POLITECNICO MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

EXECUTIVE SUMMARY OF THE THESIS

Smart Beam Management for Vehicular Networks Using ML

TESI MAGISTRALE IN TELECOMMUNICATIONS ENGINEERING

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1. INTRODUCTION

Waves propagating in the mmWave band suffer from increased path loss and severe channel intermittency, and even changing the orientation of the vehicles relative to the base station can lead to a rapid drop in signal strength [1]. To deal with these impairments, vehicular networks must be provided by a set of mechanisms in which Vehicle to Infrastructure (V2I) radio channels are established by high-directional transmission links typically using high-dimensional phased arrays to benefit from the resulting beamforming gain and to maintain acceptable communication quality. These directional radio links require precise alignment of the transmitter and receiver beams, which is achieved through a series of operations known as beam management procedures. They are essential to perform various control tasks including (i) Initial access (IA) [2] for inactive users, which allows vehicles to establish a physical link connection with the Infrastructure, and (ii) Beam tracking for connected users [3], which enables beam adjustment schemes and can trigger handover procedures, route selection and recovery of radio link failures. However, directionality can significantly delay access procedures and make performance sensitive to beam alignment. These are particularly important issues in vehicular networks and motivate the need to extend current practices to innovative smart beam management methods using machine learning algorithms.

2. 5G FRAME STRUCTURE FOR TRACKING UE

The cell search is a process on the User Equipment (UE) side that is responsible for finding cells around the location of the UE. This is done thanks to the processing of the so-called Synchronization Signal block (SSB), a structure that consists of a Primary synchronization signal (PSS), a Secondary synchronization signal (SSS), and finally Physical broadcast channel (PBCH) blocks. The SSB's are grouped into the first 5 ms of an SS burst [4] and are transmitted by a gNodeB (gNB) with a configurable periodicity TSS [5] with {5,10,20,40,80,160}ms intervals. Moreover, UE assumes a default periodicity of 20ms [6] during initial cell search or idle mode mobility. Fig. 1 shows the time and frequency structure of an SSB. Note that time and frequency are defined in terms of OFDM symbols and subcarriers. In a slot of 14 symbols, there are two possible locations for SSB's: symbols 2–5 and symbols 8–11.

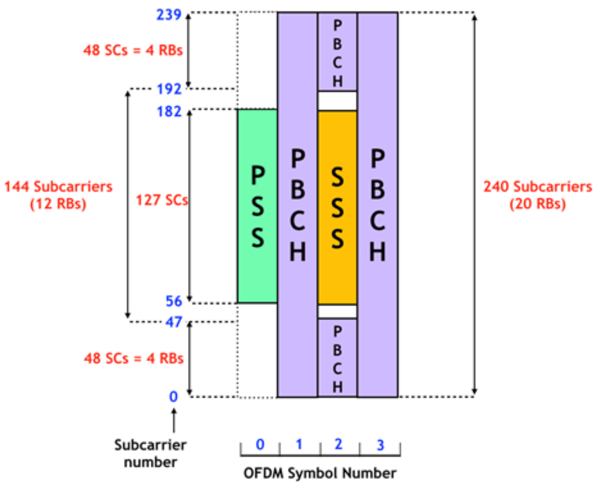

Figure 1: SSB frame structure

The maximum number of SSB's (NSSB) in a burst is frequency-dependent and is configured between NSSB{4,8,64} [6] and in mmWave frequencies above 6 GHz, there could be up to 64 blocks per burst. When considering frequencies for which beam operations are required, each SSB can be mapped to a certain angular direction. The subcarrier spacings (SCS) associated with each band are clearly defined by 3GPP which reduces UE's processing power/time for cell search. The SSB's occupy 20 Resource Blocks (RB) and there are 12 subcarriers in each RB, so there are a total of 240 subcarriers. Hence, the bandwidth occupied by a single SSB is 240 timesthe SCS. At mm-Wave frequencies, SCS considered for IA are 120 and 240 kHz, thus out of 400 MHz per carrier (total channel bandwidth (BW)), the bandwidth reserved for the SSB's would be respectively 28.8 MHz and 57.6 MHz [3]. Given that 240 subcarriers are allocated in frequency to an SSB, the remaining bandwidth in the symbols which contain an SSB is BW-240×SCS. Therefore, it is possible to either allocate the remaining bandwidth as shown in Fig. 2 for data transmission towards users or the information in the first 240 subcarriers i.e SSB is repeated in the remaining subcarriers to enhance the detection capabilities for high mobility users. And there are guard band intervals in frequency among the different repetitions of the SSB.

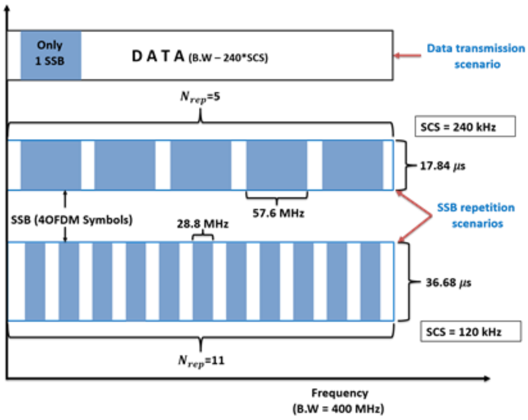

Figure 2: Data transmission and SSB Repetition scenarios

3. EXPENSE OF OVERHEAD ON HIGH MOBILITY VEHICULAR TRACKING

Narrow beams are key to establishing highly directional radio links which are desired for mmWave vehicular communications. However, they are limited to low mobility users, because vehicles moving at high speeds could suffer from a precise alignment of transmitter and receiver beams. So, to avoid beam pointing errors, the vehicle must always be in the radiation footprint (Rad_{ft}) of the gNB where the Rad_{ft} is expressed as a function of beamwidth and radial or relative distance (R_d) as represented in equation 1.

$$\mathrm{Rad_{ft}} = \Delta\theta_{3dB}\mathrm{R_d} \qquad (1)$$

The gNB estimates the new position of a vehicle every T_{SS} period and if the moving vehicle position is correctly estimated then it falls in the radiation footprint. Hence, to be correctly estimated by gNB, the limits on vehicular velocities (V_{veh}) are calculated by equation 2 as a function of radiation footprint and SSB burst periodicity.

$$V_{veh} < \mathrm{Rad_{ft}}/\mathrm{T_{SS}} \qquad (2)$$

Using equation 2 we calculated the maximum limits on vehicular velocities for which N{16,32,64} elemental antenna array could be able to establish radio channel during IA procedure whereby default T_{SS} is 20ms and plotted on Fig. 4.

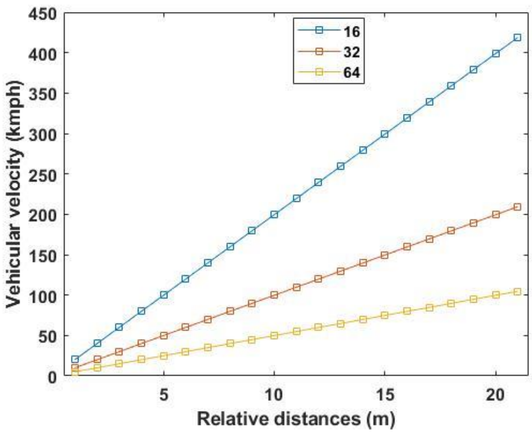

Figure 4: Velocity as a function of relative distances that can be processed by different N-elemental arrays during the IA procedure

Moving from idle to connected mode mobility, if the gNB configures SSB burst periodicity of 5ms for better estimating the high mobility vehicles, it comes with the expense of high overhead. We characterize this overhead(ρ) for IA and beam tracking in terms of the ratio between the total time and frequency resources R_{total} that are allocated to SSBs with the duration of the SSB burst, or the entire T_{SS} interval.

$$\rho = \frac{R_{total}}{T_{SS}BW} \quad (3)$$

Where the R_{total} is scheduled for the transmission of N_{SSB}, each spanning 4 OFDM symbols and 240 (or multiple of 240) subcarriers

$$R_{total} = N_{SSB} 4 T_{OFDM} 240 N_{rep} SCS \quad (4)$$

T_{OFDM} is the OFDM symbol time and is expressed in μs. From equation 4 we could observe that overhead varies with the number of SSBs per burst (N_{SSB}) and SSB burst periodicities (T_{SS}) configured by gNB. Fig. 5 shows the increasing N_{SSB} per burst can result in a large overhead.

