Towards Standardization of Millimeter Wave Vehicle-to-Vehicle Networks: Open Challenges and Performance Evaluation

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Abstract—IEEE 802.11bd and 3GPP NR V2X represent the new specifications for the next generation of Vehicle-to-Vehicle (V2V) networks, which will foresee the integration of the millimeter wave band in vehicular operations to address the high data rates and low latency requirements of V2V communications. In this paper, we review the latest standard developments and present an overview of the mmWave-specific challenges that 802.11bd and NR V2X will have to address. To the best of our knowledge, our work is the first that considers a full-stack end-to-end approach for the design of V2V networks, discussing open issues that span from the physical to the higher layers, and reporting the results of an end-to-end performance evaluation that highlight the potentials of mmWaves for V2V communications.

Index Terms—5G, millimeter wave, V2V, 3GPP, IEEE

I. INTRODUCTION

Recent advances in the automotive industry have paved the way towards Connected and Autonomous Vehicles (CAVs) to promote road safety and traffic efficiency [1]. The potential of CAVs will be fully unleashed through wireless communications to and from cellular base stations and among vehicles, a concept that is usually referred to as Vehicle-To-Everything (V2X) communication. Today, the two key access technologies that enable V2X communications are IEEE 802.11p [2] and 3GPP Cellular-V2X (C-V2X) [3] that, however, fall short of fulfilling the foreseen extreme traffic demands (in terms of, e.g., very high throughput, ultra low latency and ultra high reliability) of future vehicular services.

In this regard, different standardization activities are currently being promoted by IEEE and 3GPP, such as 802.11bd [4] and NR V2X [5] specifications, respectively, aiming at overcoming current technology limitations. Both standards encompass new architecture developments to boost wireless capacity through the use of new frequency bands up to 100 GHz, thanks to the large available bandwidth at such high frequencies. However, communication at millimeter wave (mmWave) introduces serious challenges for the whole protocol stack and requires the maintenance of directional transmissions [6], due to severe path and penetration loss: even though IEEE and 3GPP research activities are in their initial stages of development, adequate discussion on whether (and how) standardization proposals will be able to overcome such limitations is still missing.

In this paper we overview the design objectives and principles of the IEEE 802.11bd and 3GPP NR V2X paradigms for future vehicular networks. Moreover, we shed light on potential shortcomings found on the standards, that should be overcome by future releases to enable V2V operations at mmWaves. We focus on Physical (PHY), Medium Access Control (MAC), and higher layers design challenges, including the issues related to channel estimation, synchronization, mobility management, resource allocation and congestion and flow control.

Besides stimulating further research towards mmWave-compliant IEEE/3GPP specifications, in this paper we validate the feasibility of designing mmWave solutions in view of the strict requirements of future vehicular systems, a research challenge that is still largely unexplored. Therefore, in our paper we present a preliminary performance evaluation of mmWave vehicular communications considering system-level metrics, and we discuss how the peculiarities of signal propagation at mmWaves affect the end-to-end behavior of the communication system in terms of throughput, latency and packet reception probability.

II. V2V STANDARDIZATION ACTIVITIES

The Institute of Electrical and Electronics Engineers (IEEE) and the 3rd Generation Partnership Project (3GPP) are standardizing next-generation networks for vehicular applications with IEEE 802.11bd and 3GPP NR V2X. The two organizations aim at designing inter-operable specifications, so that these two technologies can coexist in the same deployment. Nonetheless, as shown in Fig. 1 they present some distinct characteristics that we will discuss in the following paragraphs.

A. IEEE 802.11bd

In March 2018, IEEE formed the 802.11 Next Generation V2X (NGV) Study Group, which targets improvements of MAC and PHY layers for V2X communications. The current IEEE specifications for V2X applications, i.e., Wireless Access in Vehicular Environments (WAVE), with the 802.11p for the PHY and MAC layers [2], despite being mature and well studied, is derived from 802.11a - 2009, and is no longer able to guarantee the present and future needs of vehicular applications.
The new amendment (commonly known as 802.11bd) targets communications in the 5.9 GHz band and, optionally, in the band from 57 GHz to 71 GHz. Receiver devices implementing NGV must be able to interpret also 802.11p messages, while transmitters have to guarantee coexistence and interoperability among 802.11a and 802.11bd. The goals are to reduce the end-to-end (E2E) latency, to increase the throughput and the communication range, up to twice that yielded by 802.11p, and to double the vehicles relative speed (i.e., up to 500 km/h). To meet these requirements, the technology guidelines investigated so far for the sub-6 GHz band are:

- the usage of Low-Density Parity Check (LDPC) codes with midambles, i.e., specific portions of a frame in between Orthogonal Frequency Division Multiplexing (OFDM) data symbols used to provide a better channel estimate in fast varying channels [7];
- flexible sub-carrier spacing, with up to 40 MHz channel bandwidth.

