Millimeter Wave Communication in Vehicular Networks: Challenges and Opportunities

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***Abstract*—The next generations of vehicles are expected to support advanced services, such as object detection and recognition, risk identification and avoidance, car platooning, and others, which will require data transmission rates of the order of gigabits per driving hour. This unprecedented amount of data to be exchanged goes beyond the capabilities of existing communication technologies and calls for new solutions. In this regard, the millimeter wave (mmWave) band is very appealing due to the potentially huge bitrates that can be achieved through mmWave links. This potential, however, is hindered by the harsh nature of the mmWave transmission channel, even more so in an automotive environment. This paper investigates the challenges that need to be addressed in order to enable mmWave automotive scenarios. Furthermore, we provide a preliminary analysis of coverage and connectivity in an automotive communication scenario based on mmWave links.**

***Index Terms*—Vehicular Communications (V2X), Millimeter Wave (mmWave), 5G, Mobility, Automotive Systems.**

I. Introduction

In recent years, communication between vehicles (V2V) and between vehicles and infrastructure (V2I), cumulatively indicated as V2X, has been investigated as a means to support basic automotive applications, like cruise control, blind spot detection, parking assistance and so on. Currently, the V2V communication protocol is the so-called *dedicated short-range communication* (DSRC), which provides a nominal coverage range of about 1 km, with achievable data rates in the order of 2-6 Mbps [1]. V2I communication, instead, makes use of the 4G-LTE connectivity below 6 GHz, enabling a data rate of up to 100 Mbps in high mobility scenarios [2].

These technologies, however, will not be able to support the massive demand for high data rates that is expected to be required by the next generation of automotive applications, which will include advanced services based on a number of sophisticated sensors, to support higher layers of automated driving. For example, Laser Imaging Detection and Ranging (LIDARs) could be used for building a tridimensional digital image of the surrounding environment and perform target recognition. Moreover, cameras, exploiting visible or infrared spectrum, could be used to detect speed limit signs and to improve the automotive driving experience. Such new sensors require transmission rates of the order of gigabits per driving hour and will generate an unprecedented amount of data that needs to be exchanged by automotive nodes (either vehicles or road-side units, belonging to the infrastructure) [3].

A possible answer to this growing demand for ultra-high transmission speeds in vehicular networks can be found in the millimeter wave (mmWave) band between 10 GHz and 300 GHz.[1] On the one hand, the vast amount of unused available spectrum has the potential to support the required higher data rates. On the other hand, the increased carrier frequency makes the propagation conditions at mmWaves more challenging. For example, blockage becomes an important issue as mmWave signals do not penetrate most solid materials (e.g., buildings made of bricks) and are subject to high signal attenuation [4]. Therefore the definition of new V2X protocols able to overcome the mmWave limitations is critical.

In this work, we overview the limits that prevent the direct employment of the existing V2X communication protocols on mmWave links, and we highlight possible solutions at the PHY and MAC layers to enable automotive networks to operate at mmWaves. As an example of the kind of analysis that is required in this context, we present a preliminary study of the coverage and connectivity in a simple automotive scenario using mmWave communication links, and show how the performance of common directional beam tracking protocols can be improved by accounting for the specific features of the automotive scenario.

II. MmWave characteristics in V2X systems

There are several appealing features in the use of mmWave frequencies for future V2X applications. Besides the huge amount of available spectrum, the small size of antennas at mmWave frequencies makes it possible to build complex antenna arrays (such as MIMO systems) and to obtain high antenna gains, thus further increasing the transmission rates. In addition, inherent security of mmWave transmissions is also improved because of the limited transmission range and the relatively narrow beamwidth that can be achieved.