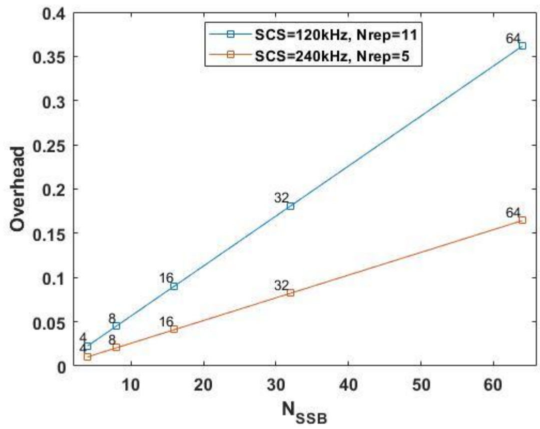

Figure 5: Overhead as a function of N_{SSB} for different SCS and T_{SS} is set to 5ms

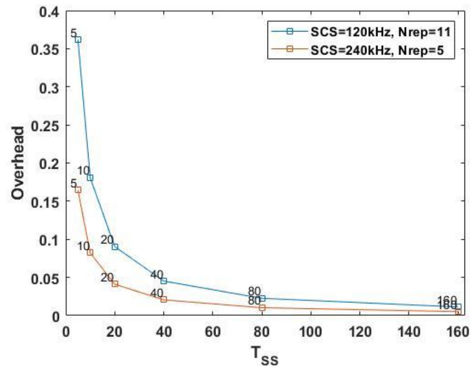

Figure 6: Overhead as a function of T_{SS} for different SCS and N_{SSB} is set to 64

Fig. 6 shows the dependency of the overhead for tracking procedures with T_{SS}, which follows an inverse proportionality law. In particular, for very small T_{SS} (i.e., 5 ms) the impact of the SSB's with repetitions in frequency is massive, with up to 43% of the resources allocated to the SSB's. For T_{SS} = 20 ms or higher, instead, the overhead is always below 10%. Hence, the design and configuration of efficient IA and beam tracking procedures are of extreme importance in vehicular networks operating at mm-waves. In this paper, we propose that knowing the geo-locations (or GPS) of vehicles and their velocities beforre they arrival at a cell, can help the gNB to decide the beamswidths based on antenna array architectures to be used for the completion of the beam sweeping and reporting procedures in a single burst, so that it is possible to increase T_{SS} (e.g., to 20 or 40 ms), and reduce the overhead.

4. NUMERRICAL RESULTS

In this thesis, we used a 32x 32 elemental Uniform planar array (UPA) to study the beam management procedures in different vehicular mobility scenarios and used an open-source traffic simulation package called Simulation of Urban Mobility (SUMO) for realistic traffic simulation data [7]. The SUMO simulation output file consists of the vehicular types (car, bus, etc.), their IDs, and respective GPS positions at every time step. The simulation gives 45 minutes of traffic data and the GPS positions of vehicles are noted every 100 ms.

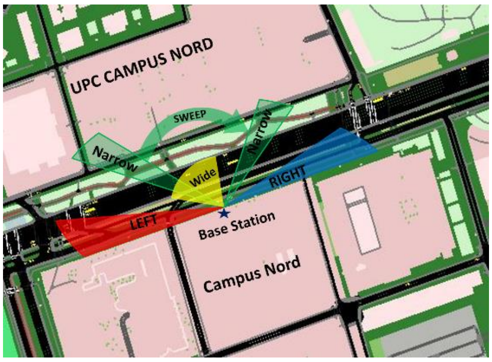

Figure 7: Beam Management Zones

This data is then processed to extract 3 feature vectors. The decision boundaries to group the data into different clusters were set based on the conditions to reduce the overhead in high mobility and to establish directional links in low mobility scenarios. These conditions are formulated based on the relation between vehicular velocities and their relative distances from the base station for a 32x32 UPA as shown in Fig.4. and they are defined as follows: 1) Vehicles moving closer to base station with high velocities are allocated wide beams or lower elemental array configurations 2) Vehicles moving at lower speeds are associated with narrow beams or higher array configurations and finally 3) Vehicles entering from acute left or right to the base station are assigned with a cosecant pattern as shown in Fig.8 which have small secondary lobes towards ground, so the errors from the ground reflection are minimized.

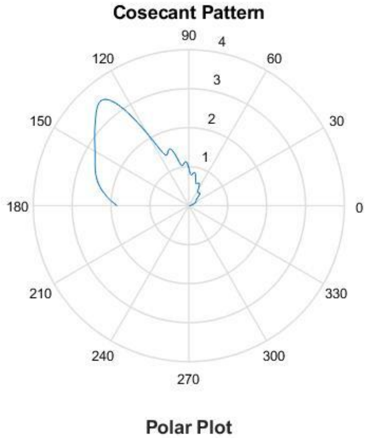

Figure 8: Cosecant Pattern

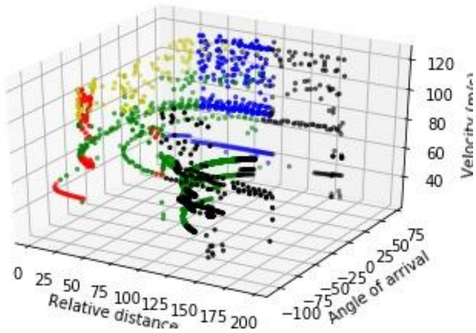

Figure 9: 3D scatter plot

Fig. 9 is a 3D scatter plot between relative distances, velocities, and Angle of arrival (AOA) of vehicles to the base station that showcases different clusters based on the decision boundaries. The yellow data points in the scatter plot are defined from condition 1 that represents a wide beam. And the green data points in the plot are defined from condition 2 that represents a narrow beam. Whereas left and right data points are defined from condition 3 which represents the cosecant pattern beams. Finally, the label out in the figure represents that there are beyond the range of serving cells. To further clarify the conditions explained above in Fig.4 and Fig.9 for beam assignment, a vehicle moving at a speed of 100 kmph and driving in a lane within the relative distance of 12m or less from the base station is assigned with the wide beam. Whereas, a vehicle with the same speed driving in a lane farther than 12m is allocated with the narrow beam.

To better represent and for better understanding of the clusters, a 2D plot, Fig. 10, a top view of the scatter plot in Fig. 9 between the AOA in the y-axis and relative distance from a base station in the x-axis is created.