No specifications for mmWaves have been released yet by the IEEE, except for a proposal to upgrade part of the PHY and lower MAC layers to those designed for 11ad/11ay high data rate scenarios [8], although these standards have been designed to target indoor communications. Therefore, there is an ongoing discussion with respect to how to address the challenges specific to this frequency range, and preliminary studies have been carried out using 802.11ad/ay.

B. NR V2X

The 3GPP has specified in Study Items for Releases 15 and 16 that C-V2X (defined specifically for LTE in Release 14, but with a forward compatible evolution path) will be extended into NR V2X, to enable next generation use cases such as vehicle platooning, advanced and remote driving, and to support high data rates for the exchange of sensors data. The novelities investigated by the 3GPP are:

- direct measurement of the Sidelink (SL) channel, or decoding of Physical Sidelink Control Channel (PSCCH) transmissions, to identify occupied SL resources;
- multiplexing of different logical channels [5], along with the definition of the resource allocation modes 1, where the base station schedules the resources, and 2, which lets the User Equipment (UE) autonomously select the sidelink transmission resources. Mode 2 is the most likely candidate for an initial deployment of NR V2X, given that mode 1 would require cellular network operators to upgrade their base stations to the NR V2X specifications, with increased deployment and management costs;
- support of mini-slot scheduling, i.e., the possibility to immediately schedule a transmission in just a portion of the 14 OFDM symbols specified for a slot, for latency-critical purposes;
- with respect to the numerology to implement at the PHY layer, no ad hoc specifications have been released yet; the assumption so far, also from a performance evaluation point of view, has been to use a flexible numerology as described in 3GPP Release 15, considering the support of sub-carrier spacing of 60 and 120 KHz in Frequency Range 2 (FR2), i.e., between 24.25 and 52.6 GHz. Many other features are derived from NR.

No further specifications have been released yet about how the resources will be selected, and which information the UE will use for the resource allocation procedure. Channel access schemes have not yet been specified for Release 16 and, due to lack of time until the end of the current release, FR2-specific enhancements will be discussed from Release 17 on.

A channel model for V2X communication both in the sub-6 GHz band (FR1) and at mmWaves (FR2) is described in [9]. It also considers an additional Vehicle Non-Line-of-Sight (NLOSv) state, occurring when the Line-of-Sight (LOS) path is blocked by vehicles, besides the Non-Line-of-Sight (NLOS) state where the path is blocked by buildings. A preliminary performance evaluation of the path loss model proposed in [9] is given in [10], which investigates different parameters such as traffic density and deployment options. However, this work does not consider the interaction with higher layers, given the early stage of development of the NR V2X specifications.
TABLE I: Millimeter wave challenges in IEEE 802.11bd and NR V2X standards.

| Layer       | Challenge                                         | Explanation                                                |
|-------------|---------------------------------------------------|------------------------------------------------------------|
| PHY Layer   | Numerology design                                 | Longer slots lead to channel variations                    |
|             | Multiple antenna arrays                           | Synchronization with distributed antennas                  |
|             | Joint radar and communication                      | Based on IEEE 802.11ad (static and indoor) scenarios       |
|             | Broad/multi/groupcast communication               | Directionality precludes broadcast operations              |
|             | Channel estimation                                 | Time-varying channel hinders the use of midambles and may   |
|             | Synchronization                                    | prevent feedback                                           |
|             |                                                    | Synchronization signals need to be directional             |
| MAC Layer   | Mobility management                                | Directionality complicates vehicle discovery and retransmit-|
|             | Resource allocation                                | CSMA strategies suffer from an increased deafness          |
|             | Interference management                           | Unscheduled and autonomous sidelink transmission prevents  |
|             |                                                    | interference coordination                                  |
| Higher Layers| Multi-hop and routing                              | Routing is complicated by highly volatile links           |
|             | Multi-RAT support                                 | Coexistence between RATs in the same frequency band, vehi-  |
|             | Congestion and flow control                       | cle and/or deployment                                      |
|             |                                                    | Suboptimal interaction between channel variability and trans-|
|             |                                                    | port layer rate estimation                                 |
| Modeling    | Channel design                                     | Effect of second order statistics, signal correlation, Doppler and fading is not characterized |

