M. Sepulcre, T. Shimizu, J. Gozálvez, M. I. Khan, O. Altintas, B. Coll-Perales, M.C. Lucas-Estañ, "LTE-V2X Scalability and Spectrum Requirements to support Multiple V2X Services", Proceedings of the 2024 IEEE 100th Vehicular Technology Conference (VTC2024-Fall), 7-10 October 2023, Washington DC, USA., doi: 10.1109/VTC2024-Fall63153.2024.10757634.

LTE-V2X Scalability and Spectrum Requirements to Support Multiple V2X Services

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***Abstract*—Connected Automated Vehicles (CAVs) will use multiple V2X services to support connected and automated driving functions. The bandwidth required to support such services will augment as CAVs are gradually deployed. It is therefore important to accurately estimate the spectrum requirements to anticipate possible scalability challenges ahead. Current estimations consider a simplified modeling of the transmitter as well as context factors such as the number of vehicles in the communication range. Moreover, they do not accurately model if the Quality of Service (QoS) of the considered V2X services is satisfied or not. This study progresses the state of the art with a novel analytical model that quantifies the bandwidth required to support multiple V2X services. The model considers the impact of the vehicular context, the transmission parameters and the communication requirements to take into account the QoS at the receiver. This is important since adapting the transmission parameters can reduce the channel load but also impacts the probability to correctly receive each packet and therefore the bandwidth required to guarantee a target QoS at the receiver. The proposed model can be adapted to different wireless technologies and messages, but is applied in this study to quantify the bandwidth required by LTE-V2X to support the transmission of CAMs, CPMs and MCMs. The study demonstrates the scalability challenges ahead to support multiple V2X services.**

Keywords— Connected Automated Vehicles, V2X, LTE-V2X, C-V2X, 5G NR V2X, scalability, bandwidth, CAM, CPM, MCM.

I. Introduction

Connected Automated Vehicles (CAVs) will make use of a wide range of V2X services to improve traffic safety and efficiency. These services are defined in industrial associations like the C2C-CC and the 5GAA, and standardized in SAE and ETSI. The continuous deployment of new V2X services increases the spectrum or bandwidth required to support connected automated driving. Accurately estimating the spectrum requirements is key for anticipating potential scalability challenges and support the planning and allocation of the spectrum. ITS America [1] identified the message types and applications that will likely be deployed in the 30 MHz spectrum proposed in the US. They highlight that the transmission of messages such as Collective Perception Messages (CPMs) and Maneuver Coordination Messages (MCMs) will require additional bandwidth. Estimations made by the C2C-CC [2] show that at least 70 MHz will be needed to support the C2C-CC applications roadmap, including Cooperative Awareness Messages (CAMs) or Basic Safety Messages (BSMs), as well as CPMs and MCMs. These estimations were agnostic to the underlying radio access technology, and similar for Europe and US markets. 5GAA made related estimations for LTE-V2X and 5G NR V2X [3]. 5GAA concluded that Day-1 V2X services based BSMs or CAMs, and advanced V2X services based on CPMs and MCMs will require between 50 and 60 MHz of spectrum. Estimations made in [2] and [3] consider a simplified modeling of the transmitter side and the vehicular context. Moreover, they do not explicitly model if the Quality of Service (QoS) of the considered V2X services is satisfied or not, and do not model the impact of transmission parameters and propagation effects. These factors are key for the estimation of the bandwidth required to guarantee a target QoS for the considered V2X services.

A more accurate estimation of the spectrum requirements should also consider the transmission parameters and their impact on the QoS at the receiver. The impact that transmission parameters like the Modulation and Coding Scheme (MCS) have on the QoS experienced at the receiver is important because adapting the MCS can reduce the channel load, but also the error protection and hence the probability to correctly receive each packet. As a result, adapting the MCS can have a direct impact on the bandwidth required to guarantee a target QoS at the receiver side.

