NR V2X Communications at Millimeter Waves: An End-to-End Performance Evaluation

Tommaso Zugno*, Matteo Drago*, Marco Giordani*, Michele Polese*, Michele Zorzi*
*Department of Information Engineering, University of Padova, Italy
email: {name.surname}@dei.unipd.it

†Institute for the Wireless Internet of Things, Northeastern University, Boston, MA
email: m.polese@northeastern.edu

Abstract—3GPP NR V2X represents the new 3GPP standard for next-generation vehicular systems which, among other innovations, supports vehicle-to-vehicle (V2V) operations in the millimeter wave (mmWave) spectrum to address the communication requirements of future intelligent automotive networks. While mmWaves will enable massive data rates and low latency, the propagation characteristics at very high frequencies become very challenging, thereby calling for accurate performance evaluations as a means to properly assess the performance of such systems. Along these lines, in this paper MilliCar, the new ns-3 module based on the latest NR V2X specifications, is used to provide an end-to-end performance evaluation of mmWave V2V networks. We investigate the impact of different propagation scenarios and system parameters, including the inter-vehicle distance, the adopted frame numerology, and the modulation and coding scheme, and provide guidelines towards the most promising V2V deployment configurations.

Index Terms—5G, millimeter wave (mmWave), NR V2X, vehicle-to-vehicle (V2V), ns-3, performance evaluation.

I. INTRODUCTION

The rapid evolution towards 5th generation (5G) wireless networks will accelerate the adoption of solutions for Connected Intelligent Transportation Systems (C-ITSs) to deliver improved traffic safety and efficiency through autonomous driving [1]. These systems, whose market estimates are in the order of 7 trillions USD, promise to make the number of road accidents drop by as much as 90%, while carbon emissions will reduce by more than 60%. The hands-free driving environment of C-ITSs can also reduce drivers’ stress and tedium, as well as increase their productivity. C-ITSs could save over 2.7 billion unproductive hours annually in the US in work commutes, according to some estimates [2].

When fully commercialized, C-ITSs will support several use cases whose requirements will likely exceed the capacity of current communication technologies for vehicular networks [3], [4]. For example, for cooperative perception services, where vehicles exchange processed sensor data to improve the coverage and accuracy of environmental perceptions, the data rate requirements can reach up to approximately 1 Gbps for high-quality uncompressed images. For advanced safety applications, instead, latency must be very small (i.e., less than 100 ms for high degree of automation) to ensure prompt reactions to unpredictable events [5].

A. Towards Millimeter Wave Vehicular Networks

Going forward into the 5G era, different standardization activities are currently being promoted as a means to overcome current technology limitations [6]. The IEEE 802.11bd standard [7], for instance, will target future vehicular service requirements through new modulation mechanisms, the introduction of midambles to improve channel estimation in fast-fading channels, and alternative OFDM numerologies. Similarly, the 3GPP has agreed on a roadmap to support C-ITSs as part of the NR V2X specifications for Rel. 16 [8].

New developments include sidelink and network architecture improvements, a flexible numerology, and a new resource allocation scheme where sidelink resources can be scheduled autonomously by the vehicles (i.e., mode 2). In particular, both standards will support operations at millimeter wave (mmWave) frequencies, up to 71 GHz, where the large available bandwidth can theoretically enable connections with data rates in the order of multiple gigabit per second [9].

Despite these promises, however, communication at mmWaves in the vehicular environment introduces several challenges that need to be addressed to ensure robustness and reliability to the end users. First, signals propagating in the mmWave spectrum suffer from severe path and penetration loss, thereby preventing long-range transmissions. Second, directional communications, which are typically established to increase the link budget through beamforming, require precise alignment of the transmitter and the receiver beams and imply increased control overhead. Also, even though directionality generally guarantees spatial isolation, the metal of vehicles may act as a reflector for the mmWave signals, thus resulting in strong interference from close-by vehicles [10]. Finally, the inherently time-varying nature of the mmWave channel may prevent long-lived connectivity, with serious impact on the whole protocol stack [11], [12].