III. V2V OPERATIONS AT MMWAVES: OPEN CHALLENGES

As introduced in Sec. I, even though the standardization is moving full pace ahead towards the first V2V deployments, the use of mmWave frequencies to support high-capacity low-latency communications introduces new challenges for the whole protocol stack which are still open for long-term research, as highlighted in the following subsections and summarized in Table I.

A. PHY Layer Challenges

a) Numerology design: Both 802.11bd and NR V2X Radio Access Technologies (RATs) support a flexible PHY frame structure, to address different QoS requirements. A longer symbol duration (i.e., a smaller subcarrier spacing) facilitates better communication accuracy (because the impact of noise is less relevant), but may also lead to remarkable channel variations within the slot, making mmWave V2V communications more challenging. Moreover, 3GPP NR V2X numerology is currently based on 3GPP NR specifications for cellular scenarios, and might therefore not fit a vehicular system, due to the harsh propagation characteristics of highly mobile vehicular nodes.

b) Multiple antenna arrays: Networks operating at mmWaves must establish and maintain highly directional transmission links to sustain an acceptable communication quality with beamforming. This is achieved using multiple high-dimensional phased arrays, possibly placed in distributed locations. Distributed antennas improve the spectral efficiency by exploiting spatial diversity, thereby resulting in less correlated channels, but raise synchronization issues and require the design of efficient transmit power allocation and resource management mechanisms.

c) Joint radar and communication: The use of mmWaves in a vehicular context is not new, with automotive radars operating in the 77 GHz spectrum. Dual-functional stacks integrating radar and V2V communications have already been investigated in the literature, but not combined yet in V2V specifications. Spectrum isolation or interference mitigation schemes typically enable their coexistence, but a better performance would be achieved by multiplexing both sensing and data on the same waveform, thereby improving spectral efficiency while reducing hardware cost and size.

d) Broad/multi/groupcast communication: The use of directionality at mmWaves prevents from examining multiple direction simultaneously, precluding broadcast communications. In this scenario, transceivers with hybrid and digital beamforming can beamform towards as many directions as the number of radio-frequency chains in the phased array, thereby achieving broad/multi/groupcast communications. Such architectures, however, are currently limited by hardware design.

e) Channel estimation: At mmWave frequencies channel estimation will introduce significant overhead, to track the channel quality in multiple spatial directions with very narrow beams. This is particularly challenging in V2V applications, where the channel varies quickly over time, as the initial estimate may rapidly become obsolete. Even though IEEE 802.11bd foresees the use of midambles to handle channel variations, beamformed mmWave transmissions require specifically tailored channel estimation and precoding techniques. Furthermore, the exchange of channel state information (e.g., through the new Physical Sidelink Feedback Channel (PSFCH) in NR V2X) needs to be timely, to avoid the feedback of stale information in scenarios with a highly variable channel (e.g., because of the increased Doppler effect at mmWaves).

f) Synchronization: IEEE 802.11bd and 3GPP NR V2X mode 2 (a) specifications support autonomous sidelink operations with base stations. In this case, vehicles must implement a set of mechanisms to maintain time and frequency synchronization with other users. One solution is to configure synchronization signals to be exchanged in pre-defined resource pools, even though the directional nature of the communication at mmWaves may slow the rate at which such information is acquired, thereby compromising robust synchronization.

