5G Evaluation Platform for Connected and Autonomous Vehicles

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Abstract

Connected vehicles are the next frontier in massive mobile communications. The field of vehicular communications has undergone a significant transformation and is interested in getting more vehicles connected to exchange essential information between vehicles and road infrastructure in order to improve traffic efficiency and safety. The introduction of the millimeter-wave (mmWave) region in 5G New Radio (NR), together with the latest release of 3rd Generation Partnership Project (3GPP) Release 16 (Rel. 16) to achieve higher data rates, autonomous vehicles are expected to push the limits of the cellular network by exploiting novel technologies, such as beamforming and massive Multiple-Input Multiple-Output (MIMO). This potentially enables several Vehicle-to-Everything (V2X) use cases for cooperative automated driving and enhanced information services.

The project proposes an approach of beam-based interference assessment for Vehicle-to-Vehicle (V2V) communications at mmWave. The perceived interference level is evaluated for a given beamset covering the full azimuthal range. This information provides useful insights on the quality of communications and the potential re-use rate of scheduled resources. In addition, the performance of 5G V2X physical-layer is evaluated by means of scheduling implementation.

1 Introduction

This chapter provides the introduction of the project, where it is explained the motivation for choosing this topic, which are the main goals and objectives, and the work plan carried out during it. The project is focused on the evaluation of beamformed V2V communications, where their link-level performance is analyzed in terms of Signal-to-Interference-plus-Noise ratio (SINR) and perceived interference level.

1.1 Motivation

The automotive industry has become one of the big driving forces towards the next generation of communication systems. This sector has undergone a massive research to address the communication capabilities in vehicles with the end goal of fully automated driving. By means of V2X communications, vehicles are able to get information from its surroundings to improve driving safety, traffic efficiency and the driver's experience. V2X encompasses various use cases by exchanging messages with infrastructure (V2I), pedestrian (V2P) or other vehicles (V2V) [1]. In addition, 5G NR is expected to push the limits of connectivity performance for such vehicular scenarios.

Such interest about the research of the vehicular sector comes from the massive traffic increase experienced in the last decades. This promotes traffic congestions which in turn leads to having more accidents on the road. In most countries, governments consider V2X as a critical technology to reduce road fatalities [2]. One of the main reasons of having such large amount of accidents concerns the decision of the drivers, as stated in [3] and [4]. According to the European Commission, an estimation on 18,800 deaths on road was registered in the last year (2020) [5]. The deaths caused by these accidents and the costs of damaging are significant issues which motivate the governments in the world to search for better solutions and to invest more money in the automotive sector.

There are already many safety applications implemented on the roads such as collision warning systems, road side alerts and road hazard warning systems. The goal is to enhance already existing applications and develop new safety applications to implement at edge User Equipment (UE), i.e. in vehicles. This will require reliable and low latency applications, in order to solve the current problems related to unreliability, network delays, data losses and cyberattacks.

1.2 Objectives

In this project, the performance of V2V communications is evaluated in terms of SINR. The study focuses on a beam-based interference assessment at mmWave bands to measure the degradation suffered in the quality of the communication due to high mobility in V2V scenarios. With beamforming techniques, connected vehicles are enabled to form narrow beams which can simultaneously or sequentially scan the 3D space to concentrate the radiation in an specific direction of interest. This selective concentration of the signal may help in the improvement of SINR and can eliminate certain undesired interference, which is common in highly dense vehicular environments.

Scheduling is another issue discussed in the project. V2X communications demand scheduling techniques to fit its novel applications. In order to satisfy the reliability requirement, a radio resource allocation strategy is needed to minimize the consumed resources in a conflict-free manner and to minimize the probability of exceeding the maximum delay [6]. By means of a scheduling technique, significant improvements can be achieved in the network in terms of latency, packet success rate and resource utilization [6]. Beamforming can alleviate this issue, allowing for a certain level of resource re-use for simultaneous communications. Thus, a combination of both beamforming and scheduling can considerably improve the performance of multi-user systems. In the beam-based interference study carried out in the present project, no scheduling technique is used and all vehicles transmit simultaneously using the same radio resources available. However, the results obtained open a debate towards the consideration of their re-utilization, so, an analysis about such reuse rate of scheduled resources is carried out.

The following points summarize the mentioned objectives:

- Make a beam-based interference study at mmWave bands to evaluate the performance of V2V communications in terms of SINR
- Compare the performance of V2V communications when omnidirectional antennas are used and when beamforming techniques are used, as well as to identify the advantages and drawbacks of each.
- With the beam-based study identify the optimal beams for each vehicular scenario and discuss different decision criterion to choose them.
- Discuss the reuse of radio resources in vehicular environments.

1.3 Work Plan

In order to reach the final objectives and goals specified at the beginning of the thesis, an structured work plan has been carried out. The timeline of this thesis goes from 15th of February 2021 to 30th of June 2021.

The first weeks were a time of familiarization with the topic. On the one hand, a literature review was made on issues such as 5G NR, V2X or beamforming, together with the documentation of quasi deterministic radio channel generator (QuaDRiGa) [7]. Then, a first contact was made with the already existing Matlab code in order to get familiar with the framework and carry out a first approach to the simulation environment. New studies were introduced and some initial results were obtained. These includes a Modulation and Coding Scheme (MCS) study, a beam-based interference evaluation using beamforming and the implementation of scheduling. Finally, efforts were focused on the final report.

Fig. 1 represents the Gantt Diagram of the project and it can be seen that the work plan is divided in three main work packages.

- Research: State of art phase about the topic

1. R1 - Literature Review: Review of the existing literature about the topic: standards, articles, technical reports, publications...
2. R2 - Review QuaDRiGa Documentation: Review the user manual the simulation code is based at.
3. R3 - Familiarisation with matlab code: Analyze the matlab code and try to understand the already performed simulations.

- Study phase: Obtaining of different measurements with the matlab code by making simulations

1. S1: First simple simulations: Simulation of simple vehicular scenarios
2. S2: MCS study: Analysys of a MCS study together with different measures as received power, signal-to-noise ratio (SNR) or data rate.
3. S3: Beamforming based simulations: Add the use of beamforming to previous simulations and analyze the differences.
4. S4: Beam-based interference evaluation: work on the beam-based evaluation where the project results are based on.
5. S5: Scheduling study: Implementation of scheduling in the already existing simulations of the project to see how the channel congestion is affected.

- Work Documentation: Work on final documentation and and extract main conclusions of the thesis

1. W1: Final results: Analysis of the obtained results and collection of those to be used in the final report.
2. W2: Final report: Document all the obtained results and based on them write the final report.

1.4 Document structure

The thesis is organized in the following way:

- In section 2, in order to get knowledge about the topic, a brief overview about the V2X landscape is given, as well as the main advances made in the last decade in the sector.
- Section 3 gives a detailed description about the framework used for making the simulations, and the methodology applied for beam-based interference assessment done.
- Section 4 presents the main results achieved in such assessment to evaluate how the traffic affects in terms of interference.

- In section 5 a study is made about the reuse of radio resources to analyze the number of vehicles that can be supported in a vehicular network while ensuring a reasonable SINR.
- Section 6 analyzes the environmental impact the project can have and the benefits that a research in the sector can bring in the future.
- Finally, in section 7 the main conclusions of the thesis are given, together with possible future enhancements.

1.5 Gantt Diagram

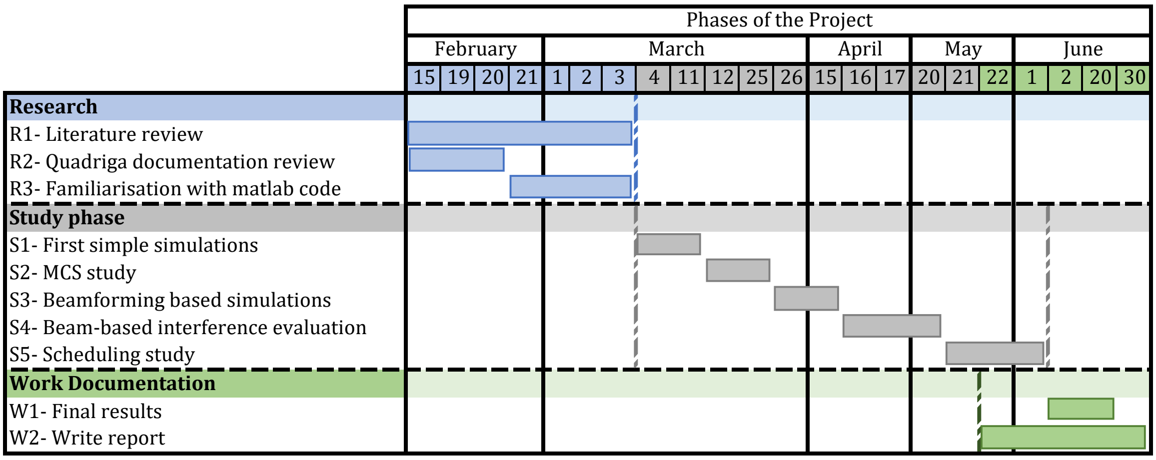

Figure 1: Gantt diagram of the project

2 State of the art

Over the last decade, the automotive industry has been working in cooperation with regulatory bodies to standardize V2X communications to ensure that all stakeholders can manage interoperability between vehicle manufacturers and road infrastructure to get standardized messages. The 5G Automotive Association (5GAA) is a global cross-industry association for connected and autonomous vehicles which encompasses more than 50 companies from the automotive and telecommunication sectors, including many world class car manufacturers. It was created to connect the telecommunication industry with vehicle manufacturers to develop end-to-end solutions for future mobility and transportation services. The goal is to develop, test and promote communication solutions for vehicles on road and initiate an standardization for such developments, in order to accelerate their commercial availability and global market penetration. Created on September 2016, it includes a large member base, being the followin 8 the founders: AUDI AG, BMW Group, Daimler AG, Ericsson, Huawei, Intel, Nokia, and Qualcomm Incorporated [8]. 5GAA considers that Cellular V2X (C-V2X) technologies are an essential step towards developing a fully integrated Intelligent Transportation Systems (ITS) via 5G NR.

The ever-growing evolution of the automotive sector aims to deliver greater safety benefits with the implementation of advanced driving system (ADS), where fully autonomous vehicles will drive us instead of us driving them. The National Highway Traffic Safety Administration (NHTSA) defines six Level of Automation (LoA) [9], but there is still a long way to go from the current LoA established until the last step of fully autonomous cars. Such evolution is expected to be progressive and will go through all the levels established by the NHTSA, which are:

- Level 0: No automation, where the human driver performs all driving tasks.
- Level 1: Driver Assistance, where the vehicle is controlled by the driver but an advanced driving assistance system (ADAS) can sometimes help the driver by simple actions like steering or braking/accelerating, but not both simultaneously.
- Level 2: Partial Automation, where the ADAS can combine both steering and braking/accelerating simultaneously, but the driver still remains in charge of the driving tasks.
- Level 3: Conditional Automation, where the ADS can perform all driving tasks but under some circumstances, so that the driver only takes action in the ADS requests it.
- Level 4: High Automation, where the ADS itself is able to perform all driving tasks under certain circumstances, so that the human need not to pay attentions in those circumstances.
- Level 5: Full Automation, where the vehicle is capable of performing all driving tasks under any circumstances and humans are just passengers.

By means of V2X communications, vehicles are able to get information from its surroundings to improve driving safety, traffic efficiency and the driver's experience. V2X encompasses various use cases by exchanging messages with infrastructure (V2I), pedestrian

(V2P), network (V2N), road side units or other vehicles (V2V) [1]. Those technologies are based on Device-to-Device (D2D) communications, which have been introduced both for C-V2X (from Release 14 forward) [10] and Dedicated Short-Range Communications (DSRC) [11].

2.1 D2D communications

DSRC technology is one of the primary areas of research and development for transportation-related networks. It is a two-way short-to-medium-range wireless communications capability that permits high data and critical data transmissions in communications-based active safety applications [12]. In 1999, 75 MHz of spectrum were allocated in the 5.9 GHz band by the US Federal Communications Commission (FCC). This part of spectrum was designated for ITS and it brought a significant research activity to develop and deploy V2X communications around the world. Such spectrum is seen to be very useful since it can support very low-latency and secure transmission, and has the ability to handle fast and frequent handovers that are inherent in high mobility vehicle environments. In addition, it is robust to adverse weather conditions and tolerant to multi-path transmissions. By 2010, the first set of radio standards for V2X where completed based on the IEEE 802.11p technology, referred as DSRC. It is foreseen that DSRC is going to be implemented for both V2V and V2I communications.