In this context, this paper progresses the state-of-the-art with a novel analytical model that quantifies for the first time the required bandwidth to support multiple V2X services considering the vehicular context (traffic density and vehicles' speed), key transmission parameters (e.g. MCS and number of retransmissions), propagation effects, and the QoS at the receiver. Compared to [2][3], the proposed model is able to estimate the spectrum needs as a function of the required QoS, and assess the potential of transmission parameters adaptation to reduce the bandwidth. These relevant analyses are not possible with existing models due to their fundamental limitations in their design. Our model is also able to estimate the QoS degradation when congestion control is applied. The model is here applied to quantify and optimize the bandwidth required for the transmission of CAMs, CPMs and MCMs following ETSI specifications using LTE-V2X. However, the model can be applied to other messages (e.g. SAE messages such as BSMs, SDSMs -Sensor Data Sharing Messages- and MSCMs -

UMH work was supported in part by MCIN/AEI/10.13039 /501100011033 (grant PID2020-115576RB-I00).

Maneuver Sharing and Coordination Messages) and wireless technologies (such as 5G NR V2X).

II. Proposed Analytical Model

The analytical model is first formulated agnostically of the underlying radio access technology with generic definitions of bandwidth and radio resources. The model will later be applied to LTE-V2X to quantify the bandwidth necessary to support multiple V2X services. The required bandwidth is computed as the number of radio channels needed to support the considered V2X services. To this aim, the proposed analytical model computes the proportion of radio resources consumed at the radio interface of an ego vehicle due to the V2X messages transmitted by a vehicle located at a distance d that simultaneously runs S services as:

$$\theta(d) = \sum_{s=1}^{S} \lambda_s \cdot \mu_s \cdot \Pr(d) \quad (1)$$

where λ_s represents the number of messages transmitted per second by the V2X service s and is expressed in Hz; the message interval is thus $1/\lambda_s$. μ_s represents the ratio of the radio resources that are necessary for the transmission of a message at a target distance (d_{tar}) with a target reliability (r_{tar}) and the total amount of resources in one second in one channel. This ratio depends on parameters such as the message size, the MCS, the SNR (Signal-to-Noise Ratio) and the target communication requirements (d_{tar} and r_{tar}) as it will be explained in section II.B. $\Pr(d)$ represents the probability that a vehicle at a distance d is able to detect as occupied the radio resources used by the transmitting vehicle.

The required bandwidth BW is computed considering that the radio resources are orthogonal [2][3]. The model computes the required bandwidth BW needed to support multiple (S) V2X services as the sum of the radio resources consumed by all vehicles transmitting V2X messages for these S services that can be detected by the ego vehicle. BW is calculated as:

$$BW(\beta) = \frac{1}{\varphi} \cdot \sum_{i=-\infty}^{+\infty} \theta(d_i) = \frac{1}{\varphi} \cdot \sum_{i=-\infty}^{+\infty} \theta(|i/\beta|) = \frac{\beta}{\varphi} \cdot \sum_{i=-\infty}^{+\infty} \theta(|i|) \quad (2)$$

where β is the traffic density in vehicles/meter, and the summation considers all vehicles i in the scenario. Following [2], φ is the maximum target channel load, and the model considers that a channel is full when its load is equal to φ.

Fig. 1 plots the high-level diagram of the main components of the proposed analytical model. The V2X services are modeled following the ETSI specifications to estimate their message rate and size, as it will be described in section II.A. The communications performance is then estimated taking into account the transmission parameters and propagation effects, as it will be presented in section II.B. The outcome is used to compute the radio resources needs for each vehicle, and then the bandwidth required for the network taking into account other factors such as the traffic density. The model is also used to compute the service quality or its capability to satisfy the application requirements. This computation takes into account whether congestion control is applied or not, since congestion control can reduce the number of transmitted packets and thus degrade the service quality compared with a scenario without congestion and a higher bandwidth.

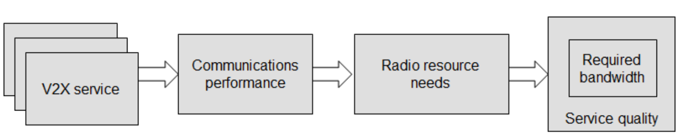


Fig. 1. Component diagram of the proposed analytical model.

