MCS Analysis for 5G-NR V2X Sidelink Broadcast Communication

Jin Yan, Jérôme Härri
EURECOM, 450 route des Chappes, 06904 Sophia-Antipolis, France
E-mail: `{jin.yan,jerome.haerri}@eurecom.fr`

***Abstract*— Leveraging Modulation and Coding Schemes (MCS) in 5G New Radio (NR) Sidelink represents one key strategy to provide sufficient capacity required by future 5G for Vehicle-to-Everything (V2X) services for intelligent vehicles. Early studies either directly adopt the previously optimised QPSK 1/2 by 802.11p/C-V2X or suggest an optimal MCS value under a particular context. In this paper, we identify a MCS value optimal under any context, by evaluating the impact of MCS on V2X broadcast communication considering multiple varying parameters (e.g. variable packet size, transmit rate or density) representative of different 5G V2X services.**

I. INTRODUCTION

Vehicle-to-everything (V2X) communication is a key paradigm for advanced driver-assistance systems, providing intelligent vehicles with complete awareness of their environments, while enabling interactions with other vehicles, pedestrians, roadside units or any connected devices. Introduced in 3GPP 5G NR rel. 16, V2X 5G NR Sidelink enables 5G low latency, high capacity and reliability V2X communication.

As described by Garcia et al. [1], most V2X services and applications for intelligent vehicles are based on a broadcast communication paradigm considering *ad hoc* resource allocations. Accordingly, performance of 5G NR V2X communications strongly depends on predefined transmit parameters. While most of them are set in V2X profiles either for WiFi or Cellular V2X (e.g. ETSI EN 302 571 [2]) which is popularly adopted by recent studies (e.g. [3]), these parameters are not yet formally defined for 5G NR V2X. Modulation and Coding Schemes (MCS) are of particular interest, as transposing default values from WiFi- or LTE-V2X directly into the innovative 5G NR physical layer will lead to inefficient V2X channel usage.

The seminal work from Jiang et al. [4] identified QPSK (1/2) as an optimal MCS value for WiFi V2X, a MCS value widely adopted in all standards and subsequent researches. Quite interestingly, LTE V2X adopted an equivalent MCS value without investigation. Ali et al. [5] performed the first system-level evaluation of an optimal MCS value for 5G NR V2X broadcast communication, leading to 16 QAM 1/2 (MCS-14). However, their study was limited to a particular cooperative awareness context considering constant and rather low transmit rate and packet sizes. Future 5G V2X services are expected to operate under more stringent conditions, with various and deeply intervened V2X messages and services offering V2X communication conditions with highly dynamic packet sizes and transmit patterns, leading to the impossibility of identifying a particular context.

In this paper, we investigate the optimal 5G NR Sidelink V2X MCS value under a more stringent set of parameters than [5], as will be required by 5G V2X services in the future. Specifically, we evaluate the impact of the MCS value on the performance of 5G V2X broadcast communication as a function of three parameters: (i) message transmit rate, (ii) transmit density, (iii) packet size. Our objective is not to identify various optimal MCS values as a function of a particular context, but a globally optimal MCS value applicable to any context.

The rest of the paper is organized as follows: Section II introduces 5G NR V2X and MCS. Section III describes the methodology used in this study, while Section IV provides evaluation results. Section V summarizes the key findings.

II. BACKGROUND

A. 5G NR V2X Sidelink Overview

Sidelink (SL) is an extension of 5G NR communication [1] to support device-to-device (D2D) communication. Defined in 3GPP since LTE rel. 12 for Proximity Services (ProSe), SL has been specified for 5G NR in rel. 16 for V2X communication. Further releases (rel.17 and 18) define SL enhancements, aiming to support more stringent requirements and operation scenarios for V2X or ProSe, such as wider coverage, reliability improvement, latency reduction or power saving [6].