The inclusion of 2G, 3G and 4G cellular communication technologies into vehicles has brought extremely successful benefits and challenges to vehicles, drivers, car manufacturers and other participants in the transportation and emergency services ecosystem. But 5G is not supposed to be 4G plus one. Although a telecommunication network is going to be deployed for the fifth time, unlike its predecessors, this time it is not primarily a technical step, such as increased data rates or better coverage. It is a paradigm change, since the network will not longer be a passive agent which only transmits information between radio links and nodes, but it will become an active agent.

Another fundamental difference of 5G is that it technically enables the permanent connectivity of many more devices than its predecessors, opening the door to the Internet of Things (IoT). The result of all these advances is such a high "reliability environment" that it enables network management of critical services as public emergency, or the implementation of new services as autonomous vehicles. 5G NR, will enhance the performance of vehicular scenarios with the introduction of mmWave bands, multi-antenna techniques and flexible numerologies. The 3GPP has already enabled many of the NR features in Release 16 to be used by vehicles and infrastructures [13].

5G NR offers new possibilities that accelerate the deployment of fully autonomous vehicles, which should ensure:

- **Reliability and accuracy:** Car manufacturers, as well as their suppliers, must ensure reliable V2X connectivity for both network-based communication and point-to-point data transmission between traffic participants. A high degree of reliability is required at all times of the day, even in the worst conditions of SNR ratio.
- **Interoperability:** Vehicle technologies must cooperate with each other seamlessly.

This is essential to enable innovative digital mobility and new on-road safety applications, as well as for research and development processes that need to be fast and efficient.

- **Global compliance and certification:** Mobile communication solutions for automotive connectivity must comply with the various international standards emanating from Institute of Electrical and Electronics Engineers (IEEE) 802.11p, Global Certification Forum (GCF), ITS and 3GPP, all in regional and global ecosystems. Innovative test solutions help to meet these standards.

Nowadays, more than 100 million vehicles on the roads are connected to cellular networks (V2N). Such V2N connections encompass a wide variety of services which include telematics, connected infotainment, real time navigation, traffic optimization, safety services (automatic crash notification (ACN) and emergency calls), recognition of slow or stationary vehicles, information alerts (traffic jams, road works...), weather conditions, other hazardous conditions... and much more applications.

C-V2X is a recent term introduced for cellular technologies applied for transportation and connected vehicles, which includes both 4G Long Term Evolution (LTE) and 5G NR releases of specifications. C-V2X is intended to work on both network-based communications (V2N) already used in the last decade, complemented with the modes of operation defined in 3GPP Release 14 (Rel. 14), which include direct communication between vehicles (V2V), as well as communication between vehicle and road side infrastructure (V2I) without the need of having any cellular network coverage or subscription [14]. By integrating the direct communications technology into mobile and other devices, C-V2X is able to further support vulnerable road users (VRUs) with vehicle t pedestrians communications (V2P). Fig. 2 illustrates the different communication modes supported in C-V2X technologies.

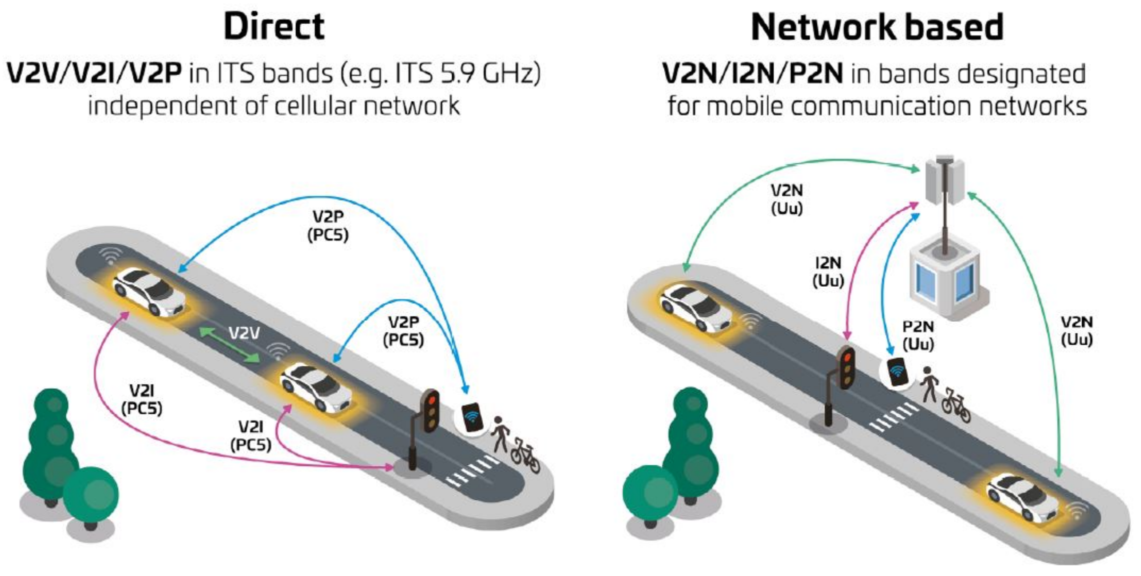

Figure 2: Direct and mobile network based communications modes supported by C-V2X [15]

By direct communication functionality, safety critical services are supported to reduce collisions, as well as automated driving is supported, and it helps also on the improvement of traffic efficiency.

2.2 3GPP Releases overview

Several wireless standards as Wireless Local Area Network (WLAN), Bluetooth or cellular networks, have been researched and proposed for V2X communications [16], but none of them has been able to satisfy the safety requirements that vehicular services need in terms of latency and availability. Cellular based and IEEE 802.11p based standards are the most promising ones at the moment, but due to the already existing LTE cellular network infrastructure, recent studies have preferred to use LTE as V2X technology [17].

Rel. 14 is a key step to next generation of cellular technologies as 5G NR. C-V2X was developed with evolution in mind, with enhancements coming in new releases. The new standards and specifications carried out by the 3GPP support backward compatibility, which means that vehicles based on old releases are able to operate with vehicles based on later releases, thus leveraging on 3GPP specifications included in Rel. 16 Release 17 (Rel. 17).

3GPP Release 12 (Rel. 12) was the first standard to introduce D2D communications using cellular technologies [18], where the first C-V2X standards where developed based on the 4G LTE air interface. This work was used by 3GPP to develop LTE V2X under Rel. 14 [19], which was later enhanced in Release 15 (Rel. 15). Then, in Rel. 16, a new C-V2X standard was developed based on the 5G NR air interface. All the study made before in Rel. 14 and Rel. 15 helped for the development of the technical work on Rel. 16.

Rel. 16 was also the first to include sidelink (SL) communications in V2X communications via 5G NR air interface. SL refers links where terminal nodes or UEs communicate directly without the data going through the network. In NR V2X communications, vehicles, Road Side Unit (RSU) and mobile devices carried by pedestrians are considered as UEs.

NR V2X is developed to complement LTE V2X and not to replace it. The idea is LTE V2X to support basic safety applications, and let NR V2X more advanced applications such as connected and automated driving issues. In order to achieve the cooperation between NR V2X and LTE V2X, Rel. 16 has defined some mechanisms at vehicle/device level to facilitate the coexistence of both technologies [20].

Regarding future releases, new study and work items have already been identified which will be collected in Rel. 17, with the purpose to enhance NR V2X SL communications. Among these enhancements, beamforming and resource allocation issues can be found [21]. In Fig. 3 a timeline summarizing the evolution of C-V2X standards under 3GPP is presented, focused on Radio Access Network (RAN) developments [21].

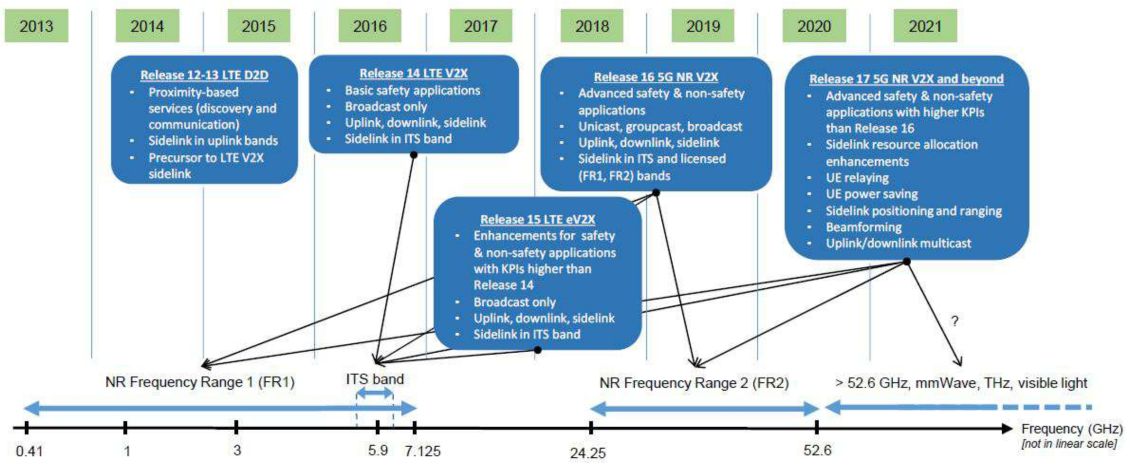

Figure 3: Progress of 3GPP work on V2X with a focus on RAN [21]

One of the major new features introduced by 5G is the mmWave frequency band. In this way, two different frequency ranges are available for the 5G technology and the different ranges have been designated, which rare:

- Frequency range 1 (Frequency Range 1 (FR1)): 410 MHz – 7.125 GHz.
- Frequency range 2 (Frequency Range 2 (FR2)): 24.25 GHz – 52.6 GHz.

Although Rel. 16 NR V2X SL can operate at both frequency ranges [22] [23], the work on Rel. 16 has been designed with a predominant focus on sub-6 GHz. As stated before, Rel. 16 does not propose beam management technique to compensate the path loss suffered at FR2 bands. However, there are certain V2X use cases that could be supported with the FR2 in order to achieve higher data rates, but with the support of beamforming to compensate the abovementioned additional path loss. These use cases include vehicles platooning, advanced driving, and extended sensors, which require high data rates in the order of 50-700 Mbps for long distances [24].

V2X communications support an increasingly automated mobility ecosystem where the need of effective interference avoidance measures is key for an efficient performance. An additional challenge for these communications is the use of directional beams which requires fast beam switching under such high mobility. The use of beamforming for vehicular scenarios is a promising enhancement [25] to the performance of currently widespread V2X technologies, which suffer from interference as a limiting factor for coverage and reliability. As beamforming enables directional transmission, spatial reuse of available resources can be allowed due to reduced interferences. Beamformed links will not only suppress the interference coming from undesired transmitters but also will improve the link budget to support mmWave communications [26]. This new paradigm in V2X might allow increased resource re-use and reliability, which as a first step requires the evaluation on the interference levels in high mobility scenarios for multi-beam antenna front-ends.

The frequency spectrum is traditionally considered a resource to be shared and the implementation of scheduling techniques can enhance the overall performance and efficiency of the network. In high-mobility traffic scenarios, the trade-off between maximizing instantaneous resource utilization and obtaining reliable quality measurements to facilitate an efficient adaptation of the radio resources to the user needs are considered as key problems [27]. In [28], a radio resource allocation scheme for D2D communications using fractional frequency reuse (FFR) is proposed, where the D2D communications can improve the overall system capacity and reduce interferences by reusing the frequency band of cellular networks and by selectively use radio resources according to their positions.

Regarding the work that 3GPP releases encompass, the enhancement of resource allocation is one of the objectives of Rel. 17. In Rel. 16, resource allocation is designed for UEs which do not have strong power limitations, as vehicles or RSUs. There are other type of UEs that present stronger power limitations, such as the devices used by pedestrians (e.g. smartphones). For these cases, longer sensing intervals are required by the user using the current Rel. 16 specifications, which severely impact the battery consumption. In this way, in Rel. 17 an improvement for resource allocation is adopted in order to reduce power consumption by using partial sensing [29], which was already considered in Rel. 14 for a variant of LTE V2X. Inter-UE coordination is another enhancement adopted for Rel. 17 [29], where an UEs coordinate between them to in order to assist each other in their resource selection. This improvement was analysed in Rel. 16 but not standardized.