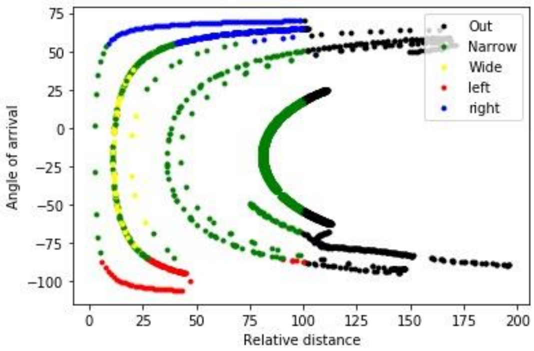

Figure 10: 2D plot between angle of arrival and relative distance form base station

This information is used to train the Kernel Nearest Neighbors (KNN) algorithm [8][9] to implement the beam patterns for vehicular channels as discussed above. The KNN algorithm is used to predict new data based on the above-mentioned decision boundaries. This KNN algorithm shows 99% accuracy in detecting the 1) high mobility vehicles and assign them wide beam widths, 2) vehicles arriving from left and right corners of the base station and allocate the cosecant pattern, and 3) assigning narrow beams for low mobility users. Further information about the performance metrics [10] of the KNN algorithm for each condition or cluster is shown in Fig.11.

	precision	recall	f1-score	support
Narrow	0.99	0.99	0.99	720
Out	0.99	0.99	0.99	336
Wide	0.70	0.88	0.78	8
left	0.88	0.93	0.90	15
right	0.93	0.99	0.96	67
accuracy			0.99	1146
macro avg	0.90	0.95	0.92	1146
weighted avg	0.99	0.99	0.99	1146

Figure 11: Classifier evolution metrics

Finally, the detailed breakdown of the beam allocation process for vehicular networks using ML is shown in Fig.12.

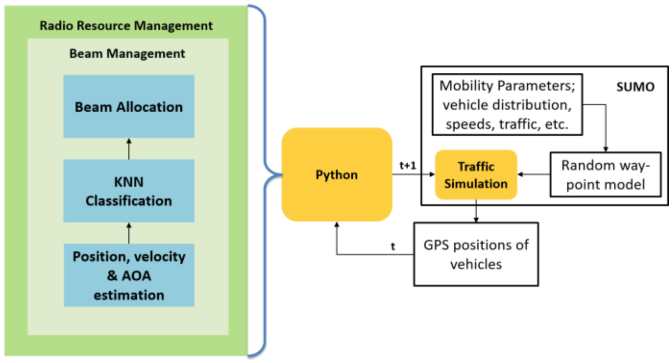

Figure 12: Block diagram of smart beam management procedure

By this classification of vehicular traffic using KNN, we can assign the best beam pairs to vehicles in high mobility scenarios which in turn reduces, misalignment errors during the IA procedure in idle mode mobility and frequent overhead usage to maintain the connectivity in connected mode mobility.

5. CONCLUSIONS

Mm-waves are widely studied to enhance the capacity of future vehicular networks. However, their performance depends on the precise beam alignment between the vehicle and the network. In this paper, we proposed a KNN based machine learning approach to solve the beam management problem by leveraging the information about the vehicle’s mobility before it arrives at the base station. This approach also incurs a considerable reduction of beam tracking overhead. Finally, the benefits of our proposal are particularly useful for the high mobility vehicular use cases envisioned for 5G.

6. REFERENCES

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7. ACKNOWLEDGEMENTS

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Smart Beam Management for Vehicular Networks Using Machine learning

TESI DI LAUREA MAGISTRALE IN
INGEGNERIA DELLE TELECOMUNICAZIONI

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Abstract (Summary)

The mmwave frequencies will be widely used in future vehicular communications. At these frequencies, the radio channel becomes much more vulnerable to slight changes in the environment like motions of the device, reflections or blockage. In high mobility vehicular communications the rapidly changing vehicle environments and the large overheads due to frequent beam training are the critical disadvantages in developing these systems at mmwave frequencies. Hence, smart beam management procedures are desired to establish and maintain the radio channels. In this thesis, we propose that using the positions and respective velocities of the vehicles in the dynamic selection of the beam pair, and then adapting to the changing environments using machine learning algorithms, can improve both network performance and communication stability in high mobility vehicular communications.

In this thesis, several aspects of next generation vehicular communications have been discussed. The main conclusions that can be extracted from the work developed in previous chapters are summarized in the following lines. After a brief overview of the literature on beam management at mmWave frequencies in chapter 2, we described the frame structure and reference signals in 3GPP NR, focusing on the settings for communication at mmWave frequencies. Then, we described beam management procedures according to different network architectures and signal transmission directions (downlink or uplink). We also evaluated the impact of several parameters (specified by 3GPP for NR) on their performance. In chapter 3, we showed that there exist trade-offs among better detection accuracy, and reduced overhead and provided the insights and guidelines for determining the optimal initial access and tracking strategies. Finally, in chapter 4, we proposed a KNN based machine learning approach to solve the beam management problem by leveraging the information about the vehicle's mobility before it arrives at the base station.

To summarize, mmWaves are widely studied to enhance the capacity of future vehicular networks. The harsh propagation at mmWave frequencies requires the implementation of directional transmissions supported by beamforming techniques to increase the link budget. Therefore, control procedures such as initial access must be updated to account for the lack of an omnidirectional broadcast channel, and the optimal beam pair with which a base station and a UE communicate should be tracked when needed. Consequently, the design and configuration of efficient IA and tracking procedures is of extreme importance in vehicular networks operating at mmWaves. The benefits of our proposal are particularly useful for the high mobility vehicular use cases envisioned for NR-V2X and beyond.

Key-words: mmwaves, radio channel, high mobility vehicles, machine learning.

Sommario

Le frequenze mmwave saranno ampiamente utilizzate nelle future comunicazioni veicolari. A queste frequenze, il canale radio diventa molto più vulnerabile a lievi cambiamenti nell'ambiente come movimenti del dispositivo, riflessi o blocchi. Nelle comunicazioni veicolari ad alta mobilità, gli ambienti dei veicoli in rapida evoluzione e le grandi spese generali dovute al frequente addestramento del fascio sono gli svantaggi critici nello sviluppo di questi sistemi a frequenze mmwave. Pertanto, sono desiderate procedure di gestione del raggio intelligente per stabilire e mantenere i canali radio. In questa tesi, proponiamo che l'utilizzo delle posizioni e delle rispettive velocità dei veicoli nella selezione dinamica della coppia di raggi, e quindi l'adattamento ai mutevoli ambienti utilizzando algoritmi di apprendimento automatico, possa migliorare sia le prestazioni della rete che la stabilità della comunicazione nelle comunicazioni veicolari ad alta mobilità .

In questa tesi sono stati discussi diversi aspetti delle comunicazioni veicolari di nuova generazione. Le principali conclusioni che si possono trarre dal lavoro sviluppato nei capitoli precedenti sono riassunte nelle righe seguenti. Dopo una breve panoramica della letteratura sulla gestione del fascio alle frequenze mmWave nel capitolo 2, abbiamo descritto la struttura del frame e i segnali di riferimento in 3GPP NR, concentrandoci sulle impostazioni per la comunicazione alle frequenze mmWave. Quindi, abbiamo descritto le procedure di gestione del fascio secondo diverse architetture di rete e direzioni di trasmissione del segnale (downlink o uplink). Abbiamo anche valutato l'impatto di diversi parametri (specificati da 3GPP per NR) sulle loro prestazioni. Nel capitolo 3, abbiamo mostrato che esistono compromessi tra una migliore accuratezza di rilevamento e un sovraccarico ridotto e abbiamo fornito le intuizioni e le linee guida per determinare l'accesso iniziale ottimale e le strategie di tracciamento. Infine, nel capitolo 4, abbiamo proposto un approccio di apprendimento automatico basato su KNN per risolvere il problema della gestione del raggio sfruttando le informazioni sulla mobilità del veicolo prima che arrivi alla stazione base.