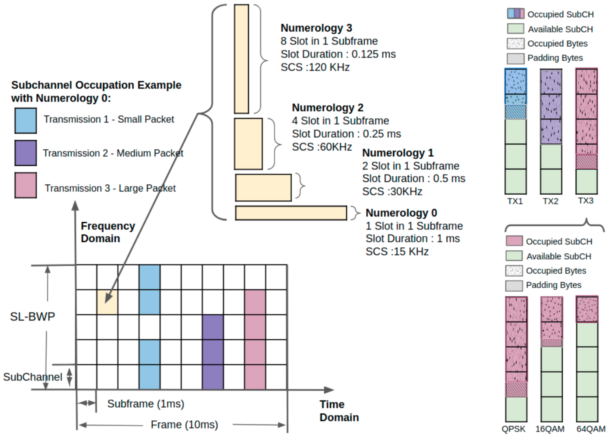


Fig. 1: 5G NR Sidelink Physical Structure

5G NR SL V2X physical resources are similar to 5G NR and span across the metrics of time and frequency domain. In the frequency domain, the bandwidth is split into 15kHz Physical Resource Blocks (PRB). In the time domain, a 10 ms frame is divided into 10 sub-frames of $1ms$. Altogether, a 15 kHz PRB of $1ms$ corresponds to one *slot* and represents the default smallest resource unit in 5G NR. 5G NR further defines *mini-slots* to enable $< 1ms$ transmit delays. Keeping the number of resources per slot equal, mini-slots proportionally increase the required frequency resources as depicted on Fig. 1. The number of slots available per 5G NR sub-frame vary according to the applied numerology. Finally, a sub-channel is a variable amount of slots (e.g. 10, 12, 15, 20, 25, 50, 75, or 100) in the frequency domain corresponding to the smallest packet allocation unit for the 5G NR scheduler.

B. 5G NR MCS for V2X SL

3GPP enables flexible 5G NR SL data rates through a numerous MCS values, which are defined on Table 5.1.3.1-1 of TS 138 214 [7] and reproduced on Table I. Impact of various MCS values on a same packet size is illustrated in the bottom right side of Fig. 1. A higher MCS value can effectively compress the packet into fewer sub-channels and consequently improve potential sub-frame packet multiplexing using 5G NR V2X SL schedulers.

The default 5G NR V2X SL mode 2(a) listen-before-talk (LBT) scheduler is, however, not adapted to PDCP-level packet multiplexing to fit to sub-channel resources for broadcast communications. Specifically, the scheduler is not capable of differentiating between a fully or partially occupied sub-channel in its resource allocation. If a particular MCS and packet size can optimally occupy all resources belonging to one or more sub-channels, different MCS values and packet sizes lead to a partial sub-channel occupation and to resource wastage as depicted respectively on the right side of Fig. 1. Accordingly, increasing the MCS may reduce the required sub-channels per packet, in turn enabling more channel resources to be distributed to other transmitters, this benefit may be lost if sub-channels end up being partially occupied. As shown on the top right side of Fig. 1, the sub-frame has enough *absolute* resources to multiplex TX_1 and TX_3 together in one sub-frame, but the scheduler does not succeed as both TX_1 and TX_3 waste one sub-channel each due to partial sub-channel usage. If the impact of the data rate (i.e MCS) on the performance of 5G V2X broadcast communication is traditionally understood to be sensitive to channel conditions, we can see that for 5G NR V2X SL, it also depends on how efficiently sub-channels are occupied and packets multiplexed.

C. Optimal V2X Broadcast MCS

Most V2X services are based on broadcast communication and on ad-hoc (infrastructure-less) resource allocation ([1]). Accordingly, vehicles need to select a default V2X MCS. Although V2X MCS has been studied for other radio access technologies over the years, comparatively limited analysis on broadcast MCS 5G NR SL can be found in recent research. Jiang et al. [4] suggested a QPSK 1/2 MCS value as optimal for ITS-G5/DSRC technology. Although widely adopted by subsequent studies, standards, and even for the LTE-V2X technology, recent works ([11], [3]) shed light on the potential benefit to increase it. Burbano-Abril et al. [8] propose a dynamic adaptive MCS methodology based on diverse traffic scenarios in order to optimize overall performance for the LTE-V2X technology. Recently, Ali et al. [5] utilise various MCS values for 5G NR V2X SL under a single packet, fixed packet size, and periodic traffic, corresponding to a Day-1 Cooperative Awareness (CA) service. Under these conditions, 5G NR MCS 14 appeared to be optimal. However, Day-2 V2X scenarios include multiple V2X services involving packets of various sizes and more stringent topology conditions, which requires a generalized investigation.