2.3 Beamforming for interference management

V2X communications support an increasingly automated mobility ecosystem that the need of effective interference avoidance measures is key for an efficient performance. An additional challenge for these communications is the use of directional beams which requires fast beam switching under such high mobility. The use of beamforming for vehicular scenarios is a promising enhancement [25] to the performance of currently widespread V2X technologies, which suffer from interference as a limiting factor for coverage and reliability. Beam tracking provides a seamless connection of the radio link between vehicles. Beamformed links will not only improve the link budget to support mmWave communications, but also suppress the interference coming from undesired transmitters [26]. This new paradigm in V2X might allow increased resource re-use and reliability, which as a first step requires the evaluation of the interference levels in high mobility scenarios for multi-beam antenna front-ends.

The phenomenon of transmitting the signal in all directions spreads power towards undesired directions, as stated in [30], so that the signal quality is reduced for all users in the scenario. In [31], it is shown that having directional pattern antennas is an efficient solution, so in this way the signal is focused to the intended users. However, having directional pattern antennas present also some limitations as hidden node problems or visibility problems. Many types of radio transmissions depend on line of sight (LOS) between transmitter and receiver. In non line of sight (NLOS) cases, wireless links can only be established if reflective paths exist between the transmitter and receiver, by means of a base station. Large buildings, trees, mountains, hills or high voltage electric lines are usually common obstacles that cause NLOS situations. Some of these obstacles reflect certain radio frequencies, whereas some others absorb signals, but in both cases radio transmissions are limited.

In [32] and [33], smart antennas are proposed as a solution to reduce the interference effect and increase the signal quality at the receiving vehicle. There are two types of smart antenna technology, which are a switched-beam antenna and an adaptive array antenna. The first one does no require complexity and an intelligent methodology, whereas the second require more processing time due to the use of feedback control bits to adjust the amplitude and phase of the transmitting signal.

The use of multi-antenna schemes at transmitter and/or receiver side can also enhance cellular system's performances. Different antenna elements can be used for transmitting multiple streams of data over the same time-frequency resources, referred to as spatial multiplexing, leads to higher data rates [34]. By adjusting the amplitude and phase of each antenna, the energy radiated over the antenna is focused in a certain direction, in such a way that constructive interference can be realized in the desired direction. This, also known as beamforming, increases directivity so that a higher link budget, data rate and coverage is achieved. Interference is reduced as well, since transmission avoids radiating power into unwanted directions and reception suppresses interfering signals coming from undesired spatial locations [34].

There are two main mechanisms to perform beamforming, which are analog beamforming and digital beamforming. The first one implements the spatial filtering in the analog domain, so signal processing is applied after digital-to-analog conversion (DAC) in transmission, and before the analog-to-digital conversion (ADC) reception. On the contrary, digital beamforming performs filtering in the digital domain, that is, before DAC in transmission and after ADC in reception.

Multiple beam transmissions can be made by multiplexing over the available time-frequency grid. On the one hand, applying time-multiplexing implies that over one beam can be transmitted at a time (Fig. 4). The procedure of switching among beams is called beam sweeping, and it provides both analog and digital beamforming. On the other hand, frequency-multiplexing offers the possibility of simultaneous transmission of multiple beams (Fig. 5), but this is only possible in the digital domain.

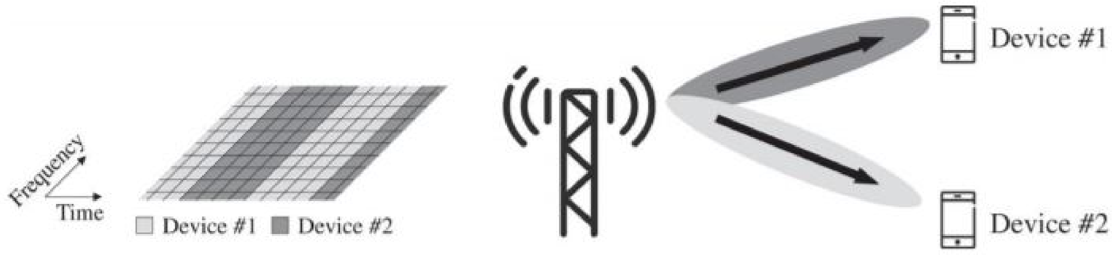

Figure 4: Time-multiplexed beamforming [34]

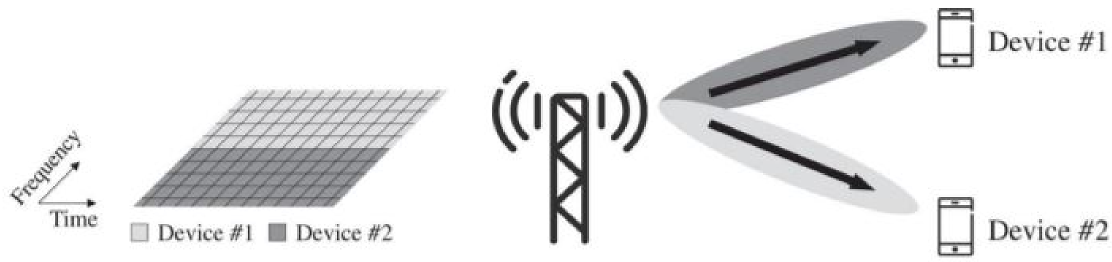

Figure 5: Frequency-multiplexed beamforming [34]

Regarding digital beamforming, it offers better beam-switching capabilities and full control over each antenna element because each antenna element is associated to an entry in a precoding matrix. However, it faces much more challenges than for the analog case at mmWave frequencies. In a fully digital baseband antenna processing, each antenna element requires a dedicated radio frequency [35]. The data converters (ADCs and DACs) have elevated consumption powers since they must manage high resolution and sampling frequencies [36]. Therefore, analog beamforming is a preferred implementation in the short term, whereas hybrid solutions combining both digital and analog approaches are topic of research [35] [37].

2.3.1 Beam Management

Beam management encompasses a collection of three fundamental procedures that aim to establish and retain a suitable beam pair. A suitable beam pair can be understood as the combination of the transmitting and receiving beams that provide the best link performance among all possible combinations for a particular use case.

The first of the three procedures that beam management encompasses is the Initial Beam Establishment, where a UE starts connection with another UE to ensure both Uplink (UL) and Downlink (DL). Beam sweeping is performed at both UEs. The transmitter first transmits synchronization signals and system information through different transmitting beams, and the receiver attempts to receive and decode this information by switching its receiving beams.

The next procedure is the Beam Adjustment. Suppose that a suitable beam pair has been chosen to establish a connection between UEs. This connection can be deteriorated due to several factors as movements, rotations, or light blockage, so there is the need to recalculate the beams by adjusting them. Beam Adjustment is the procedure in charge of adjusting or refining the existing communication beam pair if needed. In Fig. 6, the transmitter is sweeping through a beamset to transmit the Reference Signal (RS), where each DL beam has associated different RS resources.

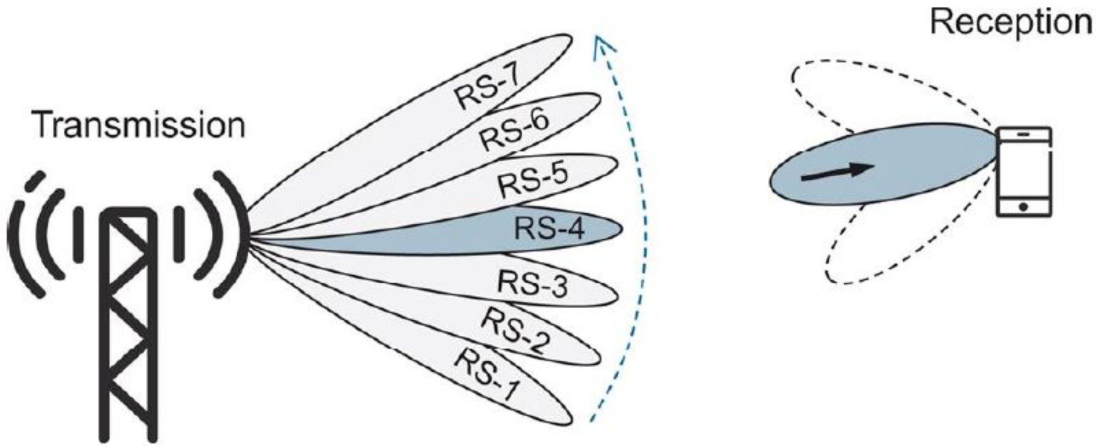

Figure 6: Beam sweeping at TX-side for beam adjustment [34]

Sometimes, due to rapid changes in the radio channel conditions, the beam adjustment procedure is not able to cope and counteract such changes. To deal with this problem, the Link Recovery procedure is used, which first identifies the beam failure (Beam Failure Detection) and then it solves (Beam Failure Recovery).

3 Framework / Methodology

The simulations done are based on a simulation framework running in a particular vehicular scenario. In such scenario, communication links are established between vehicles, which are equipped with antennas with a predetermined configuration. This section describes the system model and gives a detailed explanation of the simulation framework and the evaluation methods that have been used, as well as the relevant information to achieve the final results.

3.1 Antenna Configuration

The vehicles in the scenario are equipped with a set of mmWave arrays that enable V2V communications, located at the edges of the car rooftop as it can be seen in Fig. 7. A frequency of operation of 28 GHz is used in the simulation, so the set of mmWave arrays operate in the n257 5G band (26.50 - 29.50 GHz). The equipped antenna system consists of four panels that sectorize the azimuth in four equal sectors, giving a total steering capability of 360. Hence, each panel is designed to cover a steering range of ±45. Since the vertical deviation exhibited in V2V links is very little, the steering in the elevation plane has not been considered.

Based on the abovementioned configuration, the azimuthal range is divided into four equal sectors and each of the antenna panels faces its corresponding sector. The panels' configuration provides a finite set of beams – i.e. a beamset -. In particular, each panel divides its coverage range into 9 beams, which means that the total azimuthal range is covered by 36 equal beams with a mean half-power beamwidth of 10.

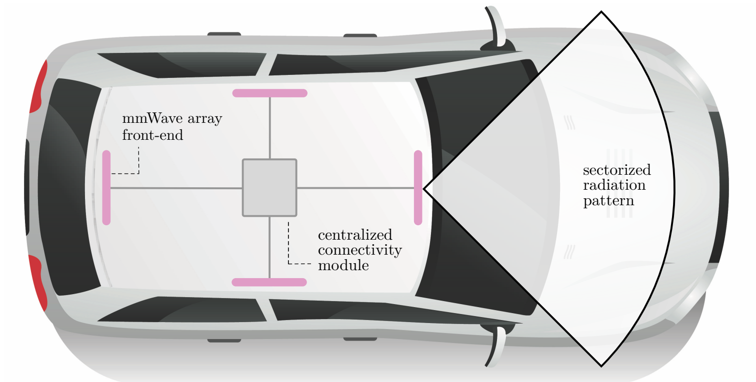

Figure 7: Top view of antenna arrays placement options

3.2 Vehicular scenario

Regarding the vehicular scenario used in the study, the simulations run on a scenario where two vehicles of interest communicate with each other at a distance d. Around them, a cloud of vehicles is placed within a radius of 200 meters, where those vehicles are located at random positions and they communicate in pairs by establishing one-to-one links between them. Regarding the vehicle pair of interest, one of them has a fixed position at the center of the scenario and the other vehicle is located at a random position within a radius of d meters.

The parameters listed in Table 1 define the configuration of the environment where the simulation runs. The chosen frequency for the simulation is 28 GHz corresponding to the 5G NR FR2 band with a bandwidth of 50 GHz. Regarding power constraints, a transmitted power of 23 dBm and a receiver noise factor of 13 dBm are used as specified in 3GPP TR 37.885 [38] for evaluation scenarios avobe 6 GHz.

Table 1: Configuration of the simulation environment

Parameter	**Value**
Parameter	Value
Operating Frequency	28 GHz
System Bandwidth	50 MHz
Transmitted Power	23 dBm
Receiver Noise Factor	13 dB
Number of vehicles	16, 32, 64
Vehicle pair distance (d)	50 m
Number of iterations	100

To analyze how the traffic around affects to a vehicle pair, the number of surrounding, interfering vehicles is gradually increased within the 200 m radius (16, 32, 64). For each traffic model, 100 random iterations are made changing the distribution of the vehicles. As the transmitting vehicle has a fixed position and since the beams emitted from the panels have fixed angles of emission, the position of the receiving vehicle is changed so that the angle of arrival of the beams is not always the same. Thus the LOS path is not fixed and results are not biased by the relative position between its azimuth of arrival (AoA) and the beam steering angle.