A. V2X services modeling

In this study, we estimate the required bandwidth for the regular transmission of CAMs, CPMs and MCMs. While CAMs are regularly broadcasted for basic awareness services, CPMs are transmitted to share information about the detected objects and MCMs to coordinate maneuvers with other vehicles. To quantify the bandwidth consumed by these messages, we estimate their size and generation frequency (or interval). V2X messages have multiple optional containers and elements that are implementation dependent or depend on the vehicular context. In this study, we identify a *best case* and a *worst case* to consider a range of message sizes and intervals.

We consider a CAM payload of 199 Bytes as *best case*, and 500 Bytes as *worst case*. These values correspond to the minimum and maximum CAM payloads in highway scenarios of one of the OEMs of [4]. We also consider the ETSI generation rules for CAMs, so that a new CAM is generated when the transmitting vehicle moves more than 4 m under free flow traffic conditions (or constant speed). The CAM interval is thus $4/v$, where v is the vehicle speed in m/s.

The CPM payload is dynamic as it depends on the number of objects detected and their dynamics. Following [5], the average size of the CPM payload is 401 Bytes in a highway scenario with 6 objects included in each CPM on average. We consider this size and 10 messages transmitted per second for the *worst case* [5]. For the *best case*, we consider the use of the Look-Ahead mechanism [6] that can reduce the load thanks to the transmission of less frequent but larger CPMs. We consider a CPM payload of 576 Bytes (11 objects per CPM) and 6 CPMs per second for the *best case* [5].

We consider the proposal of the TransAID project in [7] as a reference to define the MCM size and interval. We assume for the *best case* that vehicles broadcast on their MCM only their planned trajectory. Following [7], we then assume an MCM size of 329 bytes. The *worst case* represents the scenario where a vehicle wants to start a cooperative maneuver, and hence includes in the MCM its planned and desired trajectories. In this case, the MCM size is 609 Bytes [7]. Since no generation rules have yet been specified by ETSI for MCMs, we adopt the ETSI approach for awareness messages.

Attached to all V2X messages, we consider that BTP and GeoNetworking headers require χ_{header}=64 Bytes. In addition, an access layer header of χ_{acc}=75 bits is considered for LTE-V2X [8]. A security overhead of $\chi_{security}$=100 Bytes (full security certificate) is attached to all MCMs, and to each CAM and CPM every 0.5 seconds; the remaining CAMs and CPMs have a security overhead of $\chi_{security}$=8 Bytes. The size of the V2X messages, χ_{msg}, is then the sum of the payload size, headers and security overhead.

B. LTE-V2X modeling

The proposed model can be applied to different radio access technologies. In this study, we apply it to LTE-V2X and assume a channel bandwidth of 10 MHz. Therefore, the required bandwidth is computed as the number of 10 MHz channels needed to support the considered V2X services.

The selection of the radio interface impacts the calculation of μ_s in eq. (1). μ_s represents the ratio of the number of radio resources necessary for the reception of each message at the target distance with the target reliability and the total amount of resources in one second in one 10 MHz channel. To calculate μ_s, we need to consider that in LTE-V2X the time is structured into 1 ms sub-frames and the channel bandwidth is divided in Resource Blocks (RBs) of 180 kHz each. RBs within the same sub-frame are organized into sub-channels. A vehicle must always assign an integer number of sub-channels for the transmission of a V2X message. To compute the resources consumed by the transmission of a V2X message of a service *s*, we calculate μ_s as follows:

$$\mu_s = \rho_{msg} \cdot n_s / (1000 \cdot \rho_{bw}) \tag{3}$$

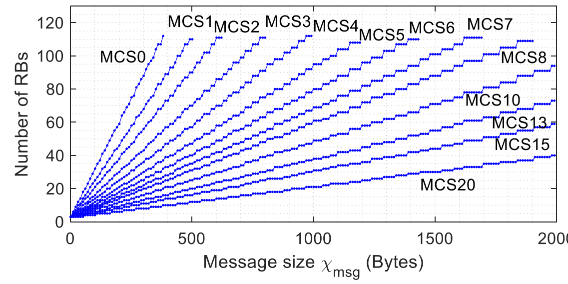
where ρ_{msg} is the number of sub-channels assigned to the message, 1000 is the number of sub-frames in one second, and ρ_{bw} is the total number of sub-channels per 10 MHz channel (ρ_{bw}=5 sub-channels). n_s is the average number of transmissions needed to achieve the target reliability (r_{tar}) at the target distance (d_{tar}). The experienced reliability and n_s are related through the following equation that assumes that transmission errors are independent:

$$r_{\exp} = 1 - \left(BLER\left(d_{tar}\right)\right)^{n_s} \tag{4}$$

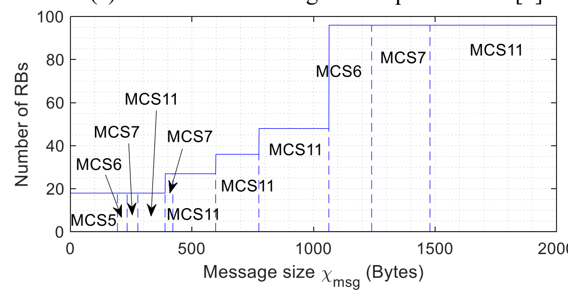
where $BLER(d_{tar})$ is the probability of receiving a message with error at a distance d_{tar}. The value n_s that is necessary to achieve the target reliability r_{tar} can be therefore computed as:

$$n_s = \max\left(1, \log\left(1 - r_{tar}\right) / \log\left(BLER(d_{tar})\right)\right) \tag{5}$$

ρ_{msg} is calculated considering that each message received by the LTE-V2X radio interface from the upper layers is encapsulated in a Transport Block (TB). The TB can occupy one or more sub-channels depending on the message size, the sub-channel size and the MCS utilized. LTE-V2X supports from MCS0 to MCS28, combining different modulation schemes (QPSK, 16QAM and 64QAM) and coding rates. Higher MCSs tend to increase the number of data bits that can be transmitted per RB by increasing the modulation order or the coding rate. As a result, higher MCSs have lower error protection. ρ_{msg} is calculated considering that each TB is transmitted with its corresponding Sidelink Control Information (SCI) that occupies 2 RBs. The number of sub-



(a) All MCSs following 3GPP specification [9]



(b) SAE mapping [10]

Fig. 2. Number of RBs required for the transmission of a message as a function of the size of the message.

channels ρ_{msg} used for the transmission of a message is then:

$$\rho_{msg} = \left\lceil \left(\Psi\left(\chi_{msg}\right) + \omega_{sci}\right) / \omega_{sch} \right\rceil \tag{6}$$

where ω_{sci}=2 is the number of RBs that the SCI occupies, ω_{sch}=10 is the number of RBs per sub-channel, and $\Psi(\chi_{msg})$ is the minimum number of RBs required for the transmission of a message. $\Psi(\chi_{msg})$ can be computed using the 3GPP standards [9], and is depicted in Fig. 2a as a function of the size of the message for different MCSs defined for LTE-V2X. Fig. 2a shows that the message size and MCS have a strong impact on the minimum number of RBs needed in LTE-V2X to transmit a message, and thus on the number of sub-channels assigned following eq. (6). In this context, it is important to note that 3GPP [9] does not impose any additional restriction on the selection of the MCS. However, SAE determines in [10] the MCS and thus the number of RBs for each message size. This mapping (shown in Fig. 2b) will also be studied in this paper.

The BLER at d_{tar} is computed as the probability that the experienced SNR at such distance is lower than a predefined threshold (SNR_{th}^{MCS}). This SNR threshold depends on the MCS because higher MCSs have lower error protection. We estimate the BLER at the required distance as [11]:

$$BLER(d_{tar}) = \frac{1}{2}\left(1 - erf\left(\frac{P_t - PL(d_{tar}) - (N_0 + SNR_{th}^{MCS})}{\sigma\sqrt{2}}\right)\right) \tag{7}$$

where P_t is the transmission power, $PL(d_{tar})$ is the pathloss at the target distance, N_o is the noise power, SNR_{th}^{MCS} is the SNR threshold, and σ is the standard deviation of the shadowing, which follows a log-normal random distribution.