TABLE I: Modulation and Coding Scheme Index

MCS Index	Modulation Order	Target code Rate	Spectral efficiency
0	2(QPSK)	120	0.2344
1	2	157	0.3066
2	2	193	0.3770
3	2	251	0.4902
4	2	308	0.6016
5	2	379	0.7402
6	2	449	0.8770
7	2	526	1.0273
8	2	602	1.1758
9	2	679	1.3262
10	4(16 QAM)	340	1.3281
11	4	378	1.4766
12	4	434	1.6953
13	4	490	1.9141
14	4	553	2.1602
15	4	616	2.4063
16	4	658	2.5703
17	6(64 QAM)	438	2.5664
18	6	466	2.7305
19	6	517	3.0293
20	6	567	3.3223
21	6	616	3.6094
22	6	666	3.9023
23	6	719	4.2129
24	6	772	4.5234
25	6	822	4.8164
26	6	873	5.1152
27	6	910	5.3320
28	6	948	5.5547

III. METHODOLOGY

A. Topology and Evaluation Design

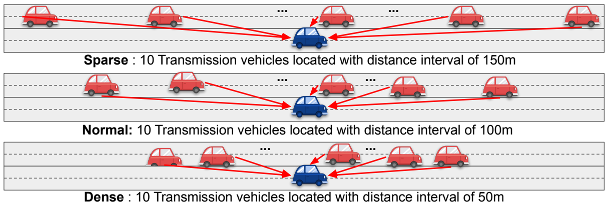
Without loss of generalities, we consider a simple two-lane traffic topology, where all transmitting vehicles are located at a configurable uniform inter-distance on the first lane, the receiving vehicle is located at the center of the topology on the second lane, an average communication performance is to be examined on receiving vehicle from all transmitters. Mobility is not considered in this study, assuming either an static or a mutually static topology. We evaluate MCS values considering three varying representative parameters: *message transmit rate*, the *number of transmitters*, and *the packet size*.

As we want to avoid the impact of other parameters than the previous three on the evaluation of the MCS, we rely on a harmonizing metric called *Communication Density* and defined as follows:

$$Dens^{comm} = \frac{Tx^{range} \times Msg^{Rate}}{Dist^{v2v}} \tag{1}$$

Varying parameters such as transmit range, traffic density, or message rate maintaining a constant communication density will lead to similar broadcast communication performances as discussed in [4].

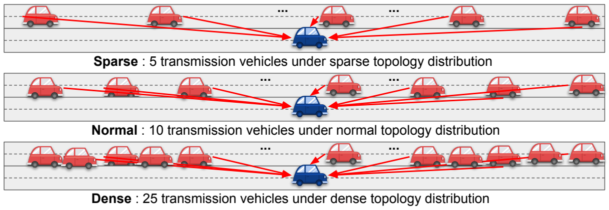
Fig. 2: Topology varying the message transmit rate.



Index	Dist^{v2v} (m)	Tx^{rg} (m)	Msg^{Rt} (Mbps)	Dist^{v2v} (m)	Tx^{rg} (m)	Msg^{Rt} (Mbps)
	Level Reference			Level A		
Dense	20	100	0.024	20	100	0.1
Normal	50	250	0.024	50	250	0.1
Sparse	100	500	0.024	100	500	0.1
	Level B			Level C		
Dense	20	100	0.5	20	100	1
Normal	50	250	0.5	50	250	1
Sparse	100	500	0.5	100	500	1

TABLE II: Settings for varying the message transmit rate

Fig. 3: Topology varying the number of transmitters.