Such challenging radio conditions are further exacerbated considering the dynamic topology of the vehicular networks, in particular in the Vehicle-to-Vehicle (V2V) scenario for which the direct applicability of the mmWave technology is still not clear and has become a research focus in the area of intelligent automotive systems. As off-the-shelf experimental
testbeds operating at mmWaves are nowadays very expensive, simulations play a key role in the process of evaluating the performance of the different design solutions for mmWave vehicular systems. This is why we recently released MilliCar\footnote{Available at https://github.com/signetlabdei/millicar}, the first open-source ns-3 module for V2V mmWave networks \cite{13}. Compared to the most common simulators for vehicular networks, e.g., Veins \cite{14}, CARLA \cite{15} or V2X Simulation Runtime Infrastructure (VSimRTI) \cite{16}, MilliCar enables full-stack end-to-end simulations of the V2V network and models the mmWave channel as well as a complete TCP/IP protocol stack and mobility of vehicles.

B. Contributions

Along these lines, in this paper we target the following two objectives. First, we validate the main functionalities of the MilliCar module through an extensive simulation campaign. We consider a scenario in which two vehicles, one behind the other, are deployed at fixed distance and speed in the same lane, and a scenario in which multiple groups of vehicles share the same wireless channel on the same road. Second, we investigate the impact of several system parameters on the end-to-end network performance. More specifically, we examine the effect of the inter-vehicle distance, the propagation scenario, the selected numerology, the Modulation and Coding Scheme (MCS), and the Radio Link Control (RLC) reordering timer on two metrics, i.e., the average communication delay and the Radio Link Control (RLC) reordering timer.

II. THE MILLICAR NS-3 MODULE

To address the need for a realistic performance evaluation of V2V networks at mmWaves, we developed MilliCar \cite{13}, an open source V2V module for the popular system simulator ns-3 \cite{18}. Fig. 1 highlights the main features of the module, which includes the implementation of the 3GPP channel model for V2V communications, with propagation, fading and beamformed operations, and physical and Medium Access Control (MAC) layers compliant with the frame structure of 3GPP NR V2X. Besides, the integration with ns-3 makes it possible to study complex, end-to-end scenarios, with several applications of the vehicles, the TCP/IP stack, the higher layers of the cellular stack from Long Term Evolution (LTE) \cite{19}, and realistic mobility patterns, also with the possibility of integrating Simulation of Urban MObility (SUMO) traces \cite{20}.

The channel model that is implemented in the simulator (and that will be used in the evaluations of this paper) follows the 3GPP report in \cite{21}, which specifies a V2V model for different scenarios (namely, urban and highway). Notably, the channel can have different conditions, i.e., the link between two devices can be in Line-of-Sight (LOS), if no obstruction is present, Vehicle Non-Line-of-Sight (NLOSv), if there is blockage of the LOS path due to other vehicles in the same street, or Non-Line-of-Sight (NLOS), if the blockage is caused by large environmental obstacles like buildings. Notice that \cite{21} defines probabilistic transitions only between LOS and NLOSv, while the NLOS condition is given by the geometry of the scenario. Therefore, we also give the possibility to use the model in \cite{22} for a fully statistical channel characterization. Pathloss and fading follow the equations in \cite{21}, which vary according to the specific channel condition. Beamforming is modeled with a Discrete Fourier Transform (DFT)-based approach that points to the LOS direction between two vehicles, and the possibility of changing the number of antenna elements in the vehicles. Interference is accounted for as well, and the error model that maps the Signal to Interference plus Noise Ratio (SINR) into an error probability for the transport blocks of the physical layer is taken from \cite{23}.