The following figures show three particular scenarios for 16, 32 and 64 vehicles. In each simulation, half of vehicles act as transmitters (in red colour) and the other half as receivers (in blue colour). As said before, for each iteration the distribution of vehicles is changed and such distribution obviously affects to the performance of the network. The vehicle pair which is analysed is indicated in the figures, where the transmitting vehicle (indicated as TX) is always positioned at the centre of the vehicle cloud, and the receiver (indicated as RX) changes its position at every iteration. Each transmitting and receiving vehicle has has a built-in antenna to carry out the corresponding communications.

In this particular iteration of the scenarios of 32 and 64 vehicles (Fig. 9 and 10 respectively), a vehicle is located between the LOS of the pair of interest, which can affect negatively to the signal quality received at the receiver side. There are other cases where although there is no vehicle interfering at the LOS between the analysed pair, some extent of SINR degradation can be perceived when an interferer is pointing towards our receiver. Having such undesired case studies increase the averaged perceived level of interference captured and, in consequence, affects the SINR.

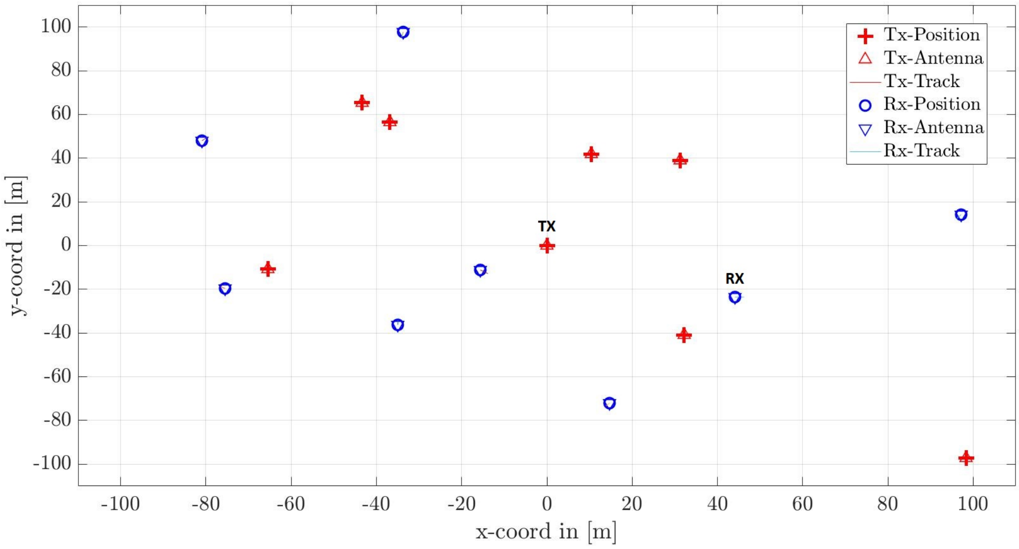

Figure 8: 16 vehicle scenario

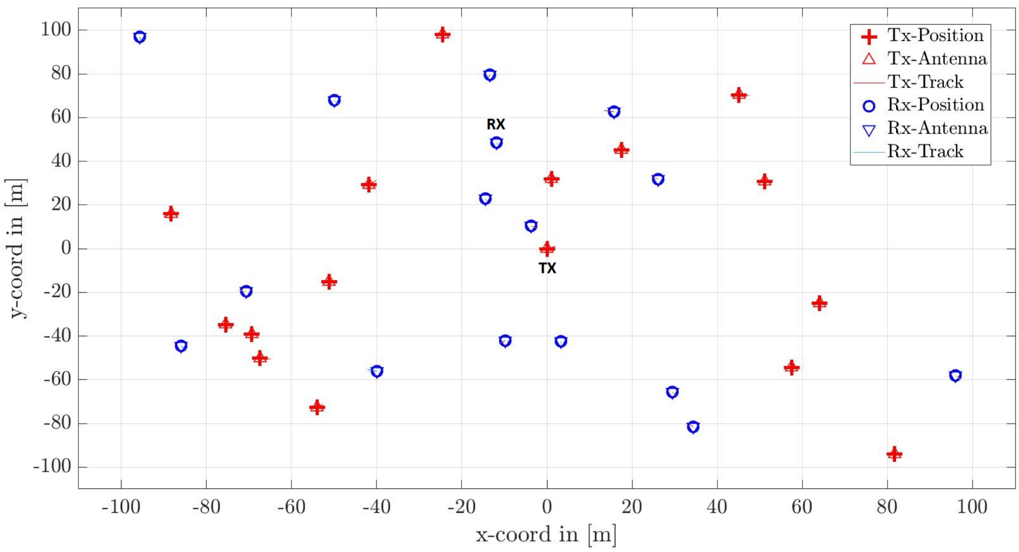

Figure 9: 32 vehicle scenario

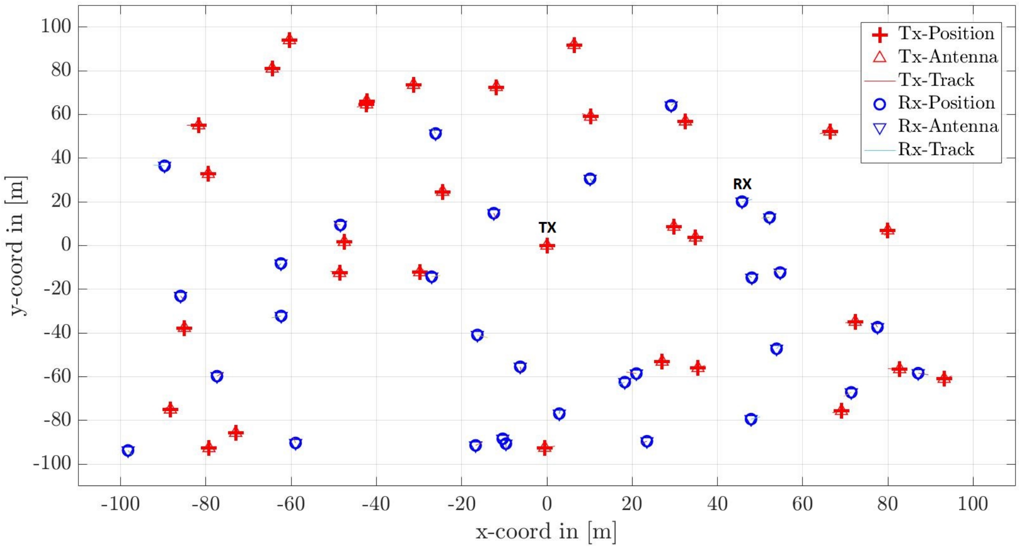

Figure 10: 64 vehicle scenario

3.3 Beam-based interference methodology

The beam-based interference evaluation carried out is presented in this section, which is the main study the project is supported on. Based on the abovementioned scenario, beamforming is used to establish links between vehicle pairs. During the simulation, all vehicles determine the most suitable beam pairs to establish a link with their corresponding pair by sweeping the entire beamset at both ends. In this way, each vehicle pair communicates using beamforming with the goal to improve the communication and reduce interferences towards undesired directions.

Once all the links are established, the receiving vehicle of the pair of interest measures the interference level for the entire beamset to obtain the spatial distribution of the interferers. The measuring vehicle scans the entire azimuth plane with the 36 beams. Centered on the chosen vehicle pair, the interference power level caused by the surrounding traffic is calculated to therefore obtain the perceived SINR. The goal is to detect the best beams in terms of SINR for future usage of the simulated specific scenario. It has to be considered that each type of scenario has its own features that will determine the specific needs for the communication link to be established. For example, the angular distribution of incoming waves differ in urban and open highway areas, changing consequently the beamforming techniques implemented for each.

The SINR is a way to measure the quality of wireless connections. In this evaluation, the signal of interest is defined as the power received from the transmitting vehicle of the considered pair, also known as Reference Signal Received Power (RSRP). The interference power is taken as incoherent superposition of the power received from the vehicles communicating around them.

To calculate the interference level for the entire beamset, the following procedure is followed. The vehicle pair under study is tagged as $i_{tx} = 1$ (transmitter) and $i_{rx} = 1$ (receiver). The rest of vehicle IDs are in the range of $i_{tx}, i_{rx} = 2, ..., Nveh/2$. In this way, the interference captured at the receiving vehicle 1 when using the beam b is:

$$I(i_{rx} = 1)_b = \sum_{i_{tx}=2}^{N_{tx}} P(i_{tx})_b \tag{1}$$

where N_{tx} is the number of transmitting vehicles at the scenario, which is half of the total number of vehicles N, and $P(i_{tx})_b$ is the power level received from transmitting vehicle i_{tx} at the beam b. As stated before, there azimuthal range is covered by 36 beams, so $b = 1, 2, ..., 36$ Note that the summation starts counting from $i_{tx} = 2$, since the power received from transmitting vehicle 1 is the reference signal received power (RSRP).

$$RSRP(i_{rx} = 1)_b = P(i_{tx} = 1)_b \tag{2}$$

Now, once the interference level and the RSRP for a specific beam b are available, the SINR for such beam can be calculated with the traditional formula of the SINR. Therefore, by changing the beam b in the calculations, the SINR for the full beamset can be calculated. The SINR for a specific beam b will be:

$$SINR(i_{rx} = 1)_b = \frac{RSRP(i_{rx} = 1)_b}{I(i_{rx} = 1)_b + N} \tag{3}$$

where N is the noise in linear scale, calculated as:

$$N = 10^{\frac{-174+10\cdot log10(BW)+NF_{RX}}{10}} \tag{4}$$

being BW the bandwidth of the system (50 MHz) and NF_{RX} the receiver noise figure (13 dB).

As far as the physical layer of 5G V2X communications is concerned, an efficient radio resource management (RRM) has a paramount importance, but in the present study no scheduling technique is used and all vehicles transmit simultaneously using the same radio resources available. However, as will be seen later, the results presented in section 4.1 open a line of research for the reutilization of radio resources due to the obtained values.

4 Beam-based interference assesment

In this section, the main results of the project are presented. They show the performance advantage achieved due to the uses of beamforming over omnidirectional antennas. As stated above, random vehicle pairs are formed and the study focuses on a specific pair to extract the metrics of interference power level, RSRP and SINR. On the other hand, the optimal beam choice is discussed in terms of SINR for the simulated specific scenarios and some statistics are shown about beam performances in terms of RSRP and SINR.

4.1 Beam-based interference evaluation

Several numerical evaluations are performed in the vehicular scenario specified in section 3.2 where the vehicles are equipped with the antenna configuration specified in section 3.1.

Fig. 11 represents the SINR obtained for the given pair using omnidirectional antenna pairs and the aforementioned beamset for a single shot of the simulation environment with 64 vehicles. The angular axis represents the azimuth, where each beam occupies a range of 10. The black line is set for the LOS angle between the two vehicles, so it points towards the transmitting vehicle. As omnidirectional antennas receive equally from all directions, a constant SINR value is obtained for such case. However, for the beamformed case, a clear peak is seen towards the angle at which the transmitter vehicle is positioned. The receiving beams which are pointing towards those angles close to the AoA of the incoming waves present a better RSRP, which could potentially lead to a better SINR. The perceived level of interference with each beam also determines the final performance in terms of SINR.