Index	Dist^{v2v} (m)	Tx^{rg} (m)	Msg^{Rt} (Mbps)	Dist^{v2v} (m)	Tx^{rg} (m)	Msg^{Rt} (Mbps)
	Level Reference			Level A		
Dense	20	500	0.0096	20	500	0.04
Normal	50	500	0.024	50	500	0.1
Sparse	100	500	0.048	100	500	0.2
	Level B			Level C		
Dense	20	500	0.2	20	500	0.4
Normal	50	500	0.5	50	500	1
Sparse	100	500	1	100	500	2

TABLE III: Settings for varying the number of transmitters.

We therefore investigate in three levels of communication densities (Level A, B, C) and for each level, we consider three topology scenarios (sparse, normal and dense). As the communication density is constant in all three topology scenarios, only the metric under study will impact the MCS performance. In order to validate our methodology, we also add a reference group (Level Reference) configured similarly to [5] and designed to verify that we reach the same conclusions under the same conditions.

1) Message Transmit Rate: In this first approach, we fix the total number of transmitters, then adjust their inter-distance ($Dist^{v2v}$) so as to let communication density be fully determined by the message transmit rate. The topology is depicted in Fig. 2, where light red vehicles are transmitters and the dark blue vehicle is the receiver. We configure our four levels and three scenarios according to parameters depicted in Table II. According to Eq. 1, the three scenarios employ a globally similar communication density.

2) Number of Transmitters: As the density of transmitters plays a key role in the performance of the 5G NR V2X SL mode 2(a) scheduler, in this step, we let the communication density be fully determined by the density of transmitters by adjusting the message transmit rate according to Eq. 1. As before, we configure the four levels and three scenarios according to parameters depicted in Table III. According to Eq. 1, the three scenarios are categorized by the vehicle density. The methodology is designed to analyse the impact brought by the number of transmitters allocated in each scenario depicted on Fig. 3 within the same or different communication density levels.

3) Packet size: Diverse packet sizes require different number of resources allocated per packet, which may not match the predefined structure as described in Section II. This can typically happen when changing the required number of resources by varying the MCS value. In that case, resources are wasted, and the consequent impact must also be investigated. We propose here a methodology to evaluate the efficiency of fitting to the 5G NR V2X SL subchannel structure as a function of the MCS value.

We first introduce a concept of effective utilization ratio ρ as expressed Eq. 2, which represents the ratio between the actual occupied bytes over the total assigned bytes.

$$\rho = \frac{S}{\gamma \times M} \tag{2}$$

S represents the packet size in bytes, γ denotes the number of required sub-channels per packet, as the larger the packet the more sub-channels are required. M represents the capacity of each resource block within a sub-channel, and is specified by the 5G NR numerology and the MCS.

ρ, however, should not be considered alone, as within a 5G NR sub-frame, multiple packets can be multiplexed, especially at higher MCS values and under heavy traffic conditions. Therefore Eq. 3 describes a multiplexing level parameter δ defined as the $floor$ function of the total number of sub-channels within bandwidth N over γ.

$$\delta = \left\lfloor \frac{N}{\gamma} \right\rfloor \tag{3}$$

Combining Eq. 2 and Eq. 3, we can evaluate the exact influence of various packet sizes typically generated by V2X services on the optimal MCS value.

B. Simulation Environment

We perform a system-level analysis relying on the ns3 simulator, enhanced with a 5G NR V2X SL stack [9]. Without loss of generalities, the wireless channel is modelled according to a standard 3GPP Model [10] for V2X highway communications, we leave a detailed investigation of the impact of more stringent channel conditions to future studies. The major determining parameters are listed in Table IV. We are calculating the average packet reception rate (PRR) among all transmitters as a key performance indicator(KPI) to determine the impact of MCS values. Each result is obtained over an average of 200 simulation runs with random seeds.

