. Hence, the total loss in the link (in dB) results as $L_{tot}(\text{dB}) = L_{PL}(\text{dB}) + L_S(\text{dB})$, where $L_S(\text{dB})$

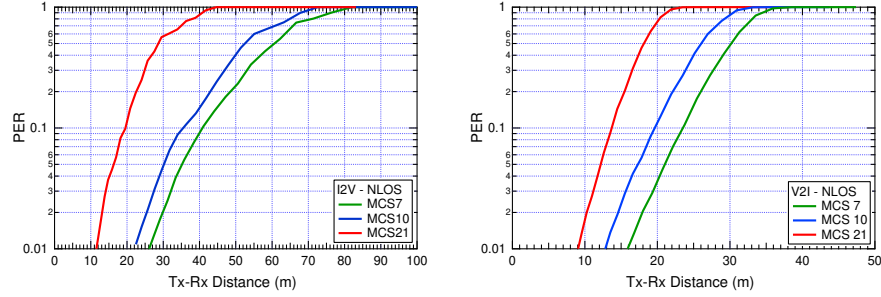


Fig. 3. PER vs. Tx-Rx distance for I2V (left) and V2I (right) for various MCSs.

denotes the additional contribution due to the shadowing. The resulting link budget equation is then $E_b/N_0 = (P_T G_T G_R) / [L_{\text{tot}} R_b k (F - 1) T_0]$, where R_b is the bit rate, k is the Boltzmann constant and $T_0 = 290$ K is the customary ambient temperature. Thus, for a given MCS, combining together the link budget equation with the PER performance evaluated as a function of the E_b/N_0 ratio in Sect. 4 specifies how the PER metric changes with the TX-RX distance d . Figure 3 gives such result for the I2V (left) and V2I (right) links for various MCSs, showing that the PER performance monotonically increases with d , even in a steep way especially for the higher MCS orders, and the I2V link enables a larger coverage.

Concluding, this work evaluated the effectiveness of NR-based V2X communication systems taking the main MCSs adopted by the NR standard into account. Performance metrics obtained by simulation allowed also to design the I2V and V2I communication links over realistic scenarios. Assuming to maintain a given PER level, the main result of the link design is that coverage extension can be achieved only by adopting a lower MCS order. Hence, in a mobile environment where typically the TX-RX distance is time-varying, appropriate resource allocation algorithms are required to adaptively choose the MCS order which makes always available the best link quality.

References

1. Anwar, W., Traßl, A., Franchi, N., Fettweis, G.: On the Reliability of NR-V2X and IEEE 802.11bd. In: 30th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC). IEEE, Istanbul, Turkey, (Nov. 2019)
2. Naik, G., Choudhury, B., Park, J.-M.: IEEE 802.11bd & 5G NR V2X: Evolution of Radio Access Technologies for V2X Communications. *IEEE Access* **7**, pp. 70169–70184 (2019)
3. Ji, H., Park, S., Yeo, J., Kim, Y., Lee, J., Shim, B.: Ultra-Reliable and Low-Latency Communications in 5G Downlink: Physical Layer Aspects. *IEEE Wireless Communications* **25**(3), pp. 124–130 (2018)
4. 3GPP: 5G NR, Multiplexing and channel coding, 3rd Generation Partnership Project (3GPP) Technical Specification (TS) **38.212**, version 16.2.0 Release 16, July 2020.
5. 3GPP: 5G NR, Physical channels and modulation, 3rd Generation Partnership Project (3GPP) Technical Specification (TS) **38.211**, version 16.2.0 Release 16, July 2020.
6. 5GCAR (Fifth Generation Communication Automotive Research and Innovation): Final 5G V2X Radio Design, Deliverable **D3.3**, version 1.1, Nov. 2019.