Per riassumere, mmWaves sono ampiamente studiati per migliorare la capacità delle future reti veicolari. La dura propagazione alle frequenze mmWave richiede l'implementazione di trasmissioni direzionali supportate da tecniche di beamforming per aumentare il budget di collegamento. Pertanto, le procedure di controllo come l'accesso iniziale devono essere aggiornate per tenere conto della mancanza di un canale di trasmissione omnidirezionale e della coppia di fasci ottimale con cui una stazione base e una UE comunicano quando necessario. Di conseguenza, la progettazione e la configurazione di efficienti procedure di IA e tracking è di estrema importanza nelle reti veicolari operanti a mmWaves. I vantaggi della nostra proposta sono particolarmente utili per i casi d'uso veicolare ad alta mobilità previsti per NR-V2X e oltre.

Key-words: mmwaves, canale radio, veicoli ad alta mobilità, machine learning.

Acknowledgements

I dedicate my Thesis to my beloved Parents, Friends and to all my Professors who enlightened me

Contents

Glossary

3GPP 3rd Generation Partnership Project
AAS Active Antenna Systems
BS Base Station
DSRC Dedicated Short Range Communications
ECC Electronic Communications Committee
eMBB enhanced Mobile Broadband
eNB Evolved Node B
ETSI European Telecommunications Standards Institute
FCC Federal Communications Commission
gNB Next Generation Node B
GPRS General Packet Radio Service
GSM Global System for Mobile communications
IMT International Mobile Telecommunications
ISM Industrial, Scientific and Medical
ITS Intelligent Transportation Systems
ITU International Telecommunication Union
LOS Line of Sight
LTE Long Term Evolution
mMTC massive Machine-Type Communications
mmWave millimeter-wave
MoM Method of Moments
NLOS Non Line of Sight
NR New Radio
NSA Non-Standalone
OFDMA Orthogonal Frequency-Division Multiple Access
PCB Printed Circuit Board
RAN Radio Access Network
RL Return Loss
SA Standalone
SNR Signal to Noise Ratio
UMTS Universal Mobile Telecommunications System
URLLC Ultra-Reliable and Low Latency Communications
UWB Ultra-wideband
V2D Vehicle-to-Device
V2I Vehicle-to-Infrastructure
V2N Vehicle-to-Network
V2P Vehicle-to-Pedestrian
V2V Vehicle-to-Vehicle
V2X Vehicle-to-Everything

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Chapter 1

Introduction

The work presented in this thesis intends to describe a system-level study of the next generation of vehicular communications. The focus is mainly put on the impact of beam management procedures on high mobility vehicular scenarios. A deep analysis is carried out, from the description to the simulation and classification of vehicular traffic.

The study covers regular beam management procedures, which were already introduced in past generations, and the need for the implementation of smart beamforming techniques for future vehicular communications. Initially, the benefits of such type of systems have to be detailed, especially emphasizing the differences in terms of performance.

1.1 Motivation

Waves propagating in the mmWave band suffer from increased path loss and severe channel intermittency, and even changing the orientation of the vehicles relative to the base station, can lead to a rapid drop in signal strength. To deal with these impairments, vehicular networks must be provided by a set of mechanisms in which Vehicle to Infrastructure (V2I) radio channels are established by high-directional transmission links typically using high-dimensional phased arrays to benefit from the resulting beamforming gain and to maintain acceptable communication quality. These directional radio links require precise alignment of the transmitter and receiver beams, which is achieved through a series of operations known as beam management procedures. They are essential to perform various control tasks including (i) Initial access (IA) for inactive users, which allows vehicles to establish a physical link connection with the Infrastructure, and (ii) Beam tracking for connected users, which enables beam adjustment schemes and can trigger handover procedures, route selection and recovery of radio link failures. However, directionality can significantly delay access procedures and make performance sensitive to beam alignment. These are particularly important issues in vehicular networks and motivate the need to extend current practices to innovative smart beam management methods using machine learning algorithms.

1.2 A Brief Look to History of vehicular communications

Vehicle to Everything (V2X) [17] is a communication method which would be used as an information interface between vehicle and other communication nodes such as networks, other vehicles, infrastructures and pedestrians. In 1999, the US Federal Communications Commission (FCC) allocated 75 MHz of spectrum in the 5.9 GHz band for Intelligent Transportation Services (ITS). The allocation triggered significant research activity around the world to develop and deploy V2X communications over the past two decades (e.g., the CAMP consortium in the US, the Car 2 Car Communication Consortium in Europe, and countless research projects).

The Vehicle to Everything (V2X) networks covers the following:

- V2V (Vehicle to Vehicle): This is applicable for short range communications. It can be in the form of direct communication or communication through Evolved Node B (eNB).
- V2I (Vehicle to Infrastructure): RSU (Road Side Unit) provides topology of the environment. This can be broadcast or multicast.

- V2N (Vehicle to Network): Vehicle can obtain information that provides convenience for a driver such as navigation and traffic situation.
- V2P (Vehicle to Pedestrian): Because of short range communication of V2P vulnerable information can be broadcasted by UE.

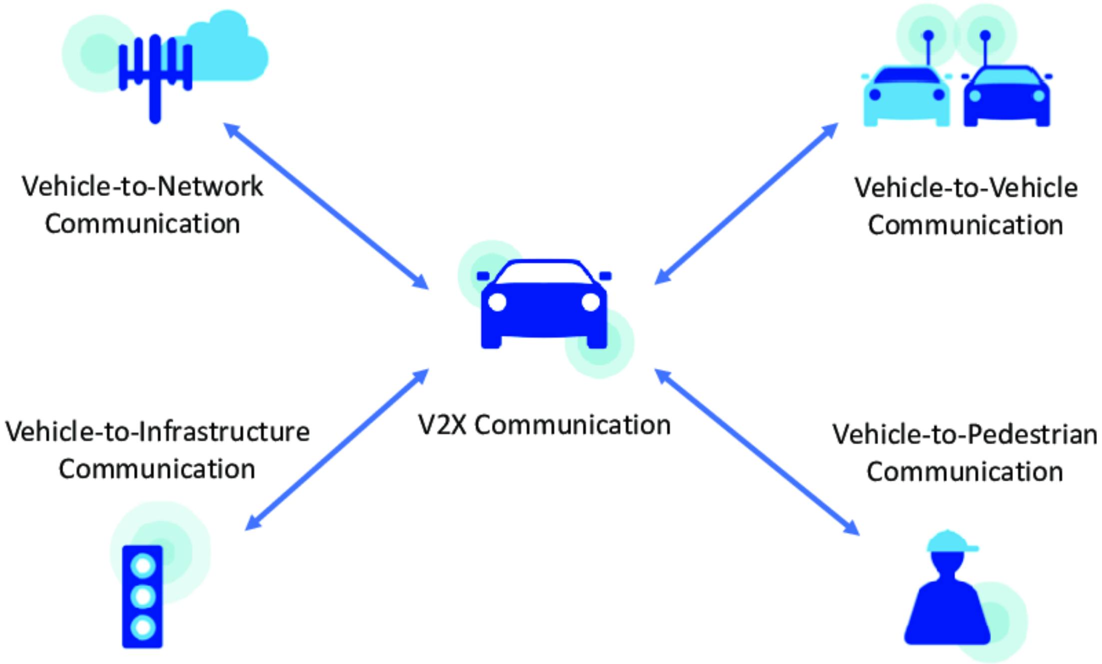

Fig.1 V2X communications

1.3 Regulatory Bodies and Standards

The two most important access technologies that support V2X communication today are IEEE 802.11p and 3GPP CellularV2X (CV2X), but they meet very limited or expected traffic requirements (for example, very high throughput, very low latency, and very high reliability) of future vehicular services.