TABLE IV: Simulation Baseline Parameters

Parameter	Value
Randomness	Seeds: 30; Run: 200
Performed Frequency	5.89GHz
Bandwidth	10MHz
Numerology	0
subchannel size	10 PRBs
Available SL symbol per slot	8/14
Sensing Window	100
Selection Window	30
Reservation Period	20
Re-transmission	Disabled
Propagation Model	3GPP LoS Channel Model [10]
Tx Power	23dBm
Antenna Setting	Array of 1x2 antenna elements

IV. EVALUATION

A. Message Rate Impact

This section analyses the impact of the message transmit rate on the packet reception rate (PRR) considering four message rate levels described on Table II. Fig. 4(a) shows the reference group considering the exact same parameter setting as in [5]. We can confirm that MCS 14 is the ideal modulation scheme value as shown in [5] under all scenarios. As the PRR drops after MCS 14 for the sparse scenario, it remains stable for the normal and dense scenarios. This can be explained by a comparatively reduced transmission range in higher traffic densities according to Eq. 1, and an increased traffic capacity offered by higher MCS values mitigating resource exhaustion and packet collisions.

The next three figures of Fig. 4 consider different communication conditions than [5]. On Fig. 4(b), the message transmit rate is slightly increased, moving the optimal MCS value to MCS 20. Although a higher transmission rate generates a higher chance of collision, the MCS 24 does not provide a significantly reduced performance compared to MCS 20, in particular with normal or sparse scenarios. When increasing the message transmission rate, we can observe that a consistent optimal PRR is reached by MCS 24, as illustrated in Fig. 4(c) and Fig. 4(d). The improved performance is particularly visible for normal to sparse scenarios, which corresponds to a representative traffic context with V2X services generating a large amount of data, such as joint Cooperative Awareness (CA) or Collaborative Perception (CP) services[1].

All in all, we can observe that only under a low message rate and communication density MCS 14 outperforms other MCS values as shown in Fig.4(a), confirming results from [5]. Under any other scenario, MCS 24 provides consistently better performances than any other MCS value.

B. Transmitter Density Impact

This section analyses the impact of the density of transmitters on the packet reception rate (PRR) considering four communication density levels described in Table III. As before, Fig. 5(a) shows the reference group, considering the exact same parameter setting as in [5] and again proves that MCS 14 is the optimal choice under all scenarios. With regards to MCS 14, the PRR achieves an optimum at 0.98 in sparse scenarios, while it reaches only 0.65 for dense scenarios. Higher MCS values degrade the PRR, but this is not significant, as MCS 24 only experiences a PRR reduction between 1% to 3%. The next three figures of Fig. 5 consider an increased and more realistic communication density compared to the comparatively low value modelled by the reference group in [5]. Fig. 5(b) shows that with an already mild increase in communication density, a PRR optimum is no longer reached by MCS 14 but rather by MCS 20. Quite interestingly, this outperforms the negative impact of a reduced Signal-to-Noise Ratio (SNR) on higher MCS values due to the increased communication density. This can be explained by a stronger benefit of an improved channel availability for the 5G NR V2X scheduler due to reduced resource requirements by higher MCS values.

When increasing the communication density, we can observe that a consistent optimal PRR is reached for MCS 24 as illustrated in Fig. 5(c) and Fig. 5(d). Moreover, normal and dense scenarios outperform sparse scenarios, this is due to the fact that more transmitters are within the reachable range with higher transmission densities, resulting in a better reception rate. When combining the previous analyses, while in certain conditions other MCS values outperform MCS 24, we observe that MCS 24 remains consistently optimum or only experiencing minor loss compared to other MCS values, and it remains definitively better than MCS 14.

C. Packet Size Impact

This section investigates the impact of packet size on optimum MCS values. We considered realistic packet size ranges between 200 bytes and 1500 bytes according to actual V2X packets sizes measured and reported in [12][13]. We applied five MCS indices from Table. I, namely 8, 12, 14 (as reference value), 16, and 24.