We use a similar model to estimate Pr(d) that is defined as the probability that a vehicle at a distance d is able to detect radio resources as occupied; Pr(d) is part of eq. (1). In LTE-

V2X, we can consider the resources of a message as occupied when we can correctly decode its SCI. Considering that the SCI is transmitted with MSC0 [9], we calculate Pr(d) as:

$$\Pr(d)=\frac{1}{2}\left(1+erf\left(\frac{P_t-PL(d)-(N_0+SNR_{th}^{MCS0})}{\sigma\sqrt{2}}\right)\right) \qquad (8)$$

where SNR_{th}^{MCS0} is the SNR threshold for MSC0.

III. Results

The proposed model has been used to quantify the required bandwidth to support V2X services based on the transmission of CAMs, CPMs and MCMs in a highway scenario with 6 lanes (3 lanes per driving direction). We study different traffic densities. For each density, we compute the vehicles' speed using the well-known Van Aerde model [12], so that the speed decreases as the density increases. We consider LTE-V2X with a 5.9 GHz carrier frequency and a transmission power P_t=23 dBm. We model the pathloss and shadowing propagation effects following the Winner+ B1 propagation model recommended for V2V. The SNR thresholds (SNR_{th}^{MCS}) used in this study to compute the BLER for each MCS are the ones reported in [13].

Table I reports the size and the number of sub-channels occupied by each V2X message. LO stands for Low security Overhead (8 bytes) and HO stands for High security Overhead (100 bytes). The table differentiates between the *best case* and the *worst case*, and compares the case in which all messages are transmitted using MCS6, and when the MCS is selected following the SAE mapping [10] (Fig. 2b). The SAE mapping results in the use of MCS11 for all messages.

Fig. 3 plots the required bandwidth to support the three V2X services as a function of the traffic density for a target reliability r_{tar}=0.9 at a target distance d_{tar}=300m. The required bandwidth is computed (using eq. (2)) as the number of 10 MHz channels needed to accommodate all messages following the proposed model. The results are shown using shaded areas, where each area is upper bounded by the *worst case* and lower bounded by the *best case*. The figure differentiates the required bandwidth for each message and all three messages. It also differentiates the use of MCS6 (Fig. 3a) and the SAE mapping (Fig. 3b). The results clearly show the scalability challenges ahead since multiple 10 MHz channels would be required to simultaneously support multiple V2X services, especially for medium and high densities.

The number of 10 MHz channels needed based on the C2C-CC estimate from [2] is 5.82. This estimate was derived considering the same three V2X services in a highway scenario with light traffic (100 veh/km) and high speed, and a transmission efficiency of 0.55 b/s/Hz, which corresponds to a data rate of 6Mbps (approx. MCS6) minus the corresponding PHY header and overhead in 10 MHz. As shown in Fig. 3a, for this particular traffic density, our model estimates that the required number of channels is between 5.54 (*best case*) and 7.78 (*worst case*). The estimated bandwidth in [2] is therefore similar to the results obtained with our model for r_{tar}=0.9 at d_{tar}=300m, and MCS6. The results obtained with the SAE mapping are shown in Fig. 3b. As it can be observed, it requires a lower number of channels (between 3.39 and 5.03 for 100 veh/km) because it uses higher MCSs (Table I) and the error protection is sufficient for the target reliability and distance considered in this figure (r_{tar}=0.9 at d_{tar}=300m).