In this sense, IEEE and 3GPP are currently promoting various standardization activities, including 802.11bd and NR V2X (New Radio) specifications to overcome the limitations of current technology. Both standards aim to increase wireless capacity by including the ability to use the lower part of the millimeter wave (mmWave) spectrum, in addition to the traditional frequencies of less than 6 GHz, which makes large parts of the width available of large chunks of untapped bandwidth. This would enable data rates on the order of hundreds of megabits per second in vehicular scenarios, improved over 3GPP CV2X and IEEE 802.11p, which can reach a maximum of several tens of megabits per second.

The V2X standards [20][21] can be classified into two parts of radio and application. The radio layer standards have been focused on in 3GPP, and the higher layer standards are developed by countries and regions to reflect the realistic and differentiated requirements of V2X applications. Based on the research progress of LTE-V2X related technologies, the development of LTE-V2X standards has been completed, and the research and development of NR-V2X is in progress by the international and national standardization organizations. The V2X technologies developed in 3GPP with technical specifications will be endorsed by the International Telecommunication Union (ITU) or ISO (International Organization for Standardization) as V2X international standards.
3GPP Release 12 (Rel. 12) was the first standard to introduce direct Device-to-Device (D2D)

communications for proximity services (ProSe) using cellular technologies. This work was used by 3GPP to develop LTE V2X, the first cellular V2X (CV2X) standards based on the 4G Long Term Evolution (LTE) air interface. LTE V2X was developed under Release 14 (Rel. 14) and was further enhanced in Release 15 (Rel. 15). It is only under Release 16 (Rel. 16) that 3GPP has developed a new cellular V2X standard based on the 5G NR (New Radio) air interface. The precursor to the technical work on Rel. 16 NR V2X was the study item (SI) approved under Rel. 15. This SI developed the evaluation methodology and assumptions for LTE and NR V2X that were necessary to evaluate and compare the various proposals to be included in the 5G NR V2X standard. Next, 3GPP approved a SI and a work item (WI) to develop the first set of 5G NR V2X standards in Rel. 16. Specifically, the SI on radio interface technologies ran until March 2019 followed by a WI that officially concluded in December 2019. This WI resulted in the first set of 5G NR V2X specifications included in the 3GPP technical specifications (TS). Fig. 2 summarizes the timeline of the development of cellular V2X standards under 3GPP with a focus on Radio Access Network (RAN) developments. The 5G NR standard was developed under Rel. 15 but it did not include sidelink (SL) aspects. SL refers to direct communication between terminal nodes or User Equipments (UEs) without the data going through the network. In NR V2X, UEs are vehicles, Road Side Units (RSUs), or mobile devices that are carried by pedestrians. Rel. 16 is the first to introduce V2X communications, including SL communications, based on the 5G NR air interface. This makes Rel. 16 NR V2X SL the first 5G V2X standard available, and a basis for future enhancements and extensions for V2X and non-V2X SL applications. As noted in, the NR V2X SL has been developed to complement and not replace LTE V2X SL communications. The goal of NR V2X SL is to support enhanced V2X (eV2X) use cases related to connected and automated driving. Some of these use cases have requirements that cannot be satisfied by the LTE V2X standard.

3GPP: With the evolution of 4G/5G cellular network communication technologies, C-V2X standardization is driven by 3GPP. The timeline of 3GPP C-V2X standardization is shown in Fig. 2.

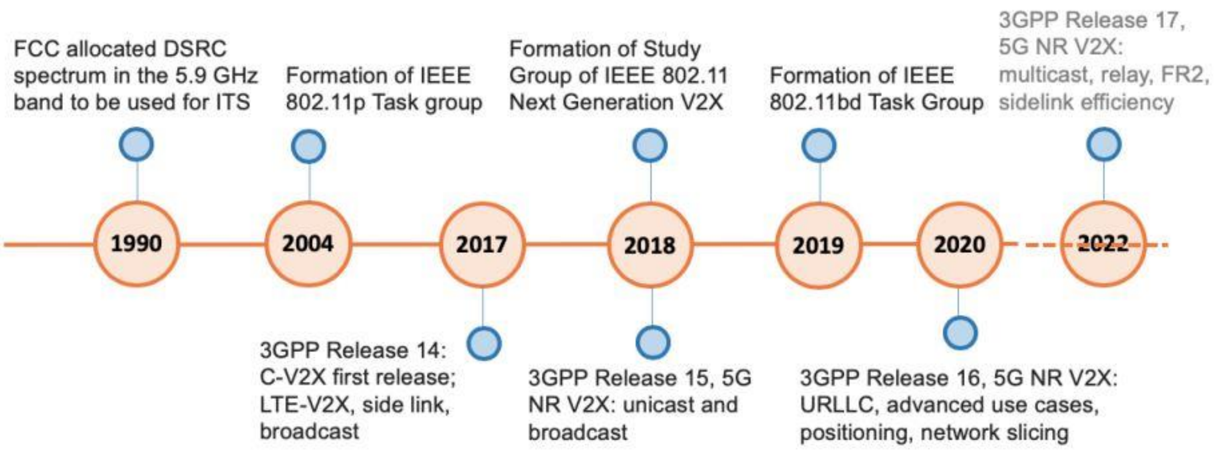

Fig.2 Timeline of V2X standards

5G NR V2X [19] is designed to complement LTE V2X. LTE V2X supports basic use cases for active security and traffic management, while 5G NR V2X supports advanced use cases and a higher degree of automation. The 5G NR V2X use cases were specified by the 3GPP Services and System Aspects (SA) working group 1 (SA1) and created by the 5GAA (Use Cases and Technical Requirements). Both 3GPP and 5GAA organize use cases into groups, and a use case can be a member of multiple groups. This section provides an overview of the usage supported by 5G NR V2X as well as the most important KPIs. For a full description, readers can consult the documents or articles on 3GPP and 5GAA on the subject. 3GPP technical report (TR) 22.886 and TS 22.186 present a comprehensive description of the NR V2X use cases and requirements, respectively. For each use case, 3GPP further distinguishes different degrees of automation following the SAE automation levels ranging from 0 (no automation) to 5 (full automation). Typically, the higher automation levels of a use case, the more stringent the NR V2X QoS requirements are. The use cases are divided in the following four groups:

I. Vehicles Platooning: This group includes use cases for the dynamic training and management of vehicle groups in trains. Exchange data regularly to ensure proper train operation. The inter-vehicle distance between vehicles in a train can depend on the available QoS.
II. Advanced Driving - This group includes use cases that enable semi-automated or fully automated driving. The vehicles share the data received from their local sensors with the surrounding vehicles nearby. In addition, the vehicles share their intention to drive in order to coordinate their trajectories or manoeuvres, thereby increasing safety and improving traffic.
III. Extended Sensors - This group enables the exchange of sensor data, either raw or processed, collected via local sensors between vehicles, RSUs, pedestrian devices and V2X application servers. The aim is to improve the perception of the environment beyond the perception capabilities of the vehicle's own sensors.
IV. Remote driving: In this group, a long-distance driver (tele operated) or a V2X application can operate a vehicle. Cases are for passengers who are unable to drive themselves, for vehicles that are in hazardous environments (e.g. in construction sites or in places with poor weather conditions), and for complex situations where automated vehicles cannot be able to drive safely and safely.