Although these new frequency bands have gathered great interest, there are many concerns regarding the transmission characteristics of the mmWave channels [5], as detailed in the following.

a) High path loss: The free space path loss scales with the reciprocal square root of the wavelength. With wavelengths in the order of millimeters, the path loss becomes very large and, hence, the communication range decreases (assuming isotropic propagation) [6]. Furthermore, raindrops are roughly the same size as the radio wavelengths and, therefore, cause scattering of the radio signal [7].

b) Low signal penetration: While signals at lower frequencies can penetrate more easily through buildings, mmWave signals do not penetrate most solid materials. As

[1]Although strictly speaking mmWave bands include frequencies between 30 and 300 GHz, the industry has loosely defined it to include any frequency above 10 GHz.

mmWave Challange	Description
Overhead	Need for frequent beam training through narrow beams and periodic beam tracking to follow the vehicles over time and maintain the alignment.
Frequent handover	Due to the small cell sizes and the rapid and sudden mmWave channel variations, vehicles are subject to frequent handover and reassociation events.
High mobility	In V2X scenarios, vehicles are expected to move very rapidly, so the selected beam pairs may need to be adapted over time, with consequent overhead and delay issues.
Doppler effect	Increased mobility and channel variations exacerbate the Doppler effect, rendering the feedback over mmWaves very challenging.
Blockage	An obstacle can jeopardize a successful communication even if the automotive nodes are perfectly aligned since mmWaves cannot penetrate through solid materials.
CI inaccuracy	When using narrow beams, errors in the GPS coordinates have a great impact on the V2X transmission (especially when using narrow beams), leading to misalignment issues.
Channel model	Absence of realistic channel measurements specifically tailored to a V2X context.

Table I: MmWave challenges in V2X systems.

a result, the movement of obstacles and reflectors, or even changes in the orientation of a handset relative to a body or a hand, can cause the channel to rapidly appear or disappear [7], [8]. For example, in [9] it was reported that the presence of three vehicles between the transmitter and the intended receiver at 200 m of distance could yield 20 dB of signal power attenuation.[2]

c) Beam directionality: In current V2X communication technologies, transmissions are mostly omnidirectional, though beamforming (BF) or other directional transmissions can be performed after a physical link between the nodes has been established. As mentioned, however, isotropic transmission at mmWave frequencies incurs severe path loss. To overcome this problem, mmWave links are typically directional, in order to exploit the beamforming gain. However, directional links may require precise alignment of the transmitter and receiver beams, and therefore there is a high risk of deafness due to beam misalignment.

Hence, those mmWave-related limitations pose new challenges, as summarized in Tab. I, for proper vehicular protocol design, and require that the next generation of mmWave automotive communication protocols support mechanisms by which the vehicles and the infrastructure can quickly determine the best directions to establish the mmWave link. Current V2X algorithms do not support these functionalities and must be extended to come up with new directional algorithms and new methods for addressing the requirements of next-generation V2X systems.

III. State of the art and challenges in V2X PHY/MAC protocols

As mentioned, mmWave links are directional, to compensate for the severe path loss incurred at high frequencies with the beamforming gain. In this respect, channel tracking and measurement reports are fundamental to properly determine the best transmitting and receiving directions. Most existing beam training approaches are based on *beam sweeping*, where the transmitting and the receiving nodes scan the angular space to search for the best beam pair [4]. However, these solutions are limited by the potentially high speed and the presence of frequent blockages on the propagation path. More efficient methods (i.e., [10]) involve some sort of hierarchical beam codebook instead of brute force exhaustive scanning. However, most of these procedures use a quasi-omnidirectional pattern in the first stage, which is ineffective in highly variant mmWave channels affected by a dominant free space path loss effect.