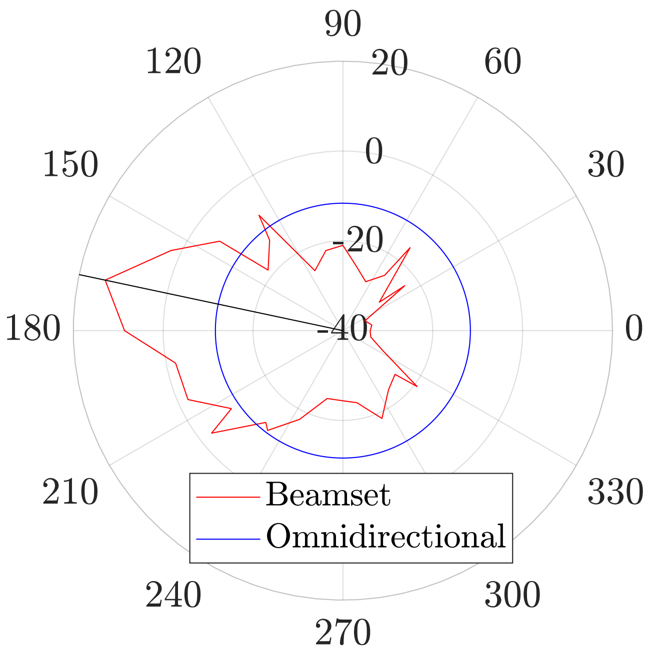

Figure 11: SINR with Omnidirectional antenna and with the beamset (for 64 vehicles scenario)

In Fig. 12 the SINR is plotted together with the RSRP and the interference power level among the beamset. Based on the plot, it can be stated that not only the beam strictly pointing towards the other car obtains the best SINR. The adjacent beams present also a good performance, sometimes even better than the beam pointing towards the transmitting vehicle. This means that the beam located in the direction of the transmitting vehicle is not always the best choice in terms of SINR. The influence of the traffic surrounding determines the interference power for each beam and this should be taken into account. There may be cases where a third vehicle is located between two vehicles which are trying to communicate, thus increasing the level of interference or degrading the desired signal due to shadowing issues (vehicle-blocked NLOS (NLOSv)) in the LOS angle between the two vehicles. This happens in Fig. 12, where a better SINR is obtained for a beam which is not pointing towards the LOS angle of the transmitting vehicle. Although the angle the other vehicle is represents a higher RSRP, the interference level at such angle is also higher than for the adjacent ones, which leads to a worse result in terms of SINR.

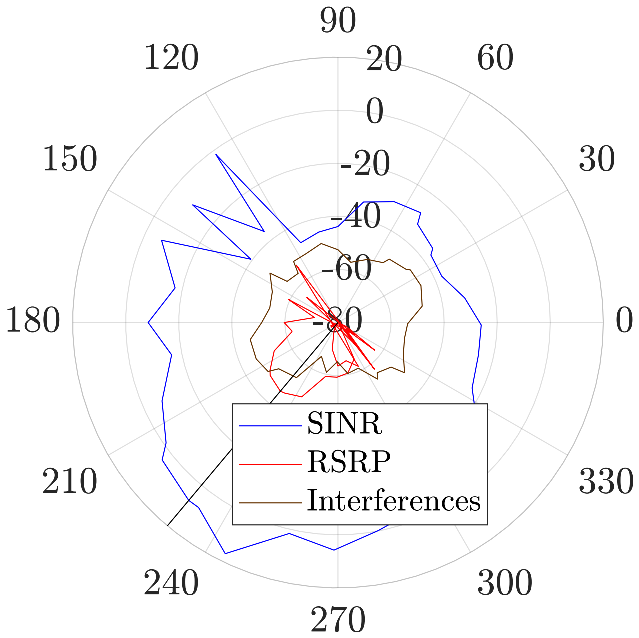

Figure 12: SINR, RSRP and Interference power level among the beamset (for 16 vehicles scenario)

This fact implies that sometimes it is a better option to choose the optimum beam based on the obtained SINR rather than on a RSRP or positioning criterion. As seen in section 3.2, in the scenarios of 32 and 64 vehicles (Fig. 9 and 10) a vehicle is interfering the LOS between the pair of interest, which may degrade the communication quality between them. In such cases, the problem can be resolved by taking an adjacent beam which is not pointing directly towards the target vehicle. There might be other cases where although a vehicle is not located in the LOS of a pair, it might use a beam pointing directly to our receiver, thus increasing significantly the interference power level.

Fig. 13 is another example of how choosing the adjacent beam in some cases improves the link quality with a better SINR value. To understand this value, if the interference level is observed at such angle, it is seen it takes a lower value. The RSRP is almost equal to the value at the target vehicle's angle, so the interference level is who determines the beam choice.

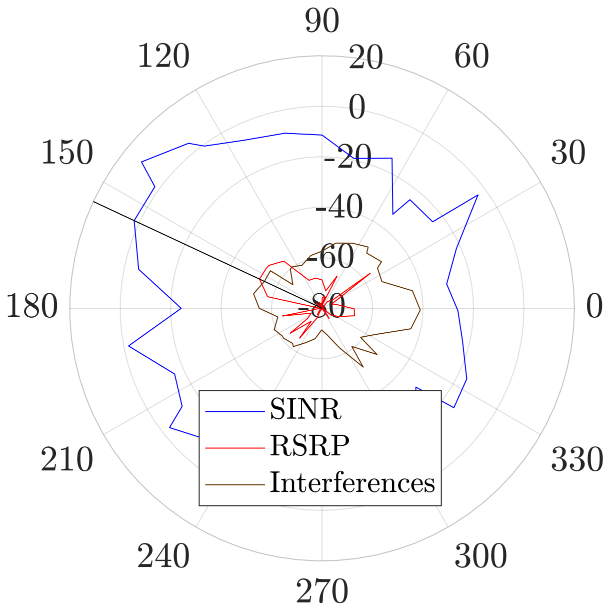

Figure 13: SINR, RSRP and Interference power level among the beamset (for 16 vehicles scenario)

4.2 Optimum beam choice in terms of SINR

It is worth mentioning that a suitable beam pair is not always related to a direct path between transmitter and receiver. To address this issue, where the optimum beam choice in terms of SINR can change depending on the traffic around, the simulation has been repeated for the three traffic configurations (16, 32 and 64 vehicles). In each iteration, the receiver's position for a fixed distance and the traffic distribution is changed. For each scenario, it is analyzed the disagreement between beam under maximum RSRP and maximum SINR criteria. Also the use of the LOS information is considered as a selection criterion. Therefore, it is possible to determine which is the most suitable beam in each case.

An statistical analysis is then carried out for the two aforementioned cases. Those statistics are shown in Tables 2 and 3, which include the following figures of merit:

- Average value of angular change
- SINR loss with respect to maximum achievable
- Percentage of cases where both criteria do not coincide

Table 2: Comparison between the beams with maximum RSRP and maximum SINR

Parameter	**Number of Vehicles**		
	16	**32**	**64**
Angular change	10.13	5.61	1.8
Power loss	-2.32 dB	-1.14 dB	-0.89 dB
Beam change percentage	62.34%	52.34%	46%

Table 3: Comparison between the beam pointing to the transmitting vehicle and the beam with maximum SINR

Parameter	**Number of Vehicles**		
	16	**32**	**64**
Angular change	25.6	19.73	19.7
Power loss	-2.72 dB	-1.4 dB	-1 dB
Beam change percentage	62.67%	55.67%	47%

The fact of increasing the number of vehicles increases the probability of having vehicles communicating in almost the entire azimuthal range, which implies having a more uniform level of interference among the beamset. This is why the higher the number of vehicles is, the less often a beam change occurs, since choosing an adjacent beam does not suppose a substantial change due to having a more uniform interference level. On the other hand, the interference level for a reduced number of vehicles may substantially change among adjacent beams which implies a considerable degradation in terms of SINR, so that a beam change occurs more often.

Looking at the tables, the beam change percentages obtained for both cases are almost equal, whereas the angular change given for them differs significantly. Such angular changes are higher for the second case where the comparison between the beam pointing to the transmitting vehicle and the beam with maximum SINR is done. This means that the beam where the maximum SINR is obtained is often closer to the beam with maximum RSRP or is even the same beam, since each beam covers a 10azimuthal range. On the other hand, as previously intuited, the beam change or angular change occurred for the second case is much higher, which means that the interferences of surrounding vehicles forces to change to the adjacent or even one more. This may happen because the interferences affect to both RSRP and SINR, so that when one of them is degraded the other one is degraded at the same time, thus decreasing the angular change.

Having less vehicles implies having a more heterogeneous interference level. This in turn implies a considerable fluctuation in terms of SINR. For 16 vehicles, using the beam at the LOS AoA instead of the best in terms of SINR, results in a loss of almost 3 dB. As the traffic around grows, the relative degradation in the SINR is reduced, which is around 1 dB.

In Fig. 14, the RSRP is maximum at the angle where the target vehicle is. However, the SINR is not maximum at such angle. At 180, the interference level captured is significantly lower and this leads to a better value of SINR compared to the obtained at the angle where the RSRP is maximum. Comparing to the result obtained in Fig. 12, this time the RSRP at the angle of maximum SINR (180) is much lower than at the angle of the receiver vehicle, but the low interference power captured at such beam plays a very important role. This implies that the optimal beam is the one pointing towards 180, which is 40away from the target vehicle. In other words, this time instead of taking an adjacent beam, a beam which is three or four beams apart is used, since there is a 40difference and each beam covers a 10range. This result is obtained for a scenario of 16 vehicles, so it helps to understand such a dramatic beam change. As stated before, the vehicle cloud in a scenario with only 16 vehicles is not very homogeneous and consequently neither is the interference level.

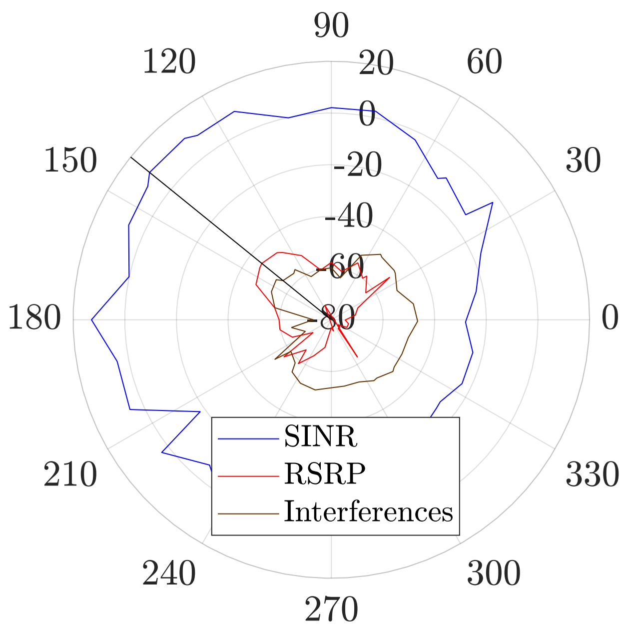

Figure 14: Beam change in a 16 vehicle scenario

5 Radio resource reuse evaluation

As next step, the re-use of radio resources is analysed in this section. In the previous section, no scheduling technique is implemented in the interference evaluation. All the vehicles in the scenario use the same resources and the results still show an acceptable link quality, since reasonable values of SINR are obtained, at least for the case of 16 vehicles. For the 32 and 64 vehicle cases, the SINR obtained is lower as expected, apart from a few isolated cases where the scenario was very favourable in terms of interference. The main objective of this study is to analyze how many vehicles can be supported in a scenario with all of them sharing the same resources. The performance is evaluated in terms of SINR to see how many vehicles can be supported while guaranteeing a reasonable SINR.

It is expected that as the number of vehicles increases, the communication quality between them will decrease. To see such evolution, a simulation is performed to analyse how the network performance is degraded. In this simulation, the SINR mean value is calculated for scenarios where the number of interfering vehicles increases gradually. The simulation starts from a 2 vehicle scenario where only the transmitter and the receiver are in the network, so there is no interference. Then, the vehicle quantity is increased in the scenario in steps of 10 until having 70 vehicles in it. For each case, 100 iterations are made and the mean value of the SINR is calculated for the two cases analysed in the previous section:

- Maximum SINR
- SINR at the angle the RSRP is maximum

From previous experience from the above simulations in Section 4, it has been observed that an increase in traffic leads to a more homogeneous interference power lever. When the number of vehicles increases, there is a higher probability to have vehicles over the full azimuthal range, so that the interference level seen by the vehicle pair in the network is almost uniform in azimuth. Taking this into account, it is expected that there will be a point where even if the number of vehicles increases, the interference level will not change a lot, so that the SINR will tend to 0. In other words, when the vehicle number simulated in the scenario tends to infinite or to a considerably large value, the degradation of the SINR will be almost negligible, due to having an uniform interference level in azimuth.

On the other hand, when there is no traffic around, i.e., when only the vehicle pair of interest is in the scenario, the maximum SINR might be achieved. When interfering vehicles are added around, the SINR is expected to decrease rapidly, since the change from having none interference to having vehicles around communicating will be noticeable.