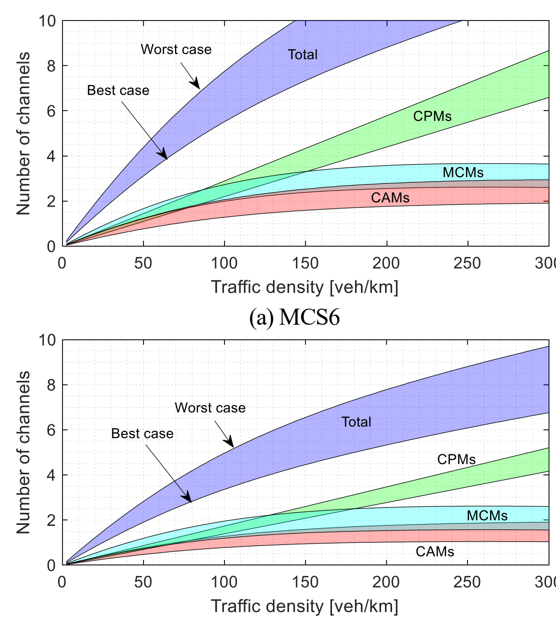
The results presented in Fig. 3 clearly show that multiple 10 MHz channels would be required to simultaneously support the transmission of CAMs, CPMs and MCMs, especially for medium and high densities. If we follow current ETSI specifications, congestion control protocols would be applied. Congestion control would adapt the generation or transmission of messages so that all the transmitted messages would fit in a single channel. That would mean that congestion control would drop or reduce the number of transmitted messages by a factor of $1/BW$, where BW is the number of required channels computed with eq. (1). The experienced reliability at the application level at the target distance d_{tar} can be then estimated when congestion control is applied as:

$$r_{\exp}^{cc}=\left(1-\left(BLER\left(d_{tar}\right)\right)^{n_s}\right)\cdot\min\left(1,1/BW\left(\beta\right)\right) \qquad (9)$$

The reliability at the target distance obtained with eq. (9) is

TABLE I. MESSAGE SIZE (χ_{msg}) AND NUMBER OF SUB-CHANNELS PER MESSAGE (ρ_{msg})

Message	Best case			Worst case		
	χ_{msg} (Bytes)	ρ_{msg} (MCS6)	ρ_{msg} (SAE)	χ_{msg} (Bytes)	ρ_{msg} (MCS6)	ρ_{msg} (SAE)
CAM (LO)	280	3	2 (MCS11)	581	5	3 (MCS11)
CAM (HO)	372	4	2 (MCS11)	673	6	4 (MCS11)
CPM (LO)	610	6	4 (MCS11)	435	4	3 (MCS11)
CPM (HO)	702	6	4 (MCS11)	527	5	3 (MCS11)
MCM (LO/HO)	455	4	3 (MCS11)	734	7	4 (MCS11)



(a) MCS6

(b) MCS SAE

Fig. 3. Required number of 10 MHz channels for r_{tar}=0.9 at d_{tar}=300m.

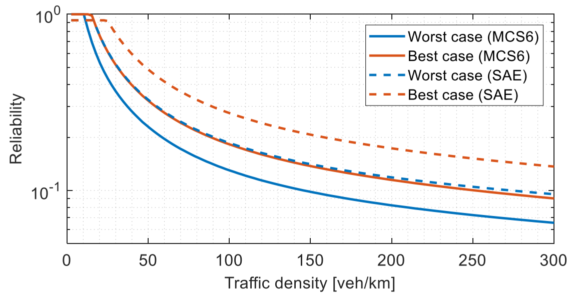


Fig. 4. Reliability at the target distance when congestion control is applied to adapt the transmitted messages to a single channel for a target reliability r_{tar}=0.9 at d_{tar}=300m.

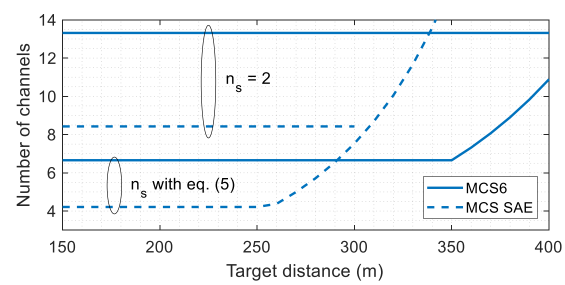
depicted in Fig. 4, for the *best* and *worst cases*, both for MCS6 and the SAE mapping. In this scenario, the highest reliability is obtained for low traffic densities. At low densities, all the messages generated by the V2X services can be transmitted because the required bandwidth is less than one channel. However, at medium and high densities, the number of messages that could be transmitted is significantly lower than the ones required by the services because of the high bandwidth demands and the application of congestion control. As a result, the experienced reliability decreases because a high number of messages would be expected at the receiver, but they would not even be transmitted. In the remaining of the paper, we will estimate the required bandwidth under different conditions without congestion control, since congestion control would adapt the generated messages to fit in one channel.