Once the nodes are directionally connected, the alignment can be maintained by using *beam tracking* mechanisms that try to maintain a consistent view of the most favorable beam directions over time. However, in highly dense or highly mobile vehicular scenarios, the corresponding peer may change frequently, thus requiring a re-alignment of the beams to maintain connectivity, an operation that resembles handover in cellular systems. Loss of beamforming information due to channel changes is another reason for handover and reassociation [11], [12]. State-of-the-art handover algorithms for automotive scenarios are suitable for situations where the velocity of the vehicles and their positions can be predicted. However, this may not be the case for mmWave V2X systems, due to the intrinsic variability of the channel over time. Recently, [13] studied handover algorithms for 60 GHz networks in outdoor environments, including those that can be applied in high speed vehicular communications. Furthermore, [14] proposes a preliminary study on designing a joint mmWave radar and communication framework for a vehicular environment based on the 802.11ad system, operating at 60 GHz. The results show that a precise velocity estimation can be achieved when relying on IEEE 802.11ad preambles and standard WiFi procedures. However, in such procedures, handover is triggered by beacon signals, which may not be available in an automotive context. Moreover, most of these solutions do not account for some data traffic performance indices, such as reliability and delay [15].

The high mobility of vehicular nodes must also be considered when designing the MAC layer. In fact a suitable beam pair may not last long enough to allow the completion of a data exchange, due to the high speed of the nodes, thus resulting in transmission errors. Moreover, the increased Doppler effect could make the assumption of channel reciprocity not valid and could impair the feedback over mmWave links, which is a potential point of failure for beam sweeping. Solutions currently proposed for mmWave cellular systems may not be suitable for vehicular communications due to the much higher speed of cars compared to that of user equipments in urban scenarios. For example, the design of a MAC layer specifically tailored to V2X systems with small cells has been addressed in [16], [17] where, however, aspects like beam alignment and blockage are not considered, so that the applicability of

[2] Other measurements showed that the obstruction due to trucks yields lower attenuation because the gap between the road surface and the truck underbody is larger than for other types of vehicles [3].

these results in the context of mmWave automotive networks is limited [3]. An automotive MAC protocol that accounts for the issues raised by directional links was instead proposed in [18]. However, the solution does not scale well with the number of beams and becomes extremely inefficient with very narrow beams. Reference [19] investigates the use of directionality for multicast in V2V networks, but the authors did not consider the deafness issue that occurs if the vehicle is pointing its receive beam away from the transmit beam, e.g., in case of beam pointing errors caused by mobility. The same problem is addressed in [20], where directional antennas are used for multicast applications in a V2I context while considering blockage effects due to large vehicles. However, the carrier frequency was 5.8 GHz, where shadowing is less severe than at mmWave frequencies. Furthermore, the solution again suffers from scalability issues with the number of beams.

Beam alignment can be favored by accurate Context Information (CI), e.g., geographical position and heading of vehicles and road-side units. On the other hand, errors in the GPS coordinates exchanged among the automotive vehicles may have a great impact on the overall performance, depending on the beamwidth. Wider beams indeed are geometrically less affected by CI inaccuracies, at the expense of reducing the communication range [4]. There is hence an unavoidable tradeoff here: wider beams ease the alignment process, but suffer from larger signal attenuation. Therefore, adaptive beamwidth techniques can greatly improve the performance of automotive networks, in terms of both throughput and reliability. In addition, CI might not always be suitable for beam tracking, in particular in dense deployments, since the direct path obtained through the GPS coordinates may be affected by blockage and therefore be suboptimal with respect to other directions. In this case, the CI can still be used to limit the search area, but the optimal alignment can only be determined through a scan of a wider angular space, at the cost of an increased overhead [21].

Finally, available measurements at mmWaves in the V2X context are still very limited, and realistic scenarios are indeed hard to simulate. In fact, the increased reflectivity and scattering from common objects and the poor diffraction and penetration capabilities of mmWaves are the main factors preventing the existing lower frequency channel models from being used for an automotive mmWave scenario. Moreover, current models for mmWave cellular systems (e.g., [22]) present many limitations for their applicability to a V2X context, due to the more challenging propagation characteristics of highly mobile vehicular nodes.

IV. New approaches for V2X communications

The above discussion makes apparent the need for innovative solutions, specifically tailored to automotive networks. For example, modern cars are equipped with many sensors that collect information about the surrounding environment. This rich CI can be exploited to improve the communication protocols, which should also account for control mechanisms and signaling channels to perform beam repointing when blockage is detected. This objective, for instance, can be achieved by coupling the mmWave data plane with a low-frequency control plane to support the required data rates, while increasing the robustness of the communication, respectively [12].