To verify these hypothesis, Fig. 15 shows the results obtained from the simulation. The red points represent the maximum SINR mean value and the blue ones the SINR mean value at maximum RSRP angle. Looking to the graphic, the difference between these two values decreases as long as the number of vehicles increases. With only two vehicles at the scenario, i.e. with no interference, they both obtain the same value, but when interfering vehicles appear on the scenario, a difference up to 3 dB can be observed. This is due to the non uniformity of the incoming waves of interferences. As long as the vehicle number is increased and the interference level becomes more uniform in the azimuthal range,

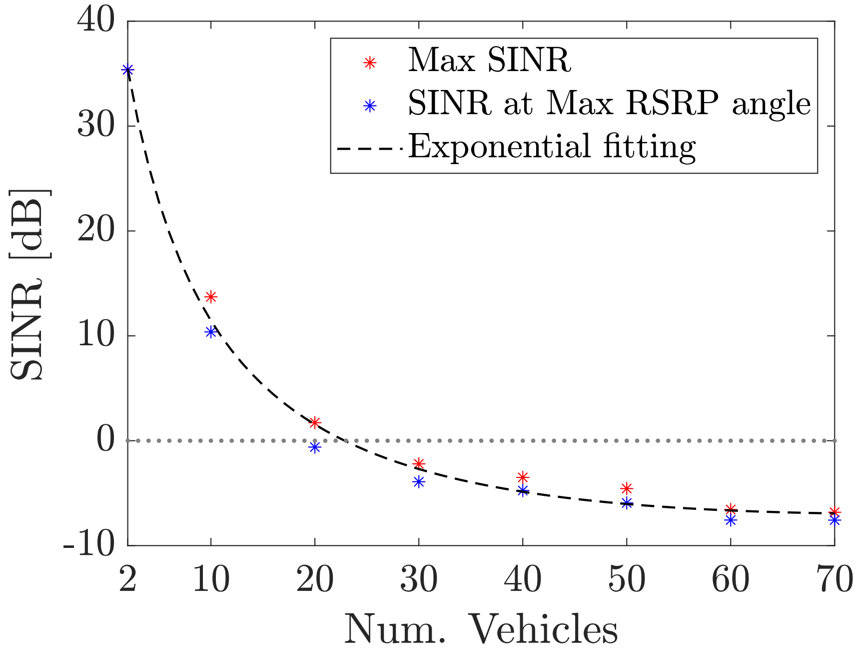

Figure 15: SINR evolution vs number of vehicles

the difference between them decreases. When the traffic is considerably large and the interference level becomes totally uniform, it is expected that both values will coincide.

Another fact to highlight is the behaviour of the curve. At the beginning it presents significant gradient so that the SINR degrades considerably. Later, from 30 vehicles onwards, the curve becomes smoother due to the fact of interferences commented before. On the other hand, another fact that justifies this behaviour is the difference of adding a new vehicle pair around depending on the current scenario. It is not the same to add a new pair when the number of interfering vehicles is null or low, or to add a pair when there are 30 more vehicles around. The impact of such addition is very different depending on the situation. This is why at the beginning the SINR starts to worsen radically.

As stated before, the idea of this evaluation is to see how many vehicles can be supported with shared resources. To see this, a line is plotted on 0 dB to show to what extent a positive SINR can be guaranteed. According to the graph, about 20 vehicles can be supported with a SINR around 2 dB. From there on, a negative SINR is obtained, which does not always mean that vehicles cannot communicate at such SINR.

Furthermore, as seen in Fig. 15, an exponential curve approximation has been calculated, so in this way, the SINR for your vehicle of interest can be approximated when a certain number of vehicles is present on the scenario. Such equation depends only in the number of vehicles, so by introducing it the SINR will be given in dB. In this way, for future works, such value can be approximated without the need of doing the whole simulation again. The equation is the following:

$$SINR = 81.38^{-0.3087 \cdot NV} - 30.05 \tag{5}$$

where NV is the number of vehicles, which includes the vehicle pair of interest. So, for example, for 8 interfering vehicles, $NV = 10$ has to be introduced in order to take into account the vehicle pair for which the SINR is going to be calculated.

Finally, it should be noted that the simulation together with equation 5 is calculated for a bandwidth of 50 MHz. If the bandwidth is increased, the result will be different, since more resources will be available, but from the other part, more background noise will be also captured. 5G NR beyond the introduction of mmWave bands also offers some other capabilities as the manipulation of the subcarriers' spacing by means of the numerology. So, by playing with all those benefits that 5G offer the physical layer can be manipulated to enhance the performance of V2X communications.

6 Environmental Impact

The goal of V2X communications is to enable the exchange of information between vehicles and infrastructure to improve road safety and efficiency, but there is another increased interest for the implementation of V2X due to its potential environmental benefits, which will reduce substantially transport emissions in order to help mitigate climate change. There is an upcoming strategy lead by the European Commission (EC) on Sustainable and Smart Mobility which intends to achieve a 90% reduction in emissions by 2050 [39].

There are several impact mechanisms to achieve such reduction of emissions, related to the existing inefficiencies of the transport and traffic system. These mechanisms, including reduction of trips, reduction of kms driven or reduction of vehicle dynamics, among others. [39].

Among the use cases that V2X communications provide, platooning, for example, allows self-driving vehicles to follow each other maintaining relatively small distances. This technique can lead to a reduction in fuel consumption and CO2 emissions. A study made about the effects of platooning on consumption, suggest that a reduction up to 15% can be achieved [40].

To sum up, by means of V2X communications, a considerable environmental is expected to be achieved, beyond the an enhancement on driving safety, traffic efficiency and driver's experience.

7 Conclusions and future development

Finally, the main conclusions extracted from the work are presented and, in addition, some ideas or suggestions are given for future development, since several lines of research have been left open.

This thesis focuses on the performance of V2V communications among the different use cases that V2X communications provide. The use of mmWave bands with its larger bandwidth provides higher transmission rates that enhance performance in terms of achievable rate, but at the same time such frequencies suffer from larger path losses. The deployment of beamforming is one of the solutions to solve this issue as shown in the results obtained. The project introduces the potential of beamforming techniques over omnidirectional antennas to deal with interferences that high mobility scenarios present in vehicular communications. The link-level performance is evaluated in terms of SINR and the results suggest a substantial improvement for the specific angles the vehicles are communicating at. Pointing a beam towards the target vehicle increases the RSRP and does not capture all the surrounding interference, but only those in the path of the beam. This leads to a potentially higher SINR value.

Furthermore, the optimal beam choice is discussed for the simulated scenarios. Beam-steering strategies may induce that the best beam should always be the one pointing strictly towards the target, but the study demonstrates that this is not always the best strategy. The traffic influences the communication quality elevating the interference level in such beam. This implies that a contiguous beam which is not pointing exactly to the target vehicle might become a better option when lower interference level is captured, thus improving the SINR. Not choosing the best beam in terms of SINR may lead to a power loss of up to 3 dB which degrades the link performance significantly.

Regarding the beam management technique used for the simulation, the optimal technique is not here discussed, which can further improve the overall performance and it is left as a future research scope.

Apart from this, the previous results open a new line of research for the re-utilization of radio resources since no scheduling technique has been implemented and still good enough results are obtained for the beamformed case in terms of SINR. In addition, a simulation is performed to find out how many vehicles can be supported with all of them re-using the available resources in the network.

According to such simulation, a vehicle pair is able to communicate with a SINR of around 2 dB with 18 more vehicles around them interfering the communication link. It is quite a significant value taking into account the number of vehicles supported with all of them reusing the same radio resources. Nevertheless, such value does not mean that an optimal performance is guaranteed, since other aspects has to be considered, as whether the demodulation system used allows such value of SINR, is not here discussed. In addition, an equation is presented to approximate the SINR for whatever number of vehicles and it is shown that when adding vehicles the degradation of the SINR differs depending on the traffic congestion at that particular moment.

Finally, it has to be said that by scheduling the radio resources the overall performance of the vehicular communications can be enhanced. The increased number of vehicles on road and the high mobility that vehicular environments present makes it necessary an implementation of such technique. Despite the fact that mmWave bands offer wider bandwidths, the spectrum is limited and the demand of application and devices connected around is increasing. Therefore, the management of available resources is an issue to be addressed and is left as future work.

References

[1] Sohan Gyawali, Shengjie Xu, Yi Qian, and Rose Qingyang Hu. Challenges and Solutions for Cellular Based V2X Communications. *IEEE Communications Surveys & Tutorials*, pages 222–255, October 2020.

[2] THALES GROUP. V2x: What is vehicle to everything? https://www.thalesgroup.com/en/markets/digital-identity-and-security/iot/industries/automotive/use-cases/v2x.

[3] V. Ratanavaraha and S. Suangka. Impacts of accident severity factors and loss values of crashes on expressways in Thailand. *IATSS Research*, pages 130–136, 2014.

[4] V. Ratanavaraha and S. Jomnonkwao. Community participation and behavioral changes of helmet use in Thailand. *Transport Policy*, pages 111–118, 2013.

[5] European Commission. Road safety: 4,000 fewer people lost their lives on eu roads in 2020 as death rate falls to all-time low. https://ec.europa.eu/commission/presscorner/detail/en/ip_21_1767, April 2021.

[6] Zahra Naghsh and Shahrokh Valaee. Conflict-Free Scheduling in Cellular V2X Communications. *IEEE/ACM Transactions on Networking*, pages 106–119, October 2020.

[7] Stephan Jaeckel, Leszek Raschkowski, Lars Thiele, Frank Burkhardt, and Ernst Eberlein. Quasi Deterministic Radio Channel Generator User Manual and Documentation. Technical report (tr), Fraunhofer Heinrich Hertz Institute, August 2017. Version 2.0.0.

[8] 5GAA. About 5gaa. https://5gaa.org/about-5gaa/about-us/.

[9] NHTSA. Automated vehicles for safety. https://www.nhtsa.gov/technology-innovation/automated-vehicles-safety.

[10] Christian Hoymann, David Astely, Magnus Stattin, Gustav Wikstrom, Jung-Fu Cheng, Andreas Hoglund, Mattias Frenne, Ricardo Blasco, Joerg Huschke, and Fredrik Gunnarsson. LTE release 14 outlook. pages 44–49, June 2016.

[11] Harding John, Powell Gregory, Yoon Rebecca, Fikentscher Joshua, and Doyle Charlene. Vehicle-to-vehicle communications : readiness of V2V technology for application. Technical report (tr), 08 2014.

[12] Kelly Hill. What is dsrc for the connected car? https://www.rcrwireless.com/20151020/featured/what-is-dsrc-for-the-connected-car-tag6, October 2015.

[13] 3GPP. Technical Specification Group Services and System Aspects;Study on enhancement of 3GPP Support for 5G V2X Services; (Release 16). Technical Report (TR) 22.886, 3rd Generation Partnership Project (3GPP), December 2018. Version 16.2.0.

[14] 5GAA. Timeline for deployment of C-V2X – Update. January 2018.

[15] 5GAA. A visionary roadmap for advanced driving use cases, connectivity technologies, and radio spectrum needs. September 2020.

[16] H. Seo, K. D. Lee, S. Yasukawa, Y. Peng, and P. Sartori. LTE evolution for vehicle-to-everything services. *IEEE Communications Magazine*, pages 22 –28, June 2016.

[17] C. Lottermann, M. Botsov, P. Fertl, and R. Mullner. Performance evaluation of automotive off-board applications in LTE deployments. *Vehicular Networking Conference (VNC)*, pages 211–218, Novemeber 2012.

[18] Xingqin Lin, Jeffrey G. Andrews, Amitabha Ghosh, and Rapeepat Ratasuk. An overview of 3GPP device-to-device proximity services. *IEEE Communications Magazine*, pages 40–48, April 2014.

[19] Shanzhi Chen, Jinling Hu, Yan Shi, Ying Peng, Jiayi Fang, Rui Zhao, and Li Zhao. Vehicle-to-Everything (v2x) Services Supported by LTE-Based Systems and 5G. *IEEE Communications Standards Magazine*, pages 70–76, July 2017.

[20] 3GPP. TR 37.985 Overall description of Radio Access Network (RAN) aspects for Vehicle-to-everything (V2X) based on LTE and NR (v16.0.0, Release 16). Technical report (tr), 3rd Generation Partnership Project (3GPP), Sept 2020. Version 16.0.0.