Referring to Eq. 2 and considering the basic NR numerology 0, M fully depends on MCS, which means that a higher modulation scheme allows more bytes to be packed into a single resource block. Fig. 6 depicts the impact of the MCS on 5G NR V2X SL resource usage efficiency according to ρ (Eq. 2) and γ (Eq. 3). The zigzagging lines with left side of the y-axis indicators represent ρ, showing periodical changes in the percentage of resource utilization. From these lines we can observe that certain packet sizes and MCS values result in a perfect utilisation of the 5G NR V2X SL subchannels. However, we can also observe from the periodical gradual increase that, for most of other packet size values, resources are wasted by not fully using all resources granted by each 5G NR V2X SL subchannel. Besides the available channel resources not actually being used, this also impacts the performance of the 5G NR V2X SL scheduler, as partially available subchannel resources can not be individually allocated to other transmitters. Still on Fig. 6, the block values representing γ shows the number of occupied 5G NR V2X SL subchannels, as can be read on the right side of the y-axis. A subchannel is considered

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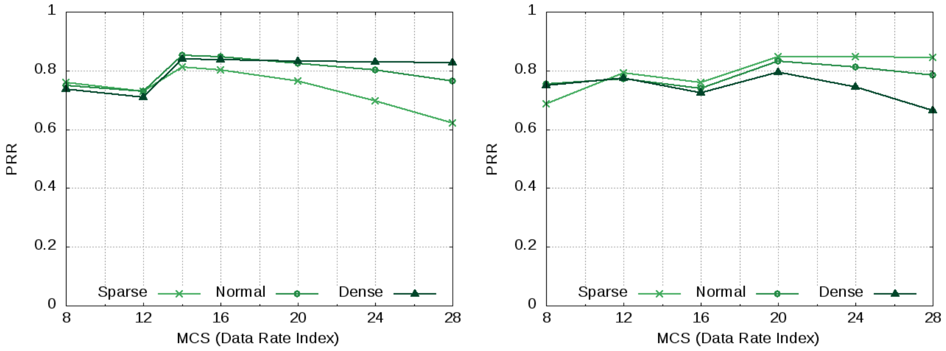
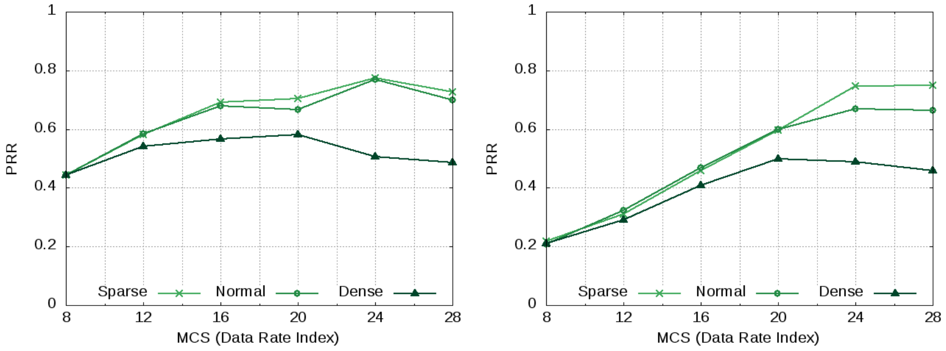
[1] At high vehicular density, the vehicular speed would be proportionally reduced, which would in turn also reduce the message generation rate.