Paper [27] makes the case that mmWave communication is the only viable approach for high bandwidth connected vehicles in both V2V and V2I applications. The overhead challenge of mmWave beam training is then studied and analyzed, and examples and simulation results show that such beam alignment overhead can be reduced by using position information obtained from DSRC.

In [23], the authors present an optimization of the beam design to maximize the data rate for non-overlapping beams, studying the effect of the overlap and comparing the coverage probability with the beamwidth design. Moreover, a mathematical formulation for the data rate and the outage probability, for a given beam design, is shown. Results agree with the intuition that narrower beams should be used towards the cell edge, where the coverage is weaker.

In [25], a location-aided beamforming strategy is proposed to achieve ultra-fast initial connection between nodes, and the resulting performance is analyzed in terms of antenna gain and latency. The presented beam strategy leverages on beams which are hierarchially refined until the desired resolution is achieved. Results show that adaptive channel estimation for harnessing location information allows the estimation time to be substantially reduced.

The authors of [26] propose a set of algorithms to perform beam alignment in a V2I scenario, from extracting information from the radar signals to configuring the beams that illuminate the different antennas in the vehicle. The key idea is to use the estimation of the covariance obtained from the radar signal (or its reflected echo) to design the initial system precoders, at the base station or at the different phased arrays in the vehicle. Simulation results confirm that radars can be a useful source of side information and help configuring the mmWave V2I links.

Article [24] considers a mmWave system that enables multi-Gbps services for high speed trains, addressing the need for frequent beam realignment. Considering a beam switching approach that leverages the position information from train control systems for efficient beam alignment, the optimal beamwidth to achieve the required throughput is derived.

In [28], the authors propose a blockage detection technique for mmWave vehicular antenna arrays that jointly estimates the locations and attenuation of the blocked antennas that result from a plethora of particles like dirt, salt, ice, and water droplets. The proposed technique does not require the antenna array to be physically removed from the vehicle and permits realtime array diagnosis. Moreover, such approach could be jointly employed with DSRC's context information to find the best path connecting two nodes, relying on the position of both the vehicles and the obstacles.

The authors in [15] propose a novel framework to dynamically and efficiently pair vehicles and optimize both transmission and reception beamwidth. The results shed light on the operational limits and practical feasibility of mmWave bands as a viable radio access solution for future high-rate V2V communications.

The main characteristics of the solutions reviewed in the section are summarized in Tab. II.

SoTA Article	Proposed Solution	Open Challenges
[23], [24]	*Beam prediction*: when a vehicle approaches a RSU, it feeds back its position and speed using DSRC. After a refining beam alignment operation has been performed, the vehicle trajectory can be predicted from speed monitoring.	- Based on DSRC (low rates) - No reaction to sudden changes - Constant speed required
[25]	*Location-aided strategy*: prior location information speeds up adaptive channel estimation. By performing a hierarchical procedure, the best beam steering direction is selected.	- Based on DSRC (low rates) - Based on quasi-omni signals
[26], [27]	*Radar-aided strategy*: use a radar mounted on the road infrastructures and on the vehicles to aid the configuration of mmWave communication links in V2I and V2V scenarios.	- Blockage reaction
[28]	*Compressive detection*: detect the location of the blocked antennas and estimate the attenuation and phase-shift coefficients caused by the blocking particles.	- Complexity - Overhead
[15]	*Distributed beam alignment*: Channel (CSI) and Queue (QSI) State Information are used to indicate the transmission opportunity and the traffic urgency, respectively. A self-organizing mechanism solves the V2V association problem in a *decentralized manner*.	- Complexity - Overhead
[12], [27]	*Multi-connectivity and context information*: use of low frequencies (e.g, DSRC, LTE) to increase the robustness to blockage and reduce the beam tracking overhead.	- GPS inaccuracies - Need for beam refining
[27]	*Node cooperation*: Spread information among neighbor vehicles and among infrastructures to build a map of the environment.	- Computational complexity - Overhead

Table II: PHY-MAC solutions for beam tracking in next-generation mmWave V2X systems.