[21] Mario H. Castañeda Garcia, Alejandro Molina-Galan, Mate Boban, Javier Gozalvez, Baldomero Coll-Perales, Taylan Şahin, and Apostolos Kousaridas. A Tutorial on 5G NR V2X Communications. *IEEE Communications Surveys Tutorials*, pages 1–1, February 2021.

[22] 3GPP. TS 38.101-1 NR; User Equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone (v16.3.0, Release 16). Technical report (tr), 3rd Generation Partnership Project (3GPP), March 2020. Version 16.3.0.

[23] 3GPP. TS 38.101-2 NR; User Equipment (UE) radio transmission and reception; Part 2: Range 2 Standalone (v16.3.1, Release 16). Technical report (tr), 3rd Generation Partnership Project (3GPP), March 2020. Version 16.3.1.

[24] 3GPP. TS 22.186 Service requirements for enhanced V2X scenarios (v16.2.0, Release 16),”. Technical report (tr), 3rd Generation Partnership Project (3GPP), June 2019. Version 16.2.0.

[25] Ilmari Maskulainen, Petri Luoto, Pekka Pirinen, Mehdi Bennis, Kari Horneman, and Matti Latva-aho. Performance evaluation of adaptive beamforming in 5G-V2X networks. *2017 European Conference on Networks and Communications (EuCNC)*, July 2017.

[26] Nivetha Kanthasamy, Alexander M. Wyglinski, and Raghvendra Cowlagi. Effects of Interference on Beamforming-Enabled Vehicular Networks in Multipath Propagation Environments. *2020 IEEE 91st Vehicular Technology Conference*, May 2020.

[27] Jens Zander. Radio resource management in future wireless networks: requirements and limitations. *IEEE Communications Magazine*, pages 30–36, August 1997.

[28] Hyang Sin Chae, Jaheon Gu, Bum-Gon Choi, and Min Young Chung. Radio resource allocation scheme for device-to-device communication in cellular networks using fractional frequency reuse. *The 17th Asia Pacific Conference on Communications*, October 2011.

[29] LG Electronics. RP-193257. New WID on NR sidelink enhancement. *3GPP TSG RAN Meeting 86, Sitges*, Dec. 2019.

[30] Rami Sabouni and Roshdy M. Hafez. Performance of DSRC for V2V communications in urban and highway environments. *2012 25th IEEE Canadian Conference on Electrical and Computer Engineering (CCECE)*, April 2012.

[31] R.-T. Juang. Performance analysis of V2V DSRC communicationswith reconfigurable antenna. *Proceedings of the 19th ITS World Congress*, October 2012.

[32] Anand Prabhu Subramanian, Vishnu Navda, Pralhad Deshpande, and Samir R. Das. A measurement study of inter-vehicular communication using steerable beam directional antenna. *Proceedings of the fifth ACM international workshop on VehiculAr Inter-NETworking(VANET '08)*, pages 7–16, September 2018.

[33] Salil Kumar Sanyal, Quazi Md. Alfred, and Tapas Chakravarty. A novel beam-switching algorithm for programmable phased array antenna. *Progress in Electromagnetics Research*, pages 187–196, January 2006.

[34] Juan David Sanchez Silva. Beam management for 5g nr, December 2019.

[35] Foad Sohrabi and Wei Yu. Hybrid Digital and Analog Beamforming Design for Large-Scale Antenna Arrays. *IEEE Journal of Selected Topics in Signal Processing*, pages 501–513, January 2016.

[36] C.H. Doan, S. Emami, D.A. Sobel, A.M. Niknejad, and R.W. Brodersen. Design considerations for 60 GHz CMOS radios. *IEEE Communications Magazine*, pages 132 – 140, December 2004.

[37] Shuangfeng Han, Chih lin I, Zhikun Xu, and Corbett Rowell. Large-scale antenna systems with hybrid analog and digital beamforming for millimeter wave 5G. *IEEE Communications Magazine*, pages 186 – 194, January 2015.

[38] 3GPP. Technical Specification Group Radio Access Network; Study on evaluation methodology of new Vehicle-to-Everything (V2X) use cases for LTE and NR; (Release 15). Technical Report (TR) 37.885, 3rd Generation Partnership Project (3GPP), June 2019. Version 15.3.0.

[39] Eleni Charoniti, Gerdien Klunder, Peter-Paul Schackmann, Max Schreuder, Ramon de Souza Schwartz, Dawn Spruijtenburg, Uilke Stelwagen, and Isabel Wilmink. Environmental Benefits of C-V2X for 5GAA - 5G Automotive Association E.V. . Technical report (tr), TNO innovation for life, November 2020.

[40] Youssef Bichiou and Hesham Rakha. Vehicle Platooning: An Energy Consumption Perspective. *2020 IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC)*, pages 1–6, September 2020.

Appendices

As an outcome of this thesis, in collaboration with the supervisor, the following paper was published in Simposium of the Union Radio-Scientifique Internationale (URSI) 2021.

Beam-based Interference Assessment of Vehicular Communications at mmWave Bands

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***Abstract*—The field of vehicular communications has undergone a significant transformation and is interested in getting more vehicles connected to improve traffic efficiency and safety. The introduction of the millimeter-wave (mmWave) region in 5G New Radio (NR) to achieve higher data rates and the implementation of beamforming techniques to address the issue of higher propagation losses, potentially enables several Vehicle-to-Everything (V2X) use cases for cooperative automated driving and enhanced information services. This paper proposes an approach of beam-based interference assessment for Vehicle-to-Vehicle (V2V) communications at mmWave. The perceived interference level is evaluated for a given beamset covering the full azimuthal range. This information provides useful insights on the quality of communications and the potential re-use rate of scheduled resources.**

I. Introduction

The automotive industry has become one of the big challenges towards the next generation communication system. This sector has undergone a massive research to address the communication capabilities in vehicles with the end goal of fully automated driving. By means of V2X communications, vehicles are able to get information from its surroundings to improve driving safety, traffic efficiency and the driver's experience. V2X encompasses various use cases by exchanging messages with infrastructure (V2I), pedestrian (V2P) or other vehicles (V2V) [1].

Those technologies are based on Device-to-Device (D2D) communications, which have been introduced both for Cellular V2X (C-V2X) (from Release 14 forward) [2] and Dedicated Short-Range Communications (DSRC) [3]. The latter benefits from low-latency protocols to create an adhoc network between the vehicles [4]. On the contrary, LTE-V2X is backed by the cellular network to provide ubiquitous coverage and support very high mobility [5]. In addition, 5G NR is expected to push the limits of connectivity performance for such vehicular scenarios with the introduction of mmWave bands, multi-antenna techniques and flexible numerologies. The 3GPP has already enabled many of the NR features in Release 16 to be used by vehicles and infrastructures [6].

The use of high frequencies for vehicular communications is a noteworthy option to support very low latencies and higher data rates thanks to the wide bandwidth that mmWave bands provide. However, mmWave systems suffer from larger path loss and penetration losses than those operating at sub-6 GHz bands. One solution to this issue is to deploy beamforming at both transmitter and receiver sides with the so-called beam management procedures. To align the beams at both ends and to ensure link stability, beam management embraces a set of features and procedures such as beam determination to select suitable beam pairs, beam refinement to improve link throughput, and beam sweeping to cover the desired angular sector [7].

V2X communications support an increasingly automated mobility ecosystem that the need of effective interference avoidance measures is key for an efficient performance. An additional challenge for these communications is the use of directional beams which requires fast beam switching under such high mobility. The use of beamforming for vehicular scenarios is a promising enhancement [8] to the performance of currently widespread V2X technologies, which suffer from interference as a limiting factor for coverage and reliability. Beamformed links will not only improve the link budget to support mmWave communications, but also suppress the interference coming from undesired transmitters [9]. This new paradigm in V2X might allow increased resource re-use and reliability, which as a first step requires the evaluation on the interference levels in high mobility scenarios for multi-beam antenna front-ends.

In this paper, the performance of V2V communications is evaluated in terms of Signal-to-Interference-plus-Noise (SINR). The study focuses on a beam-based interference assessment at mmWave bands to measure the degradation suffered in the quality of the communication due to high mobility in V2V scenarios.

II. System Model

A simulation framework runs in a particular vehicular scenario where the vehicles are equipped with antennas with a predetermined configuration. This section describes the system model and gives a more detailed explanation of the simulation that has been carried out.

A. *Vehicular scenario*

The simulation runs on a scenario where two vehicles of interest communicate with each other at a distance d and a cloud of vehicles is placed within a radius of 200 meters. Those vehicles are located at random positions and they communicate in pairs by establishing one-to-one links between them. Regarding the vehicle pair of interest, one of them has a fixed position and the other vehicle is located at a random position within a radius of d meters.

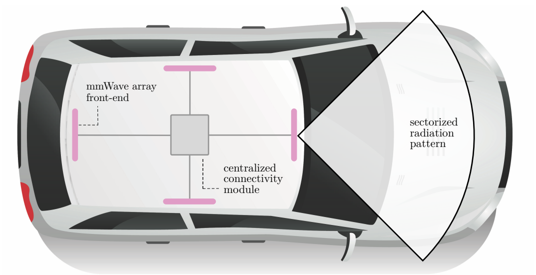

Fig. 1: Top view of antenna arrays placement options.

B. Antenna configuration

The vehicles in the scenario are equipped with a set of mmWave arrays that enable V2V communications, located at the edges of the car rooftop as it can be seen in Fig. 1. A frequency of operation of 28 GHz is used in the simulation, so the set of mmWave arrays operate in the n257 5G band (26.50 - 29.50 GHz). The equipped antenna system consists of four panels that sectorize the azimuth in four equal sectors, giving a steering capability of 360°. Hence, each panel is designed to cover a steering range of ±45°. Since the vertical deviation exhibited in V2V links is very little, the steering in the elevation plane has not been considered.

Based on the abovementioned configuration , the azimuthal range is divided into four equal sectors and each of the antenna panels faces its corresponding sector. In addition, the panels' configuration provides the emission of a finite set of beams – i.e. a beamset -. In particular, each panel divides its coverage range into 9 beams, which means that the total azimuthal range is covered by 36 equal beams with a mean half-power beamwidth of 10°.

C. Beam-based interference evaluation

During the simulation, all vehicles determine the most suitable beam pairs to establish a link with their corresponding pair by sweeping the entire beamset at both ends. The optimal beam management technique is not discussed in this paper and it is left as future work. In this way, each vehicle pair communicates using beamforming with the goal to improve the communication and reduce interferences at the sidelobes.

The interference level is measured for the entire beamset to obtain the spatial distribution of the interferers. Each interferer is assumed to point towards its corresponding receiver, and the measuring vehicle scans the entire azimuth plane with the 36 beams. Centered on the chosen vehicle pair, the interference power level caused by the surrounding traffic is calculated to therefore obtain the perceived SINR. The goal is to detect the best beams in terms of SINR for future usage of the simulated specific scenario. It has to be considered that each type of scenario has its own features that will determine the specific needs for the communication link to be established. For example, the angular distribution of incoming waves differ in urban and open highway areas, changing consequently the beamforming techniques implemented for each.

The SINR is a way to measure the quality of wireless connections. In this evaluation, the signal of interest is referred to as the power received from the transmitting vehicle of the considered pair, also known as Reference Signal Received Power (RSRP). The interference power is taken as uncoherent superposition of the power received from the vehicles communicating around them.

An efficient spectrum or radio resource management (RRM) has a paramount importance but in the present study no scheduling technique is used and all vehicles transmit simultaneously using the same radio resources available. However, the results presented in section III open a line of research for the reutilization of radio resources due to the obtained values. The frequency spectrum is traditionally considered a resource to be shared and the implementation of scheduling techniques can enhance the overall performance and efficiency of the network. In high-mobility traffic scenarios, the trade-off between maximizing instantaneous resource utilization and obtaining reliable quality measurements to facilitate an efficient adaptation of the radio resources to the user needs are considered as key problems [10]. In [11], a radio resource allocation scheme for D2D communications using fractional frequency reuse (FFR) is proposed, where the D2D communications ca improve the overall system capacity and reduce interferences by reusing the frequency band of cellular networks and by selectively use radio resources according to their positions.

III. Numerical Results

The simulation runs in an environment determined by the parameters listed in Table I. As stated above, random vehicle pairs are formed and the study focuses on a specific pair to extract the metrics of interference power level, RSRP and SINR.