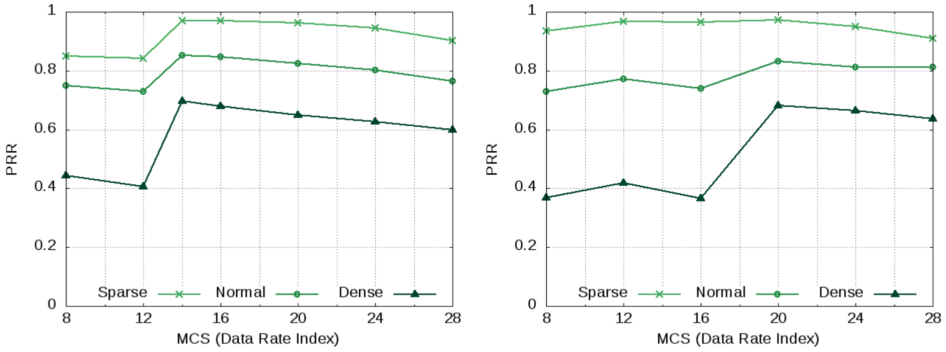


(a) Reference Level [5] (b) Level A

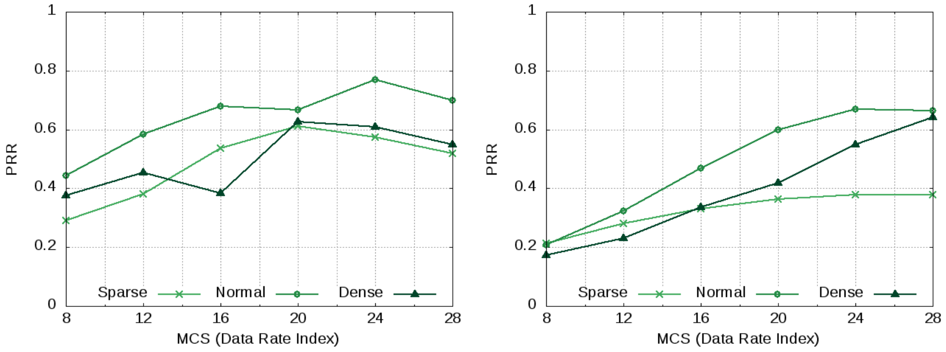


(c) Level B (d) Level C

Fig. 4: Message Rate Impact Result



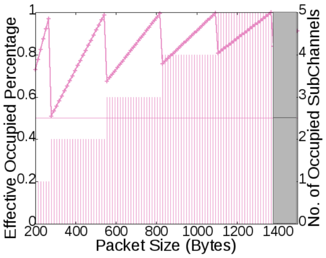
(a) Reference Level [5] (b) Level A



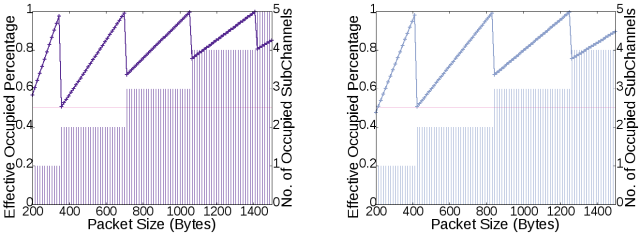
(c) Level B (d) Level C

Fig. 5: Number of Transmitter Impact Result

occupied when at least one of its internal resource is used by at least one packet. The grey part indicates the limited resources available per subchannel does not allow packet sizes larger than 1350 bytes to be transmitted using MCS 12. We can also see that a higher MCS value requires less subchannel occupation for larger packets. If a packet size of 1200 bytes requires all 5 available subchannels with a MCS 12, only 2 subchannels are required for MCS 20 and MCS 24, thus enabling an increased packet multiplexing per 5G NR V2X SL subframe.

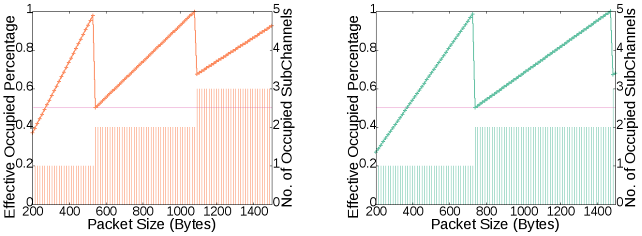


(a) MCS-12



(b) MCS-14

(c) MCS-16



(d) MCS-20

(e) MCS-24

Fig. 6: Sub-channel Occupation over different Packet size

Multiplexity Capacity within One Sub-Frame							
Size / MCS	200	400	600	800	1000	1200	1400
12	5	2	1	1	1	1	—
14	5	2	2	1	1	1	1
16	5	5	2	2	1	1	1
20	5	5	2	2	2	1	1
24	5	5	5	2	2	2	2

TABLE V: MCS impact on 5G NR V2X Multiplexing

To better illustrate this point, a theoretical calculation of packet multiplexing numbers is shown in Table V. As expected, a higher MCS supports more packets being multiplexed than lower MCS. We can observe that MCS 24 enables a 5 packets multiplexing per sub-frame up to 600 bytes, compared to 200 bytes supported by MCS 14. This corresponds to a 200% improvement in capacity and in delay, as more packets can be multiplexed in a 1ms sub-frame.