The physical layer implementation models the frame structure for NR V2X \cite{8}, which inherits two of the Orthogonal Frequency Division Multiplexing (OFDM) numerologies of NR, i.e., numerology 2, with a subcarrier spacing of 60 kHz and 4 slots of 14 symbols for each subframe (1 ms), and numerology 3, with 120 kHz as subcarrier spacing and 8 slots. The MAC layer is Time Division Multiple Access (TDMA)-based, with transmissions from different vehicles assigned to different slots, according to a pre-established scheduling pattern. Additionally, MilliCar adopts the Adaptive Modulation and Coding (AMC) scheme of the ns-3 mmWave module \cite{23}, with the possibility of configuring a fixed MCS when feedback on the channel condition is not available. Finally, the custom implementation of the physical and MAC layers is connected to the RLC and Packet Data Convergence Protocol (PDCP) layers of the LTE module, which handle the forwarding of packets to the TCP/IP stack, and buffering and segmentation.
to match the transport block size at the MAC layer.

### III. PERFORMANCE EVALUATION

In this section, we present the results of the performance evaluation conducted with the MilliCar module. We developed two simulation scenarios, i.e., Scenario A, described in Sec. III-A, and Scenario B, described in Sec. III-B. In particular, the former has been designed to analyze the impact of different system parameters, namely the MCS, the inter-vehicle distance, the RLC configuration, and the selected numerology, on the end-to-end communication performance, and to compare the system behavior in different propagation scenarios. The latter, instead, considers the presence of multiple groups of vehicles travelling on the same road and evaluates the performance achieved with different modulation and coding schemes and antenna settings. For each scenario, we carried out a simulation campaign and computed some metrics of interest by averaging the results of multiple independent runs. Table I summarizes the parameters used in our simulations.

| Scenario A | Scenario B |
|------------|------------|
| Distance   | [25, . . . , 500] m | 40 m |
| Speed      | 20 m/s | 20 m/s |
| Propagation scenario | [Urban , Highway] | Highway |
| Antenna size | 4 × 4 | [1 × 1, 2 × 2, 4 × 4] |
| Bandwidth  | 100 MHz | 100 MHz |
| Carrier frequency | 28 GHz | 28 GHz |
| Numerology | [2, 3] | 3 |
| MCS        | [0, 14, 28] | [0, 28] |
| RLC mode   | Unacknowledged | Unacknowledged |
| RLC reordering timer | [1, . . . , 100] ms | 10 ms |
| RLC buffer size | 512 kBytes | 512 kBytes |
| UDP source rate | 800 kbps | [10, 50, 100] Mbps |

and sends them to the other vehicle, i.e., the client, using a User Datagram Protocol (UDP) application.

First, we studied the performance of the end-to-end delay and PRR at increasing values of the inter-vehicle distance, focusing on the 3GPP Highway scenario. We assessed these metrics for LOS and NLOSv channel conditions and, for a more detailed insight, we compared the results obtained using different numerologies (i.e., n = 2 and n = 3) and MCSs. In Figure 2a we show that, in the LOS regime, at lower distances numerology 3 guarantees the lowest average delay. This is motivated by the fact that, as described in Sec. II, for this numerology the subframe in divided into 8 slots (with respect to 4 slots for numerology 2), resulting in shorter OFDM symbols, to fit the same subframe duration. On the other hand, it is more difficult to observe a difference between the different numerologies if we consider the NLOSv channel condition, as illustrated in Figure 2b which generally results in a significantly higher end-to-end delay compared to the LOS case. In NLOSv, in fact, some packets can be lost due to a bad channel state. In addition, as the receiving RLC entity implements a reordering procedure for all the received Packet Data Units (PDUs), it has to wait for missing packets in the receiving window until the reordering timer expires: this may increase the packet delay regardless of the numerology that is selected. It should also be mentioned that, when using MCS 28 in LOS, the average delay grows remarkably if we increase the inter-vehicle distance above 250 m as a result of degraded channel conditions, as shown in Figure 2a. However, at such long distances, in a real scenario the path would likely be obstructed by other vehicles and, in this case, we expect that the delay will evolve as shown in Figure 2b for the NLOSv regime. Moreover, it can be noticed that for MCS 28 in NLOSv, the average delay shows a decreasing behavior when considering distances above 150 m. This is a consequence of the high packet loss rate experienced at such distances, which results in less congested buffers for the remaining packets. As a side note, our results also confirm that better resilience is offered by MCS 0, which guarantees a delay as low as around 1.3 ms, even at 250 m in NLOSv.