TABLE I: Configuration of the simulation environment

Parameter	Value
Operating Frequency	28 GHz
System Bandwidth	50 MHz
Transmitted Power	23 dBm
Receiver Noise Factor	13 dB
Number of vehicles	16, 32, 64
Vehicle pair distance (d)	50 m
Number of iterations	100

To analyze how the traffic around affects to a vehicle pair, three simulation environments are taken with 16, 32 and 64 vehicles within the 200 m radius scenario. For each traffic model, 100 random iterations have been made changing the distribution of the surrounding vehicles. The pair of interest to be analyzed is located at the center of the vehicle cloud in all iterations. The transmitter has a fixed centered position and the receiver is moved at each iteration within a 50 meter radius circle. As the transmitting vehicle has a fixed position and since the beams emitted from the panels have fixed angles of emission, the position of the receiving vehicle is changed so that the angle of arrival of the beams is not always the same. Thus the line of sight (LOS) path is not fixed and results are not biased by the relative distance between its azimuth of arrival (AoA) and the beam steering angle.

Fig. 2 represents the SINR obtained for the given pair using omnidirectional antenna pairs and the aforementioned beamset configuration. The angular axis represents the azimuth, where each beam occupies a range of 10°. The black line is set for the LOS angle between the two vehicles, so it points towards the transmitting vehicle. As omnidirectional antennas receive

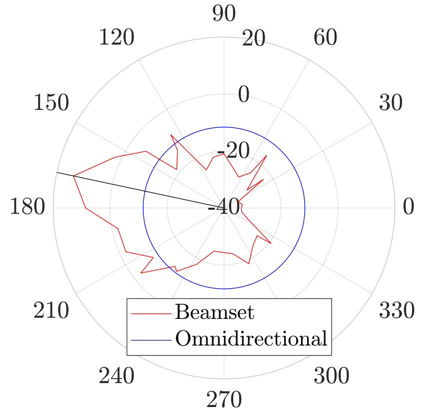

Fig. 2: SINR with Omnidirectional antenna and with the beamset (for 64 vehicles scenario)

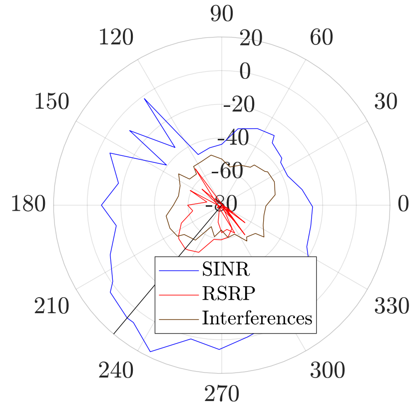

Fig. 3: SINR, RSRP and Interference power level with the beamset (for 16 vehicles scenario)

equally from all directions, a constant SINR value is obtained for such case. However, for the beamformed case, a clear peak is seen towards the angle at which the transmitter vehicle is positioned. The receiving beams which are pointing towards those angles close to the AoA of the incoming waves present a better RSRP, which could potentially lead to a better SINR. Nevertheless, the perceived level of interference with each beam also determines the final performance in terms of SINR.

Based on the obtained results, it can be stated that not only the beam strictly pointing towards the other car obtains the best SINR. The adjacent beams present also a good performance, sometimes even better than the beam pointing towards the transmitting vehicle. This means that the beam located in the direction of the transmitting vehicle is not always the best choice in terms of SINR. The influence of the traffic surrounding determines the interference power for each beam and this should be taken into account. There may be cases where a third vehicle is located between two vehicles which are trying to communicate, thus increasing the level of interference in the LOS angle between the two vehicles. This happens in Fig. 3, where a better SINR is obtained for a beam which is not pointing towards the LOS angle of the transmitting vehicle. Although the angle the other vehicle represents a higher RSRP, the interference level at such angle is also higher than for the adjacent ones, which leads to a worse result in terms of SINR.

This fact implies that sometimes it is a better option to choose beams based on the obtained SINR rather than on a RSRP or positioning criterion. To evaluate this, the simulation has been repeated for the three traffic configurations (16, 32 and 64 vehicles) changing the receiver's position for a fixed distance and the traffic distribution. For each scenario, it is analyzed whether the beam with the maximum RSRP value coincides with the beam with the maximum SINR and whether the SINR at the LOS AoA and the maximum SINR value coincide. Therefore it is possible to determine which is the most suitable beam in each case.

An statistical analysis is then carried out for the two aforementioned cases. Those statistics are shown in Tables II and III, which include the following figures of merit:

- Average value of angular change
- SINR loss suffered due to a beam change
- Percentage of cases where both criteria do not coincide

TABLE II: Comparation between the beams with maximum RSRP and maximum SINR

Parameter	**Number of Vehicles**		
	16	32	64
Angular change	10.13°	5.61°	1.8°
Power loss	-2.32 dB	-1.14 dB	-0.89 dB
Beam change percentage	62.34%	52.34%	46%

TABLE III: Comparation between the beam pointing to the transmitting vehicle and the beam with maximum SINR

Parameter	**Number of Vehicles**		
	16	32	64
Angular change	25.6°	19.73°	19.7°
Power loss	-2.72 dB	-1.4 dB	-1 dB
Beam change percentage	62.67%	55.67%	47%

The fact of running a simulation with random positions of vehicles increases the probability of having vehicles communicating in almost the entire azimuthal range when the number of vehicles is high, which implies having a more uniform level of interference among the beamset. This is why the higher the number of vehicles is, the less often a beam change occurs, since choosing an adjacent beam does not suppose a substantial change due to having a more uniform interference level. On the other hand, the interference level for a reduced number of vehicles may substantially change among adjacent beams which implies a considerable degradation in terms of SINR, so that a beam change occurs more often.

Having less vehicles implies having a more heterogeneous interference level. This in turn implies a considerable fluctuation in terms of SINR. For 16 vehicles, using the beam at the LOS AoA instead of the best in terms of SINR, results in a loss of almost 3 dB. As the traffic around grows, the relative degradation in the SINR is reduced, which is around 1 dB.

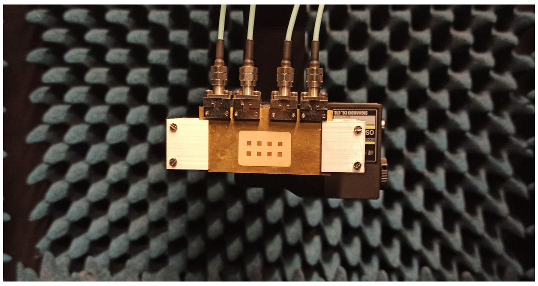

Fig. 4: 4-element 2×1 patch antenna array

IV. Measurement Campaign

The numerical analysis demands an experimental validation to support the aforementioned outcomes. As a first stage, a mmWave array is built, corresponding to one of the car panels. Before its integration into a realistic scenario, the beamset is validated in a controlled environment and the antenna behavior is thus characterized.

A. Testing Setup

The antenna array is composed by four 2×1 patch subarrays. The array is mounted in a 60×120×60 cm anechoic chamber [12] as depicted in Fig. 4. The setup includes linear shifters to move the antennas along the XY plane and rotors to orient the antennas to any azimuth angle between 0 and 360° as well as to roll the antenna under test (AUT) around its normal axis. A horn is used as reference antenna (RA) and a SP4T RF switch (ADRF5045) commutes the signal from/to the vector network analyzer (VNA) taking the measurements.

The AUT is placed at 50 cm from the reference antenna. It rotates in steps of 5° while the switch commutes between the 4 antennas at each angular step. Once the measurements are obtained for the entire azimuth range, the results are calibrated and the beamforming stage is performed in post-processing. The four measured diagrams are combined with their amplitude and phase for the given beamset.

B. Results

With the abovementioned setup, the array coverage is studied. From Fig. 5, some relevant parameters can be extracted:

- The array gain is 7.85 dB with respect to the single element.
- The coverage from -45° to 45° in azimuth is completely covered with the 9 beams.
- Each beam has a -3 dB beamwidth of 30°, which is sufficient to overlap with the others within the steering range.

The next step is to assess the effect of real beamforming antenna patterns to support the findings in simulation. This work is expected to be completed by the time of the conference.

V. Conclusions

This paper shows the potential of beamforming techniques to deal with interferences that high mobility scenarios present in V2V communications. The link-level performance is evaluated in terms of SINR at mmWave bands and the results show a substantial improvement for the specific angles the vehicles are communicating at. Beam-steering strategies may

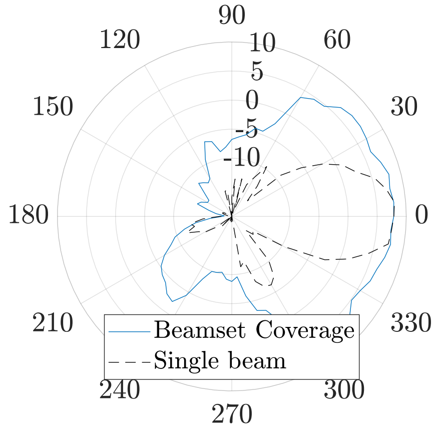

Fig. 5: Radiation Diagram of a single beam and superposed beamset

induce that the best beam should always be the one pointing strictly towards the target, but the study demonstrates that this is not true. The traffic influences the communication quality elevating the interference level in such beam. This implies that a contiguous beam which is not pointing exactly to the target vehicle might become a better option when lower interference level is captured, thus improving the SINR.

The optimal beam management technique is not here discussed, which can further improve the overall performance and it is left as a future research scope. In addition, the previous results open a new line of research for the re-utilization of radio resources since no scheduling technique has been implemented and still good enough results are obtained for the beamformed case.

Acknowledgements

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References

[1] S. Gyawali, S. Xu, Y. Qian, and R. Q. Hu, "Challenges and Solutions for Cellular Based V2X Communications," *IEEE Communications Surveys & Tutorials*, pp. 222–255, October 2020.

[2] C. Hoymann, D. Astely, M. Stattin, G. Wikstrom, J.-F. Cheng, A. Hoglund, M. Frenne, R. Blasco, J. Huschke, and F. Gunnarsson, "LTE release 14 outlook," pp. 44–49, June 2016.

[3] H. John, P. Gregory, Y. Rebecca, F. Joshua, and D. Charlene, "Vehicle-to-vehicle communications : readiness of V2V technology for application." Technical Report (TR), 08 2014.

[4] D. B. Rawat, B. B. Bista, G. Yan, and S. Olariu, "Vehicle-to-Vehicle Connectivity and Communication Framework for Vehicular Ad-Hoc Networks," *2014 Eighth International Conference on Complex, Intelligent and Software Intensive Systems*, July 2014.

[5] S. Gyawali, S. Xu, Y. Qian, and R. Q. Hu, "Challenges and Solutions for Cellular based V2X Communications," *IEEE Communications Surveys & Tutorials*, 2020.

[6] 3GPP, "Technical Specification Group Services and System Aspects;Study on enhancement of 3GPP Support for 5G V2X Services; (Release 16)," 3rd Generation Partnership Project (3GPP), Technical Report (TR) 22.886, December 2018, version 16.2.0.

[7] ——, "Technical Specification Group Radio Access Network; Study on New Radio Access Technology; Physical Layer Aspects; (Release 14)," 3rd Generation Partnership Project (3GPP), Technical Report (TR) 38.802, September 2017, version 14.2.1.

[8] I. Maskulainen, P. Luoto, P. Pirinen, M. Bennis, K. Horneman, and M. Latva-aho, “Performance evaluation of adaptive beamforming in 5G-V2X networks,” *2017 European Conference on Networks and Communications (EuCNC)*, July 2017.
[9] N. Kanthasamy, A. M. Wyglinski, and R. Cowlagi, “Effects of Interference on Beamforming-Enabled Vehicular Networks in Multipath Propagation Environments,” *2020 IEEE 91st Vehicular Technology Conference*, May 2020.
[10] J. Zander, “Radio resource management in future wireless networks: requirements and limitations,” *IEEE Communications Magazine*, pp. 30–36, August 1997.
[11] H. S. Chae, J. Gu, B.-G. Choi, and M. Y. Chung, “Radio resource allocation scheme for device-to-device communication in cellular networks using fractional frequency reuse,” *The 17th Asia Pacific Conference on Communications*, October 2011.
[12] M. Sellés, G. González-López, and L. Jofre-Roca, “Embedded Sensor Transmission Optimization with a X-Wave mini-Anechoic Chamber,” in *2020 XXXV Simposium Nacional de la Unión Científica Internacional de Radio (URSI Málaga, 2020)*, Sep 2020.