V. Coverage and connectivity analysis for mmWave V2X systems

In this section we propose a preliminary coverage and connectivity analysis (similar to the throughput evaluation carried out in [29] and referred to ultra-dense networks) in mmWave-based vehicular systems. The purpose is to exemplify some of the complex and interesting tradeoffs that have to be considered when designing solutions for mmWave automotive scenarios.

We hence consider a simple but representative V2I scenario, where a single Automotive Node (AN, i.e., a car) moves along a road at constant speed V and Infrastructure Nodes (INs, i.e., static mmWave Base Stations) are randomly distributed according to a Poisson Point Process (PPP) of parameter ρ nodes/km, so that the distance d between consecutive nodes is an exponential random variable of mean $\mathbb{E}[d] = 1/\rho$ km (see, e.g., [30]).

We say that an AN is within coverage of a certain IN if, assuming perfect beam alignment, the Signal-to-Interference-plus-Noise-Ratio (SINR) is the best possible for the AN, and it exceeds a minimum threshold, which we set to $\Gamma_0 = -5$ dB. Due to the stochastic nature of the signal propagation and of the interference, the coverage range of an IN is a random variable, whose exact characterization is still unknown but clearly depends on a number of factors, such as beamwidth, propagation environment, and level of interference that, in turn, depends on the spatial density of the nodes.

To gain some insights on these complex relationships, we performed a number of simulations and evaluated the mean coverage range R_{comm} when varying the node density and the antenna configuration of the nodes. Tab. III collects the main simulation parameters, which are based on realistic system design considerations. To provide a realistic assessment of mmWave micro and picocellular networks in a dense urban deployment, we considered the channel model obtained from recent real-world measurements at 28 GHz in New York City. Further details on the channel model and its parameters can be found in [22].[3]

[3]As pointed out in Section III, channel models specifically tailored to a V2X scenarios are still lacking.

Parameter	Value	Description
W_{tot}	1 GHz	Total system bandwidth
DL P_{TX}	30 dBm	Transmission power
NF	5 dB	Noise figure
f_c	28 GHz	Carrier frequency
τ	-5 dB	Minimum SINR threshold
N_{BS}	{4, 64}	BS MIMO array size
N_{veh}	{4, 16}	Vehicular MIMO array size
T_{RTO}	{0.025, 0.1, 0.2, 0.5, 1} s	Slot duration
V	{10, 20, 30, 100, 130} km/h	Vehicle speed
R_{comm}	Varied	Communication radius

Table III: Main simulation parameters.