B. MAC Layer Challenges

The issues that mmWaves introduce at the MAC layer in V2V scenarios stem from the lack of omnidirectional sensing...
and signaling, due to directional transmissions. Beamforming, indeed, introduces deafness to vehicles which are not beam-aligned, and complicates the design of channel access and neighbor discovery schemes. Moreover, the challenges add to those typical of the MAC layer in vehicular ad hoc scenarios.

a) Vehicle discovery and mobility management: Directionality complicates an efficient and quick discovery of neighboring vehicles. In a cellular, Wireless Local Area Network (WLAN) or Vehicle-to-Network (V2N) context, the base stations have fixed locations. In V2V scenarios, instead, both endpoints move and could be within reach for just a few seconds. Therefore, there is a need to design in 802.11bd and NR V2X signaling schemes that allow the vehicles to discover each other in a short time frame, even when considering mmWave directional transmissions, and rapidly adapt the communication endpoint in highly mobile environments. Moreover, the volatility of the connection given by the mmWave channel and the mobile vehicles makes retransmissions more complex.

b) Channel access and resource allocation: As mentioned in Sec. II, the 3GPP\(^2\) will likely introduce contention-based channel access in NR V2X (i.e., with the aforementioned mode 2), as in IEEE 802.11bd. Therefore, when both specifications will be extended to mmWaves, they will need to cope with the interaction between directionality and the channel sensing schemes. The classic Carrier Sense Multiple Access (CSMA) strategies, which are subject to the hidden node problem even in sub-6 GHz bands, suffer from an increased deafness at mmWaves. Moreover, contention avoidance messages, which are generally broadcast to signal the intent to occupy the channel, may not be received by every vehicle. Finally, the high mobility of the nodes may introduce unforeseen collisions, but also clear channel uses, when a vehicle that is transmitting changes path. Therefore, the design of efficient uncoordinated channel access procedures in dynamic vehicular scenarios at mmWaves is even more challenging than in WLAN systems.

c) Interference management: Directional communications at mmWaves can isolate the users, reducing the interference and leading the network to a noise-limited regime [13]. Future 802.11bd and NR V2X specifications promote direct vehicular communications in the out-of-coverage scenario, where vehicles autonomously determine sidelink transmission resources, thereby making it unfeasible to configure centralized and coordinated network operations. The contention-based channel access mechanism further complicates interference management in vehicular systems.

C. Higher Layer Challenges

a) Multi-hop communications and routing: Multi-hop relaying schemes represent a possible solution to extend the limited mmWave range for V2V. In particular, two far-away vehicles may be interested in communicating through another vehicle that acts as relay. This introduces new challenges in the design of the V2V procedures, to cope with addressing and efficient routing of packets in networks with highly volatile links, exacerbating the issues that traditionally affect vehicle ad hoc networks [1].

b) Multi-RAT support: In next-generation V2V networks, different technologies could coexist in the same frequency band, vehicle, and/or deployment. Therefore, the protocol stack of various RATs will need to be integrated, to strike a balance between performance and flexibility. Another interesting research challenge is related to how it is possible to efficiently disseminate the information over the different RATs, to combine the benefits of complementary technologies.

c) Congestion and flow control: Communication in V2V scenarios will be mostly among two peer vehicles, in a bursty fashion, and can exploit a massive amount of bandwidth in mmWave. For these short flows, TCP may not be needed, and could actually worsen the performance, with the application layer that, throttled by the congestion window growth, cannot immediately use the available capacity. With multi-hop communications and longer flows, instead, congestion control is needed. In this case, however, the available congestion control algorithms may suffer the suboptimal interaction between the channel variability and the rate estimation at the transport layer, with consequent high latency and low resource utilization [14]. Finally, another challenge is how to provide reliability at the transport layer, if needed, e.g., through retransmissions, network coding or other Forward Error Correction (FEC) schemes.

D. Modeling Challenges

Accurate channel and protocol stack modeling at mmWaves is an essential step towards proper vehicular protocol design. The 3GPP has specified how to characterize mmWave propagation for NR V2X operations in [9], without, however, investigating second order statistics (e.g., spatio-temporal correlation). This prevents the applicability of existing models to dynamic environments. Additionally, the effect of the correlation among signals in a multipath environment, e.g., the role played by ground undulation, road surface roughness and/or reflection from adjacent vehicles, is currently underestimated [10]. The impact of Doppler and fading, which is critical at high frequencies, has also not yet been numerically characterized.

IV. END-TO-END PERFORMANCE EVALUATION

In this section, we present a preliminary end-to-end performance evaluation of V2V communications operating at mmWave frequencies, to determine if the requirements introduced in Sec. IV are satisfied and to study the effects of the unique propagation characteristics experienced at high frequencies in vehicular environments.