In Figures 3 and 4 we plot the PRR and average delay, respectively, as a function of the inter-vehicle distance and

![Figure 2](image_url)
the channel conditions, i.e., urban or highway, for a fixed numerology $n = 3$. In particular, Figures 3a and 3b exemplify that better end-to-end performance can be obtained using the urban path loss configuration with LOS and NLOSv conditions, hence resulting in a lower latency, as represented by Figures 4a and 4b. This is motivated by the fact that, in an urban environment, the communication benefits from reflections from walls and/or environmental blockages, which are more likely in street canyons. In this scenario, however, static objects are also more likely to completely block the signal, thus resulting in communication outage. This is demonstrated by Figures 3c and 4c, where the trend of the curves is switched and urban propagation results in reduced PRR (up to $-80\%$) and increased latency (up to $+50\%$) compared to highway propagation.

Finally, in Figure 5 we study how the average end-to-end delay and the PRR are affected by different values of the RLC reordering timer. In particular, we can see from Figure 5a that higher values of the reordering timer do not significantly affect the reception ratio, which is almost constant inside the confidence intervals regardless of the modulation and coding scheme. Since we are using RLC unacknowledged mode and we are not implementing any Hybrid Automatic Repeat reQuest (HARQ) techniques at the MAC layer, lost packets are not retransmitted, therefore, if there are some missing packets in the receiving window, the reordering timer associated to each packet has to expire before they can be forwarded to the upper layers, which results in an increased experienced delay, as shown in Figure 5b.

B. Impact of Interference and Resource Allocation

In Scenario B, we considered two groups of vehicles traveling in the same direction on different lanes. Each group is composed of two vehicles, one behind the other, moving at a constant speed of 20 m/s and keeping a safety distance of 40 m. Within a group, the rear vehicle acts as a server and generates data packets which are sent to the front vehicle. We considered an ON-OFF traffic model, in which a UDP source keeps switching between the ON and the OFF states. During the ON state, the source generates packets at a constant rate for 100 ms, while in the OFF state it stays idle for a random amount of time, which follows an exponential distribution with mean 100 ms. All vehicles operate at 28 GHz with a bandwidth of 100 MHz, possibly interfering in case of concurrent transmissions, and are equipped with a Uniform Planar Array (UPA) of $N \times M$ antenna elements to establish directional communications.

In this context, we evaluate the impact of the interference on the communication performance by considering different system configurations. In Figure 6a, we plot the average SINR experienced as a function of the inter-group distance, i.e., the distance between the two groups of vehicles, and...
Figure 5: Performance comparison as a function of the RLC reordering timer, for numerology $n = 3$, NLOSv channel condition, and inter-vehicle distance equal to 150 m.

Figure 6: Performance comparison as a function of the inter-group distance for different antenna configurations and MCS 14. The UDP source rate is 10 Mbps.

Figure 7: Average throughput as a function of the UDP source rate and the modulation and coding scheme, with or without the orthogonal scheduling of the resources. The antenna configuration is $2 \times 2$.

of the antenna size. It can be seen that the SINR increases with the inter-group distance as a consequence of the weaker effect of the interference. The trend is similar for all the antenna configurations, but the SINR curve has a different offset depending on the number of antenna elements that are used. Indeed, Figure 6a demonstrates that the average PRR at the application layer increases for larger antenna arrays, which are able to focus the transmitted power on narrower beams, hence achieving a higher directivity that can possibly reduce the interference. Specifically, only the $4 \times 4$ configuration is able to provide a reliable data delivery (i.e., PRR $\approx 1$), regardless of the inter-group distance. For all other antenna architectures, perfect reception is guaranteed when the inter-group distance is higher than 80 m and 600 m for the $2 \times 2$ and $1 \times 1$ configurations, respectively.