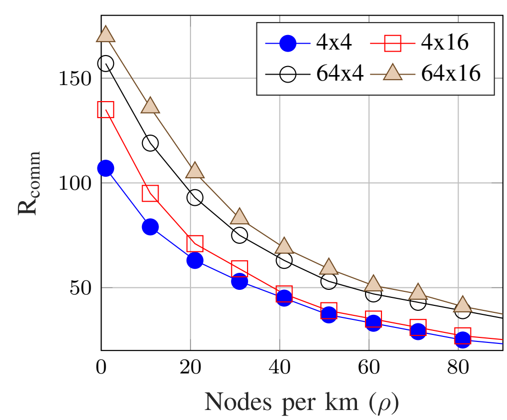
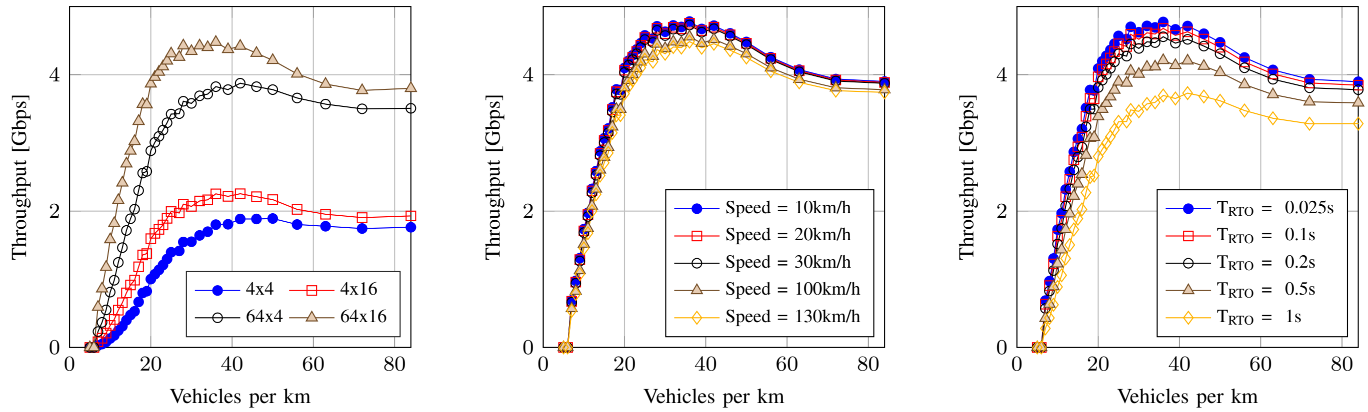


Fig. 1: Average coverage range R_{comm} versus the node density ρ, for different MIMO configurations.

A set of two dimensional antenna arrays is used at both the INs and the ANs. INs are equipped with a Uniform Planar Array (UPA) of 2×2 or 8×8 elements, while the ANs exploit an array of 2×2 or 4×4 antennas. The spacing of the elements is set to $\lambda/2$, where λ is the wavelength.

In general, as depicted in Fig. 1, R_{comm} increases with the number of antennas, thanks to the narrower beams that can be realized, which increase the beamforming gain. On the other hand, R_{comm} decreases as the density of nodes increases, because of the larger amount of interference received at the AN from the INs due to their reduced distance.

As we pointed out in Section III, a directional beam pair needs to be determined to enable the transmission between



(a) Throughput for different MIMO configurations ($T_{\mathrm{RTO}} = 200$ ms, $V = 90$ km/h).

(b) Throughput for different speeds ($T_{\mathrm{RTO}} = 200$ ms, MIMO configuration 64×16).

(c) Throughput for different slot durations ($V = 90$ km/h, MIMO configuration 64×16).

Fig. 2: Average throughput within a time slot of duration T_{RTO} when varying the node spatial density ρ.

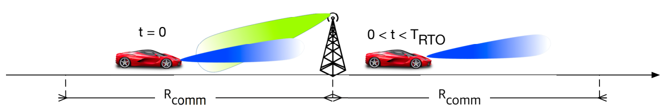


Fig. 3: At the beginning of the slot, the AN is connected to the IN, steering the beam to an angle of $0°$. When moving at constant speed V during the slot, the AN passes the IN (now on its left). Since the beam direction cannot be updated during the slot, the link between the AN and the IN will be lost until the beginning of the next slot.

two ANs, thus beam tracking heavily affects the connectivity performance of a V2X mmWave scenario. In this analysis, according to the procedure described in [11], [12], we assume that measurement reports are periodically exchanged among the nodes so that, at the beginning of every slot of duration T_{RTO}, ANs and INs identify the best directions for their respective beams. Such configuration is kept fixed for the whole slot duration, during which nodes may lose the alignment due to the AN mobility. In case the connectivity is lost during a slot, it can only be recovered at the beginning of the subsequent slot, when the beam tracking procedure is performed again. It is hence of interest to evaluate the AN connectivity, i.e., the fraction of slots in which the AN and the IN remain connected (since the AN is in the IN's coverage range), as a function of the following parameters: (i) the MIMO configuration; (ii) the vehicle speed V; (iii) the slot duration T_{RTO}; (iv) the node density ρ.