The results shown in Fig. 3 and Fig. 4 were computed considering a target reliability r_{tar}=0.9 at a target distance d_{tar}=300m. With this configuration, only one transmission (n_s=1) is required to satisfy the target communication requirements with both MCS6 and the SAE mapping. However, the use of higher MCS with the SAE mapping increases the probability of error, and this can challenge the system when the communication requirements are more stringent. The impact of the communication requirements is analyzed in Fig. 5. It plots the required bandwidth to simultaneously support the transmission of CAMs, CPMs and MCMs for a traffic density of 100 veh/km. The results are shown as a function of the target distance (Fig. 5a) and the target reliability (Fig. 5b). Results are derived when the number of transmissions n_s is equal to 2 and when n_s is derived using eq. (5). The figure only depicts configurations that satisfy the target reliability and distance. The results in Fig. 5 show that the required bandwidth does not depend on the communication requirements when n_s=2. With n_s=2, the communication requirements are satisfied in most of the considered configurations except when using the SAE mapping and the target distance is higher than 300 meters (Fig. 5a) or the target reliability is higher than 0.99 (Fig. 5b). This is the case because the SAE mapping uses a high MCS that does not provide sufficient error protection with n_s=2.

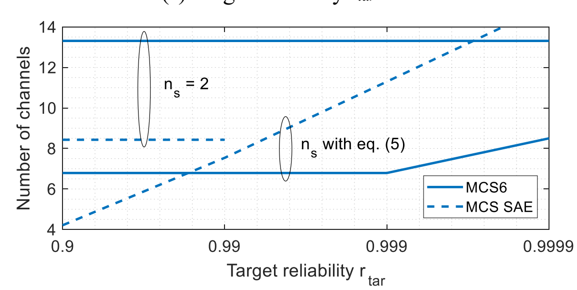
This challenge can be resolved if we adapt the number of transmissions, n_s, necessary to satisfy the communication requirements to the channel conditions using eq. (5). In this case, the use of the SAE mapping can meet the communication requirements (target reliability and distance) but at the cost of significantly increasing the required bandwidth compared to the case in which transmissions are configured with MCS6. This is the case because the use of the SAE mapping needs a higher number of transmissions than MC6 for the same communication requirements. For example, MCS6 can satisfy a target reliability of 0.99 at a target distance of 350m with *ns*=1. On the other hand, the use of the SAE mapping requires increasing *ns* to more than 3 to satisfy the same communication requirements.

It is important to highlight how the curves in Fig. 5 for MCS6 and the SAE mapping cross when n_s is adapted using eq. (5). When the target distance or reliability are low, the use of high MCSs with the SAE mapping can reduce the number of 10 MHz channels necessary to support the three V2X services and satisfy the communication requirements. However, when these requirements increase, the SAE mapping augments the number of channels required because a higher MCSs needs a higher n_s compared with MCS6 to satisfy the communication requirements.

Compared to [2] (5.82 channels), Fig. 5 shows that the use of the SAE mapping could reduce the bandwidth required down to around 4 channels when the communication requirements are low, thanks to the use of a high MCS. However, when the communication requirements are high, the number of channels needed can be higher than 5.82 due to the need of more robust MCS and/or a higher number of transmissions. These results show that increasing the MCS can improve the transmission efficiency under non-stringent communication requirements. However, the use of high MCSs can increase the required bandwidth when these requirements augment, because high MCSs reduce the probability of reception due to their low error protection. The adaptation of the MCS should hence carefully



(a) Target reliability r_{tar}=0.99



(b) Target distance d_{tar}=300m

Fig. 5. Required number of 10 MHz channels for MCS6 and the SAE mapping for 100 veh/km and averaging the best and worst cases.

consider the link level quality as it is more inefficient to transmit more bits per packet (with high MCSs) if these bits have to be retransmitted for a correct reception due to a low error protection.