The presence of a centralized scheduling mechanism could prevent the occurrence of packet collisions by splitting the available resources among the groups in an orthogonal manner. However, reducing the amount of resources accessible to each terminal may limit the achievable throughput. Moreover, the usage of a robust modulation and coding scheme, coupled with a high antenna gain, could provide protection against the interference and enable proper communication performance even without a scheduling mechanism, but at the cost of a lower capacity. We evaluated this trade off by analyzing the average throughput achieved for different modulation and coding schemes, either with or without the orthogonal split of the radio resources among the groups, as reported in Figure 7. With MCS 0, i.e., the most robust modulation and coding
scheme, both strategies are not always able to satisfy the offered traffic. However, in case of shared resources, the system provides a higher throughput thanks to the larger amount of available resources. Instead, for MCS 28 both strategies offer enough resources to accommodate the offered traffic. We notice that the use of directional antennas mitigates the effect of interference and guarantees high performance even without a coordinated scheduling mechanism.

IV. Conclusions and Future Work

In this paper we tested the MilliCar module that we recently released for ns-3, to evaluate the end-to-end performance of V2V networks operating at mmWaves. We considered two simulation scenarios in which vehicles operate through directional communications to exchange data packets using a UDP application, and we investigated the impact of several system-level parameters, including the numerology, the MCS, the antenna array size, the RLC reordering timer, the propagation scenario, and the communication distance. Our results demonstrated that proper beamforming design could mitigate the effect of interference and improve the efficiency by increasing the reuse of the available resources, thereby ensuring higher communication performance, though at the cost of additional complexity (e.g., to align the transmit/receive beams). Also, we proved that, while the RLC reordering timer does not impact much on the PRR, it makes the average end-to-end delay increase significantly, especially for increasing MCSSs. Finally, we analyzed the effect of different scheduling options and we concluded that for MSC 0, i.e., modulation and coding scheme that yields the lowest datarate at the physical layer, the system provides a higher throughput when sharing the available resources, thanks to the robustness of this MCS against errors caused by the interference.

As part of our future work, we will integrate new features to the MilliCar module based on the latest proposals in the 3GPP NR V2X standardization process, including a more realistic beam management mechanism and a dedicated medium access control scheme.