For space constraints, we do not report here the mathematical model we developed to carry out this analysis (which can however be found in [31]), but we only describe the main results. At the beginning of a time slot, the AN can be either in a connected (C) state, if it is within the coverage range of an IN, or in an idle (I) state, if there are no INs within a distance R_{comm}. Starting from state C, the AN can either maintain connectivity to the serving IN for the whole slot duration, or lose the beam alignment and get disconnected. This second event is illustrated in Fig. 3. Starting from state I, instead, the AN can either remain out-of-range for the whole slot of duration T_{RTO}, or enter the coverage range of a new IN within T_{RTO} (*catch-up*). Even in this second case, however, the connection to the IN will be established only at the beginning of the following slot, when the beam alignment procedure will be performed. Therefore, preservation of the connectivity during a slot requires that the AN is within the coverage range of the IN at the beginning of the slot and does not lose beam alignment in the slot period T_{RTO}. In this case, the vehicle can potentially send data with a rate $R(d)$ that depends on the distance d to the serving IN.

We note that, as the node density is increased, the average distance between the AN and the IN decreases and, hence, the average bit rate experienced by the AN in case of connectivity becomes larger. On the other hand, the smaller coverage range will increase the probability of losing connectivity during a slot and will determine an increment of the frequency of handovers.

In Fig. 2 we report the average throughput $B = \mathbb{E}[R(d)]$, when varying some system parameters. It is rather interesting to observe that, in all considered configurations, the throughput exhibits a similar pattern when varying the node density ρ.

For small values of ρ, B initially increases with ρ. In this region, the SINR increases with ρ because the reduction of the mean distance to the serving IN is more significant than the increase of the interference coming from the neighboring INs. Moreover, the distance between adjacent INs is still sufficiently large to allow for a loose beam alignment (thanks to the widening of the beam with the distance), so that the connectivity between the AN and the IN is maintained for a relatively large number of slots.

After a certain value of ρ (approximately 40 nodes/km in our scenario), B starts decreasing. In this region, the interference from close-by INs becomes dominant and the perceived SINR degrades. Moreover, the closer the distance between the IN and the AN, the smaller the beam widening and, hence, the higher the risk of losing connectivity during a slot.

We also observe that the throughput grows as V decreases since a slower AN is less likely to lose connectivity to the serving IN during a slot. Similarly, the throughput grows as T_{RTO} decreases, because the beam alignment is repeated more frequently, reducing the disconnection time. However, the overhead (which is not accounted for in this simple analysis) would also increase, thus limiting or even nullifying the gain. Finally, as shown in Fig. 1, the throughput grows with the MIMO array size due to the increased achievable communication range R_{comm} of the nodes.

VI. Conclusions and Future Work

In this work, we surveyed the state of the art in MAC protocols for vehicular applications, highlighting the challenges that arise in a mmWave context and presenting the main factors that limit their applicability to a next-generation automotive environment. The key point is that, in order to compensate for the increased isotropic path loss experienced at higher frequencies, next-generation mmWave automotive communication must provide mechanisms by which the vehicles and the infrastructure determine suitable directions of transmission to exchange sensory information. Finally, a preliminary connectivity and throughput analysis shows that the performance of the automotive nodes in highly mobile mmWave scenarios strictly depends on the specific environment in which the vehicles are deployed, and must account for several automotive specific features such as the vehicle's speed, the beam tracking periodicity, the node density and the MIMO antenna configuration.

As part of our future work, we aim at identifying advanced beam tracking procedures to enhance the performance of the moving nodes in a mmWave automotive context. For example, the directionality of the vehicles and the information about the positions of the roadside units can be exploited to select serving INs that are possibly suboptimal in terms of current SINR, but can guarantee more stable and durable connections and reduce the number of handovers. Moreover, more realistic scenarios will need to be simulated to further validate the presented results, once channel models specifically tailored to a V2X context are available.

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