V. CONCLUSION

In this paper, we demonstrate that a 64QAM (MCS 24) corresponds to an optimal modulation and coding rate for 5G NR V2X sidelink broadcast communication, which represents a major change from the previously admitted values.The difference between this study and previous studies is that we considered in our methodology heterogeneous types of transmit characteristics and densities, representing more realistic communication patterns expected for 5G V2X services. This study shows that packets requiring fewer V2X physical resources (with small packets or under higher MCS) permit a more efficient spectral efficiency under 5G NR strict subchannel numerology. In future work, we intend to generalize this study to include higher numerology as well as investigating optimal modulation and coding for NR V2X sidelink groupcast communications.

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REFERENCES

[1] M.H.C. Garcia, A. Molina-Galan, M. Boban, J. Gozalvez, Javier, B. Coll-Perales, Baldomero, T. Şahin and A. Kousaridas, "A Tutorial on 5G NR V2X Communications", in *IEEE Communications Surveys Tutorials*, vol.23, pp 1972-2026, 2021.

[2] ETSI EN 302 571 V2.1.1, Intelligent Transport Systems (ITS); Radiocommunications equipment operating in the 5 855 MHz to 5 925 MHz frequency band, 2017.

[3] R. Molina-Masegosa, J. Gozalvez and M. Sepulcre, "Comparison of IEEE 802.11p and LTE-V2X: An Evaluation With Periodic and Aperiodic Messages of Constant and Variable Size," in *IEEE Access*, vol. 8, pp. 121526-121548, 2020.

[4] D. Jiang, Q. Chen, and L. Delgrossi, "Communication Density: A Channel Load Metric for Vehicular Communications Research", in *Proc. of the IEEE International Conference on Mobile Adhoc and Sensor Systems (MASS)*, Pisa, Italy, 8-11 Oct. 2007.

[5] Z. Ali, S. Lagén, Sandra, L. Giupponi, and R. Rouil, "3GPP NR V2X Mode 2: Overview, Models and System-level Evaluation", in *IEEE Access* vol. 9, pp. 89554-89579, 2021.

[6] M. Harounabadi, D.M. Soleymani, S. Bhadauria, M. Leyh and E. Roth-Mandutz, "V2X in 3GPP Standardization: NR Sidelink in Release-16 and Beyond", in *IEEE Communications Standards Magazine*, vol.5, pp12-21, 2021.

[7] 3GPP TS 138 214 V16.3.0, "5G; NR; Physical layer procedures for data", 2020.

[8] A. Burbano-Abril, B. McCarthy, M. López-Guerrero, V. Rangel and A. O'Driscoll, "MCS Adaptation within the Cellular V2X Sidelink", in *Proc. of the IEEE Conference on Standards for Communications and Networking (CSCN)*,15–17 December 2021.

[9] N. Patriciello, S. Lagén, B. Bojović, and L. Giupponi, "An E2E simulator for 5G NR networks", in *Simulation Modelling Practice and Theory*, Vol. 96, 101933, Nov. 2019.

[10] T. Zugno, M. Polese, N. Patriciello, B. Bojović, S. Lagén, M. Zorzi, "Implementation of a Spatial Channel Model for ns-3", in *Proc. of the Workshop on ns-3 (WNS3)*, pp. 49–56, June 2020.

[11] M. Sepulcre, J. Gozalvez and B. Coll-Perales, "Why 6 Mbps is Not (Always) the Optimum Data Rate for Beaconing in Vehicular Networks," in IEEE Trans. on Mobile Computing, vol. 16, no. 12, pp. 3568-3579, 1 Dec. 2017.

[12] ETSI TR 103 562 V0.0.16, "Intelligent Transport Systems (ITS) Vehicular Communications; Basic Set of Applications; Analysis of the Collective Perception Service (CPS)". 2019.

[13] ETSI TR 103 300-1 V2.1.1, "Intelligent Transport Systems (ITS) Vehicular Communications; Vulnerable Road Users (VRU) awareness; Part 1: Use Cases definition", 2019.