1.4 Challenges and Objectives

The main goal of this thesis is to provide tools and techniques to better understand and evaluate vehicular communications at future 5G frequency bands. We identified the following challenges by the introduction of mmWave frequencies into V2X systems in Release 16.

a) Numerology design: Both 802.11bd and NR V2X Radio Access Technologies (RAT) support a flexible physical frame structure to meet different quality standards requirements. In general longer symbol durations (i.e., a lower subcarrier spacing) improve the communication accuracy (because the impact of noise is less relevant), but can also lead to significant channel fluctuations within a slot in vehicular systems operating at mmwave frequencies as a result. Hence as a result the structure of the NRV2X frame can be configured autonomously, ie different sub frames can be assigned to different numerology. In this way it would be possible to arrange a shorter symbol duration times to support high data rates, low latency applications (e.g. for vehicle platooning and/or remote driving), while a smaller subcarrier spacing may be reserved for narrowband communication to exchange basic safety and security information. In addition, the 3GPP NR V2X numerology is currently based on 3GPP NR specifications for cellular scenarios and therefore may not fit into a vehicular system due to the rigid propagation properties of highly mobile vehicle nodes.

b) Multiple antenna arrays: mmWave vehicular networks must establish directional transmission links to maintain an acceptable beamforming communication quality. This is achieved through high dimensional phased antenna array systems, possibly placed in distributed locations. Distributed antenna systems improve spectral efficiency by taking advantage of spatial diversity, resulting in less correlated channels, but could pose synchronization problems and requires the design of efficient mechanisms for allocating transmit power and managing resources efficiently. Studies are required before distributed antenna solutions can be applied to vehicle networks.

c) Radars and shared communications: The use of millimetre waves in the vehicular context is not new as automotive vehicular radars operate in the 77 GHz spectrum. Utilizing the dual-functionalities by integrating radar and NR V2X communications have been investigated by 3GPP, but not proposed yet in recent releases. In general, spectrum isolation or interference mitigation schemes generally allow their coexistence but better performances could be achieved by multiplexing the acquisition and data on the same waveform, thereby improving resource utilization while reducing hardware size and cost.

d) Broadcast / Multiple / Group Communication: The directionality can prevent millimetre wave broadcast communication when different directions cannot be used at the same time (as in analog beamforming). On the other hand, transceivers using hybrid and digital technology can radiate in many directions as the number of radio-frequency chains in the phased array, which enables broad/multi/group cast communication. However, these architectures are currently limited by hardware design and suffer from high power consumption and computational complexity, which is critical given the limited resources on board budget car models. To be energy efficient, digital/ Hybrid beam formers must use suitable precoding techniques and converters with one or a few bit resolution. Modes with which receiving vehicles can temporarily deactivate their radio channel interface can lead to considerable energy savings in temporary traffic such as in vehicular scenarios.

e) Channel estimation: The tracking of the channel quality in several spatial directions increases the overhead of the channel estimation in mmWaves. This is especially difficult in vehicular applications where the channel changes rapidly over time and the initial estimate can quickly become out of date. Although IEEE 802.11bd provides for the use of midambles to handle channel variation, mmWave beamformed transmissions require specially tailored channel estimation and precoding techniques. Furthermore, the exchange of CSI (using sidelink) must be timely in order to avoid feedback of outdated information in scenarios with a highly variable channel (e.g. due to an increased doppler effect in mmWaves).

f) Synchronization: The specifications of IEEE 802.11bd and 3GPP NR V2X mode 2 support autonomous side-link operations with base stations. In this case, the vehicle must maintain or acquire time and frequency synchronization with other users. The synchronization signals exchanged in predefined resource pools, although the directional characteristics of millimeter-wave communications can reduce the rate at which such information is acquired, thereby compromising robust synchronization.

Hence, our main objective in this thesis is to address the above challenges posed by the mmWaves in future vehicular networks, so propose a machine learning based approach to efficiently handle future V2X networks.

1.5 Work Plan

After analysing the challenges posed by the introduction of mmWaves in the future vehicular networks, we came to a conclusion that smart beam management procedures are required to handle the above challenges efficiently and that paved the basis for this thesis. If you see, the project is divided in four main parts:

- Conduct a comprehensive study on the Beam management procedures
- Then design of an Ultra-wideband (UWB) mmWave antenna
- Create a simulation of a realistic traffic scenarios
- Finally, classify V2I communication environments using Machine Learning

In addition, documentation and writing tasks must be carried out as well as the preparation of the final presentation.

Chapter 2

Overview of Beam Management in 5G NR

The flexibility present in 5G is fundamental to integrate a huge amount of services into the technology, with resource planning in advance for services that have not even been conceived yet. This chapter will be devoted to introduce aspects of 5G that are relevant to understand what Beam Management (BM) refers to, as well as their intrinsic flexibility.

The procedures that allow beamforming in communication, from the Beam Management (BM) framework, are briefly described. The Initial Beam Establishment (IBE), one of the BM procedures, the state of the art of its implementations is reviewed. Some terms and concepts have been added or changed since LTE, they will be properly mentioned to convey clarity herein. A device is regarded, as in 5G, as a User Equipment (UE) and it establishes connection with a Base Station (BS), also called gNodeB (gNB) in 5G NR. When the flow of information goes from a gNB to a UE, the transmission is regarded as a Downlink (DL) transmission whereas information flow from a UE to a gNB is referred to as an Uplink (UL) transmission.

2.1 Beam Correspondence

As described at the beginning, information flow between a gNB and a UE mainly has two possibilities, an UL and a DL direction. Consider a scenario where beamforming is applied to both gNB and UE for communication where the gNB is transmitting with a certain DL transmit (TX) beam and the UE is receiving with a certain DL receive (RX) beam. Certain time was usually required to select this beam pair for communication link establishment. UL communication can benefit from the beam selection performed in the DL by choosing the same beam pair to exchange information. By doing it, the necessary time to find another beam pair for UL communication can be spared. This is made under the assumption that a beam pair used for DL communication provides the same link budget when used for UL communication. The assumption is called Beam Correspondence, it is an important concept that may increase the efficiency of a communication system. Nevertheless, beam correspondence does not hold in all cases, as there might be many impairments that prevent the gNB and the UE from using the same spatial filtering for DL and UL. Its indication is still work in progress in the 3GPP specifications, where a tolerance requirement for UEs of the handheld type is defined in 3GPP 38.101-2 Section 6.6.4.2. Whereas the conditions for reference signals are still to be defined. To the best knowledge of the author, results of applied research in this topic are scarcely published or strongly copyrighted.

2.2 Beam Management

As pointed out in chapter 1, 5G NR's characteristic beam-centric design is key to operate at mm-wave frequencies. This feature is supported by Beam Management (BM), a collection of 3 fundamental procedures that aim at establishing and retaining a suitable beam pair. A suitable beam pair can be roughly understood as the combination of a transmit and receive beams that provides connectivity.

2.2.1 Initial Beam Establishment

Initial beam establishment (IBE) [2][3]is the process by which the UE initiates a connection with the gNB. The connection safety must be ensured in UL and DL. Therefore, as shown in Fig. 4, beam scanning is performed at both the UE and the gNB. The gNB first transmits synchronization and system information for various DL-TX beams, switched in a manner depending on the capabilities and available strategies. The UE attempts to receive and decode this information by switching its DL-RX beam. Please note that multiple cells send information through different DL beams at the same time because multiple UEs are trying to use their available RX-DL beams to establish a connection at the same time. If the synchronization from the system and the reception and decoding of information are successful, then the standard is evaluated to consider the new cell to be valid and sufficient. One of those cells is selected and communication is established through a process called initial access or initial acquisition (IA). A suitable beam pair associating the suitable cell with the UE is found within IA. Then a sub-process called Random Access (RA) is performed, in which the necessary information is transmitted through the appropriate found beam pair. The negotiation between the gNB and UE regarding the transmission of gNB's DL-TX and potential UL-RX beams is achieved by assigning identifiers and corresponding time-frequency resources to each beam.