REFERENCES

[1] N. Lu, N. Cheng, N. Zhang, X. Shen, and J. W. Mark, “Connected vehicles: Solutions and challenges,” IEEE Internet Things J., vol. 1, no. 4, pp. 289–299, Aug. 2014.
[2] L. M. Clements and K. M. Kokkelman, “Economic effects of automated vehicles,” Transportation Research Record, vol. 2606, pp. 106–114, 2017.
[3] M. Giordani, A. Zanella, T. Higuchi, O. Altintas, and M. Zorzi, “Performance Study of LTE and mmWave in Vehicle-to-Network Communications,” IEEE 17th Annual Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net), 2018.
[4] M. Giordani, A. Zanella, T. Higuchi, O. Altintas, and M. Zorzi, “On the Feasibility of Integrating mmWave and IEEE 802.11p for V2V Communications,” in IEEE 88th Vehicular Technology Conference (VTC-Fall), Aug 2018.
[5] 3GPP, “Service requirements for enhanced V2X scenarios (Release 15),” TS 22.186, Sept 2018.
[6] T. Zugno, M. Drago, M. Giordani, M. Polese, and M. Zorzi, “Towards Standardization of Millimeter Wave Vehicle-to-Vehicle Networks: Open Challenges and Performance Evaluation,” Submitted to IEEE Communications Magazine, 2020. [Online]. Available: https://arxiv.org/abs/1910.00300
[7] IEEE, “802.11 NGV proposed PAR,” Study Group on 802.11 bd (TGBd) 802.11-18/0861r8, May 2019.
[8] 3GPP, “Study on NR Vehicle-to-Everything (V2X),” TR 38.885, March 2019.
[9] M. Giordani, A. Zanella, and M. Zorzi, “Millimeter wave communication in vehicular networks: Challenges and opportunities,” in 6th International Conference on Modern Circuits and Systems Technologies (MOCAST), May 2017.
[10] V. Petrov, J. Kokkonen, D. Molchanov, J. Lehtomäki, M. Juntti, and Y. Kagachvily, “The Impact of Interference on the Side Lanes on mmWave/THz Band V2V Communication Systems With Directional Antennas,” IEEE Transactions on Vehicular Technology, vol. 67, no. 6, pp. 5028–5041, June 2018.
[11] M. Giordani, A. Zanella, and M. Zorzi, “LTE and Millimeter Waves for V2I Communications: An End-to-End Performance Comparison,” in IEEE 89th Vehicular Technology Conference (VTC2019-Spring), 2019.
[12] M. Zhang, M. Polese, M. Mezzavilla, J. Zhu, S. Rangan, S. Panwar, and M. Zorzi, “Will TCP Work in mmWave 5G Cellular Networks?” IEEE Communications Magazine, vol. 57, no. 1, pp. 65–71, January 2019.
[13] M. Drago, T. Zugno, M. Polese, M. Giordani, and M. Zorzi, “MilliCar – An ns-3 Module for mmWave NR V2X Networks,” to be presented at the Workshop on ns-3, 2020. [Online]. Available: https://arxiv.org/abs/2002.10347
[14] C. Sommer, R. Gernan, and F. Dressler, “Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis,” IEEE Transactions on Mobile Computing, vol. 10, no. 1, pp. 3–15, January 2011.
[15] A. Dosovitskiy, G. Ros, F. Codevilla, A. Lopez, and V. Koltun, “CARLA: A real urban driving simulator,” in Proceedings of the 1st Annual Conference on Robot Learning, 2017.
[16] B. Schunemann, K. Massow, and I. Raudsch, “A novel approach for realistic emulation of vehicle-2-x communication applications,” in IEEE Vehicular Technology Conference, 2008, pp. 2709–2713.
[17] T. Zugno, M. Polese, F. Codella, B. Bujovic, S. Lagen, and M. Zorzi, “Implementation of A Spatial Channel Model for ns-3,” to be presented at the Workshop on ns-3, 2020. [Online]. Available: https://arxiv.org/abs/2002.09341
[18] T. R. Henderson, M. Lacage, G. F. Riley, C. Dowell, and J. Kopena, “Network Simulations with the ns-3 Simulator,” SIGCOMM demonstration, vol. 14, no. 14, p. 527, 2008.
[19] N. Baldo, M. Miozzo, M. Requena-Esteso, and J. Nin-Guerrero, “An open source product-oriented LTE network simulator based on ns-3,” in Proceedings of the 14th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems, ser. MSWiM ’11. Miami, Florida, USA: Association for Computing Machinery, 2011, p. 293–298. [Online]. Available: https://doi.org/10.1145/2068897.2068948
[20] S. Kuehlmann, P. Schmager, A. Festag, and G. Fettweis, “Simulation-Based Evaluation of ETSI ITS-G5 and Cellular-VC s in a Real-World Road Traffic Scenario,” in IEEE 88th Vehicular Technology Conference (VTC-Fall), Aug 2018, pp. 1–6.
[21] 3GPP, “Study on evaluation methodology of new Vehicle-to-Everything (V2X) use cases for LTE and NR,” TR 37.885, Dec. 2018.
[22] M. Boban, X. Gong, and W. Xu, “Modeling the Evolution of Line-of-Sight Blockage for V2V Channels,” in IEEE 84th Vehicular Technology Conference (VTC-Fall), Sep. 2016.
[23] M. Mezzavilla, M. Zhang, M. Polese, R. Ford, S. Dutta, S. Rangan, and M. Zorzi, “End-to-End Simulation of 5G mmWave Networks,” IEEE Communications Surveys Tutorials, vol. 20, no. 3, pp. 2237–2263, Third quarter 2018.