A. System Model

We conducted a simulation campaign using ns-3, an open source network simulator which includes accurate models for several communication stacks and enables the collection of end-to-end metrics, e.g., throughput, latency, packet error ratio, among others. In particular, the ns-3 wave [15] module enables the simulation of vehicular communication systems bases on the IEEE WAVE standard [2]. We extended the physical layer model of the wave module to enable the modeling

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\(^2\)So far, the 3GPP has specified a scheduled MAC for cellular networks, with a strict partitioning of the resources among the different users.
of V2V communication systems operating at mmWaves. Also, we added new classes implementing the antenna and channel models described in the 3GPP Technical Report 37.885 [9] for above-6-GHz V2V links. In our simulation scenario, we considered two vehicles moving along the same lane, one behind the other, at a constant speed of 15 m/s, hence the distance between the two remains constant during the whole simulation. They communicate through a wireless link operating at 60 GHz and with a bandwidth of 396 MHz. Both vehicles have a sectorized Uniform Planar Array (UPA) antenna with 4 sectors and 16 antenna elements per sector. The front vehicle transmits User Datagram Protocol (UDP) packets of size 60 KBytes with constant rate. Table II summarizes the simulation parameters we considered. We evaluated the system performance in two different propagation environments, i.e., urban and highway, using different Modulation and Coding Scheme (MCS) configurations and application source rates. For each parameter combination, we obtained the metrics of interest by averaging the results of multiple independent simulations.

### B. Results

In Figure 2a and 2b we evaluated the average throughput achieved at the application layer by varying the relative distance between the vehicles in two different MCS configurations, i.e., 16 QAM with code rate 2/3 (configuration 1) and 64 QAM with code rate 5/6 (configuration 2), respectively. In both cases, we considered application source rates of 0.5 Gbps (in blue) and 1 Gbps (in red) and compared the system performance in urban (dashed lines) and highway (solid lines) propagation environments.

The results we obtained show that, when the two vehicles are close, the system achieves better performance in highway scenarios, but the gap shrinks as the distance increases and, when configuration 2 is used, the trend reverses at a distance of 50 m. This behavior reflects the characteristics of the signal propagation in the two environments. In the highway case, the signal usually propagates in free space, thus ensuring a high LOS probability. In the urban case, instead, the presence of several obstacles could more likely obstruct the LOS path, but also improve the communication capabilities at longer distances through reflections [10].

It can be noticed that configuration 2 is able to achieve a higher throughput with respect to configuration 1, but the performance decays faster with increased distance. In fact, at a distance of 10 m, configuration 2 is able to achieve a throughput of 1 Gbps in the highway scenario; on the contrary, configuration 1 is not able to deliver all the offered data, thus introducing buffering at the transmitter. However, when the two vehicles are further away than 10 m, configuration 1 outperforms configuration 2, because the higher distance between constellation symbols and the stronger FEC scheme provide a better protection against harsher propagation conditions.

In Figure 3 we compared the average end-to-end latency achieved by the two system configurations in the highway environment at a distance of 10 m. With $R = 0.5$ Gbps, configuration 1 shows a higher latency due to the lower transmission rate. With $R = 1$ Gbps, only configuration 2 is able to handle the offered traffic, while with configuration 1 the transmission queue becomes unstable and grows until it is full, resulting in increased latency and packet loss.

This behavior is proved by Figure 4, which shows the packet reception ratio achieved with configuration 1. When considering the highway scenario with source rate of 1 Gbps, at a distance of 10 m, about 15% of the generated packets are lost.
lost due to drops at the transmission queue. The performance is worse in urban conditions, since the error probability is higher.

V. CONCLUSIONS AND FUTURE WORK

In this work, we provided an overview of the ongoing standardization activities for vehicular communications at mmWaves, showing similarities and differences between the IEEE 802.11bd and 3GPP NR V2X specifications. In addition, we detailed the main challenges related to high-frequency operations considering the whole protocol stack. Finally, we presented a preliminary end-to-end performance evaluation of a mmWave V2V communication system. The results we obtained show that the usage of the mmWave spectrum enables high data rates (in the order of Gbps), low latency and high reliability but only at short distances. The presence of obstacles, such as other vehicles or buildings, limits the peak performance but improves the communication range thanks to reflections. As future work, we plan to evolve our end-to-end simulator following the guidelines from standardization bodies. Furthermore, we intend to use this simulator to design novel solutions to overcome the challenges posed in Section III and to evaluate the overall performance.

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