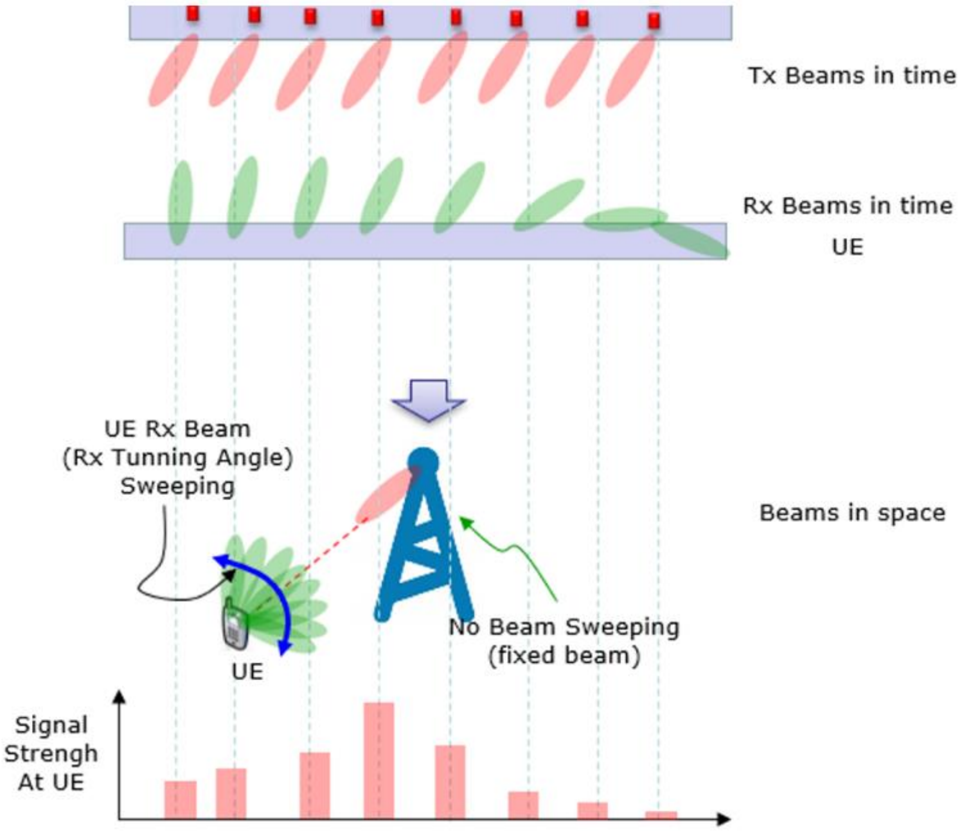

Fig.3(a) Beam sweeping at UE

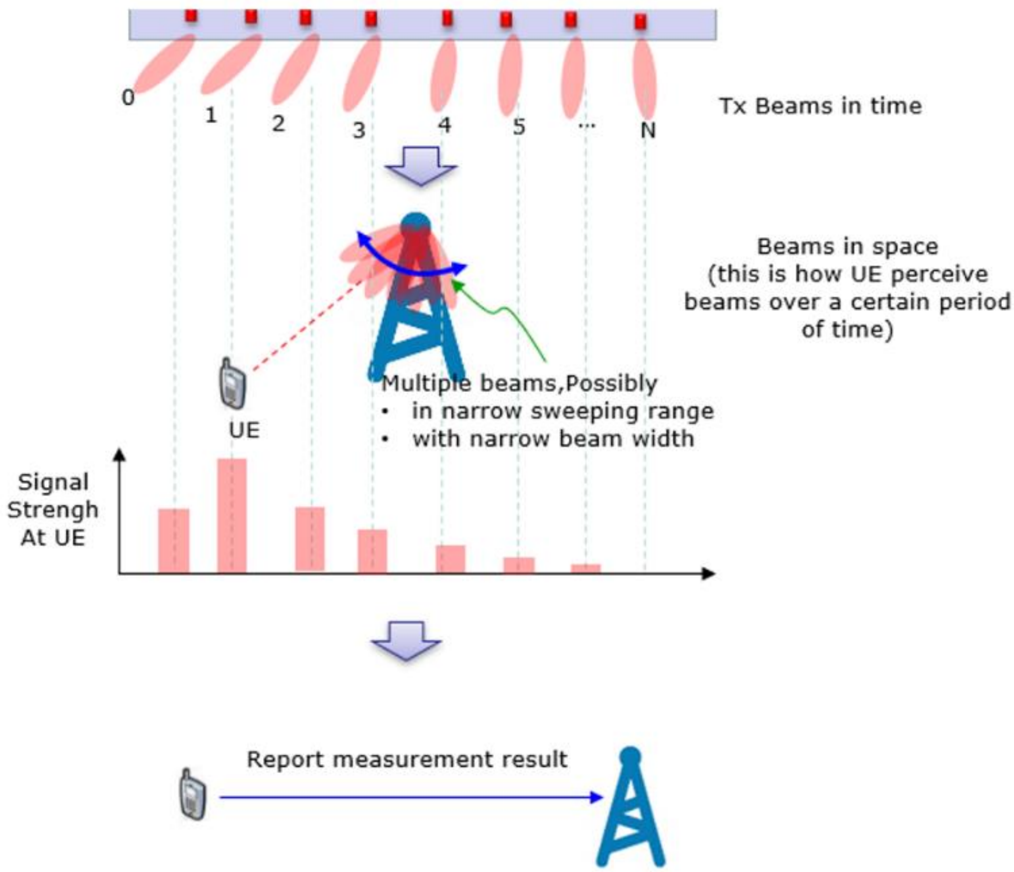

Fig.3(b) Beam sweeping at gNB

Beam pair selection is directive to be performed inside the random access procedure, according to the 3GPP guidelines. There is a great deal of flexibility in its implementation, so research and comprehensive studies are thus broad in this area. The main concern is when initially establishing a connection between the gNB and the UE and the time that it takes to do so is the latency, which is influenced by the number of beam pairs that need to be compared before making a decision. Therefore, the focus of future research is on latency reduction. When attempting to reduce the impact of latency on the power strength of the links, a consequent compromise between latency and the power strength is achieved in IBE. The beam pair that achieves the highest power strength among all connection pairs can be regarded as the best beam pair.

An overview of Release16 of the initial access proposals for millimeter-wave communication shows a concentrated interest in a comprehensive and iterative assessment of beam pairs prior to selecting a particular beam pair, the comprehensive search refers to an exhaustive search approach of all possible beam pairs that gNB and UE perform together. The exhaustive search result would match the best pair among all the pairs of beams available. Iterative search, to the understanding of the author, can be also interpreted as a variant of the exhaustive search approach. This assertion is motivated by the fact that in the first iteration a comprehensive beam pair evaluation is carried out with a sparse beam distribution over a relatively large space section, while subsequent iterations carry out a comprehensive evaluation of beam pairs with a denser beam distribution in a smaller space the previous iteration.

gNB and UE. There are broadcast opportunities where the UE can report the selection of a particular beam and they are mapped for each beam, but not simultaneously. To the best of the author's knowledge, there are no published results that take into account the timing structure of the transmission event in the 3GPP specifications. It also fails to take into account the fact that lower powers can also enable communication in published results, which is observed when examining the Key Performance Indicators (KPIs) that are used to provide a framework for comparing different approaches to detect latency and detection error probability.