This important trade-off is captured by the proposed model that can be used to identify the optimum MCS. Fig. 6 depicts the required bandwidth for a traffic density of 100 veh/km as a function of the MCS for different target distances and reliability levels and adapting n_s with eq. (5). Fig. 6 shows that there is an optimum MCS that minimizes the required bandwidth for each target distance and reliability. The required bandwidth is high when the MCS is low because the high error protection decreases the amount of data bits included per packet. Increasing the MCS can reduce the required bandwidth as we can increase the number of data bits per packet and still guarantee a high probability of correct reception at the target distance. If the MCS is increased beyond the optimum MCS, the required bandwidth exponentially increases due to their very low error protection.

The results in Fig. 6 show that between 6 and 8 channels of 10 MHz would be required for target distance of 300m and a target reliability of 0.99, for 100 veh/km and MCS6. For these communication requirements, the required bandwidth could be reduced to around 5 or 6 channels with MCS8. If the target communication requirements are higher (e.g. d_{tar}=400m, r_{tar}=0.999), at least 10 channels would be required, due to the need of a more robust MCS and a higher number of transmissions to satisfy the target QoS. If the QoS requirements are lower, adaptive transmission schemes that increase the MCS could reduce the required bandwidth to 3 channels (for d_{tar}=200m, r_{tar}=0.9). These results clearly demonstrate the need to carefully consider the effects at the receiver side of adapting the MCS, and the impact of this adaptation on the required bandwidth to satisfy the required QoS when supporting multiple V2X services.

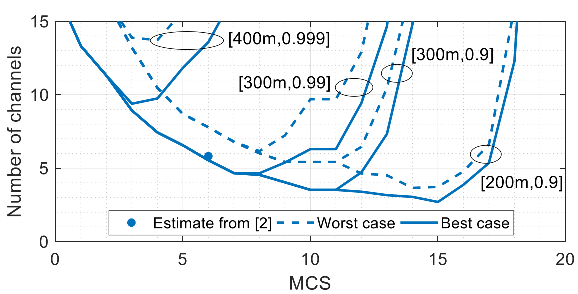


Fig. 6. Required bandwidth as a function of the MCS for 100 veh/km and different target communication requirements [d_{tar},r_{tar}].

IV. Conclusions

This paper proposes an analytical model that quantifies the required bandwidth to simultaneously support multiple V2X services for connected automated driving. The model progresses the state-of-the-art by considering not only traffic factors (like the traffic density and the speed), but also the characteristics of the radio interface, transmission parameters, and the QoS requirements. Notably, the model accounts for the impact that transmission parameters like the MCS have on the QoS experienced at the receiver. The conducted analysis demonstrates that considering the impact of the radio interface and its transmission configuration on the capacity to support target QoS requirements is important for an accurate estimation of the bandwidth necessary to support multiple V2X services. For example, our results show that increasing the MCS can reduce the required bandwidth with non-stringent QoS requirements, but notably increase it to satisfy more demanding QoS requirement. Our study also highlights the spectrum requirements and scalability challenges ahead that will need to be addressed for simultaneously supporting multiple V2X services. In particular, our study estimates that between 6 and 8 channels of 10 MHz would be required to support the transmission of CAMs, CPMs and MCMs in a representative traffic density of 100 veh/km/lane with MCS6. In these conditions, the number of channels can be reduced to 5 or 6 with a higher MCS. Under stringent QoS requirements, the number of channels needed would be increased to more than 10, but if these requirements are relaxed, the bandwidth required can be reduced up to 3 channels. The conducted study reveals that there is room for spectrum optimization with the dynamic adaptation of the transmission parameters. However, future scalability challenges to support higher densities will also require addressing the problem from the higher layers of the stack, e.g. by a more intelligent generation of information.

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