The probability of link establishment failure can be understood as the probability that the selected beam pair is not the best beam pair. In fact, the minimum received power requirement for a UE, known as receiver sensitivity (RX), is also defined by 3GPP specifications. Values above this limit should increase the performance and may also enhance the throughput. If a selected beam pair is not the best pair but somehow is above the required RX sensitivity, it should also be able to establish communication between the gNB and the UE. This means that the probability of link failure analyzed in the measurements does not necessarily mean the probability that the connection between the gNB and the UE is not established. Given the above, latency and receive performance could be set as the KPI that sets the results in the context of the 3GPP guidelines. Therefore an applied research initiative is needed to address such impacts. The proposal contained in this thesis consists then in a novel latency-dynamic initial access scheme that is aware of the geolocation information of UE (vehicle) and gNB selects the optimal beam pair based on this information.

2.2.2 Cell Search

The cell search is a process on the User Equipment (UE) side that is responsible for finding cells around the location of the UE. This is done thanks to the processing of the so-called Synchronization Signal block (SSB)[10][11], a structure that consists of a Primary synchronization signal (PSS), a Secondary synchronization signal (SSS), and finally Physical broadcast channel (PBCH) blocks. The SSB's are grouped into the first 5 ms of an SS burst and are transmitted by a gNodeB (gNB) with a configurable periodicity T_{SS} with {5,10,20,40,80,160}ms intervals. Moreover, UE assumes a default periodicity of 20ms during initial cell search or idle mode mobility. Fig. 4 shows the time and frequency structure of an SSB. Note that time and frequency are defined in terms of OFDM symbols and subcarriers. In a slot of 14 symbols, there are two possible locations for SSB's: symbols 2–5 and symbols 8–11.

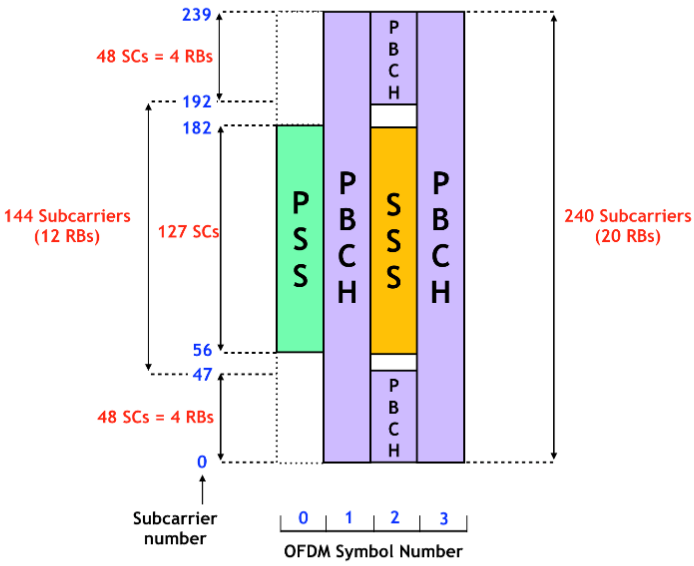

Fig. 4. SSB frame structure

The maximum number of SSB's (N_{SSB}) in a burst is frequency-dependent and is configured between N_{SSB}{4,8,64} and at mm-wave frequencies, there could be up to 64 blocks per burst. When considering frequencies for which beam operations are required, each SSB can be mapped to a certain angular direction which reduces UE's processing power/time for cell search. And the subcarrier spacing's (SCS) associated with each band are clearly defined by 3GPP. The SSB's occupy 20 Resource Blocks (RB) and there are 12 subcarriers in each RB, so there are a total of 240 subcarriers. Hence, the bandwidth occupied by a single SSB is 240 times the SCS. At mm-wave frequencies, SCS considered for IA are 120 and 240 kHz, thus out of 400 MHz per carrier (total channel bandwidth (BW)), the bandwidth reserved for the SSB's would be respectively 28.8 MHz and 57.6 MHz respectively. Given that 240 subcarriers are allocated in frequency to an SSB, the remaining bandwidth in the symbols which contain an SSB is BW − 240 × SCS. Therefore, it is possible to either allocate the remaining bandwidth as shown in Fig. 5 for data transmission towards users or the information in the first 240 subcarriers i.e SSB is repeated in the remaining subcarriers to enhance the detection capabilities for high mobility users. And there are guard band intervals in frequency among the different repetitions of the SSB.

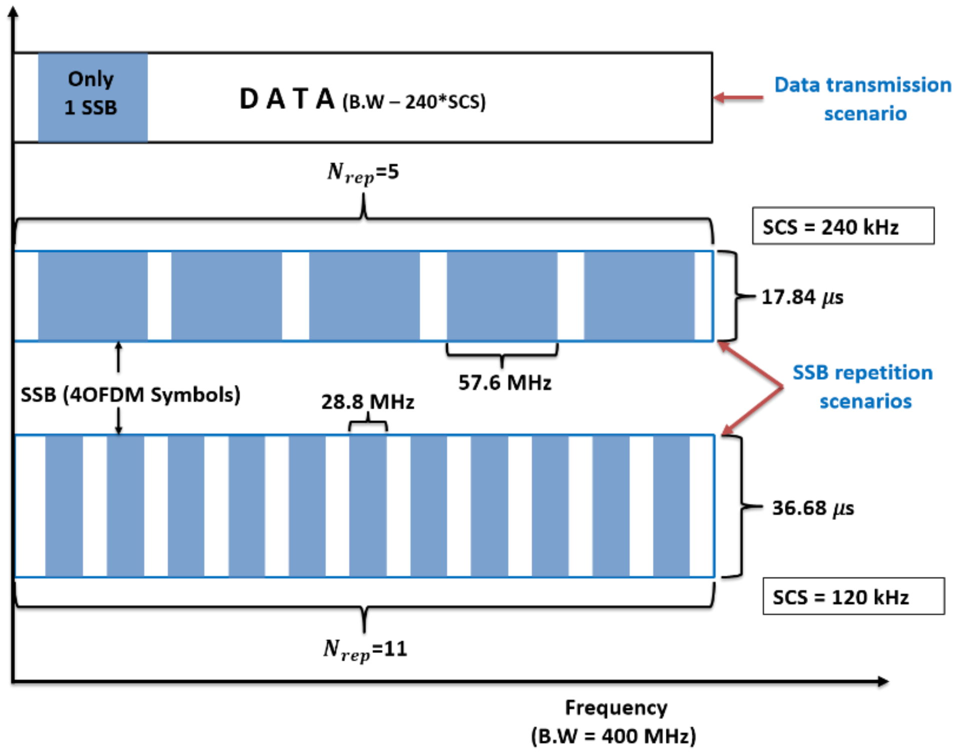

Fig. 5. Data transmission and SSB Repetition scenarios

Therefore, performing beam pair comparison metrics is important to establish the proper connection. It is defined in section 5.1 of 3GPP 38.215 as "the linear average value of the power contribution (in [W]) of the resource element carrying the secondary synch signals".
The mechanism of UE to measure and determine the best transmit beam is shown in Figure 6, and the steps are as follows.

i) Transmit multiple SSBs at specific intervals.
ii) Identify each SSB by a unique number called SSB Index
iii) Each SSB can transmitted via a specific beam radiated in a certain direction
iv) Multiple UEs are located at various places around the base station (gNB).
v) The UE measures the signal strength of each SSB it detected within a certain period of time (a period of one SSB Set).
vi) According to the measurement results, UE can identify the SSB index with the strongest signal strength. This SSB with the strongest signal strength is the best beam for the UE 1. (For example: Beam #1 is the best beam (the beam selected for UE1 and Beam#7 is the best beam for the UE 2)

Please note that the different beams that are being transmitted is determined by how many SSBs broadcasted in the SSB Burst (a set of SSBs being transmitted in 5 ms period of a SSB transmission).

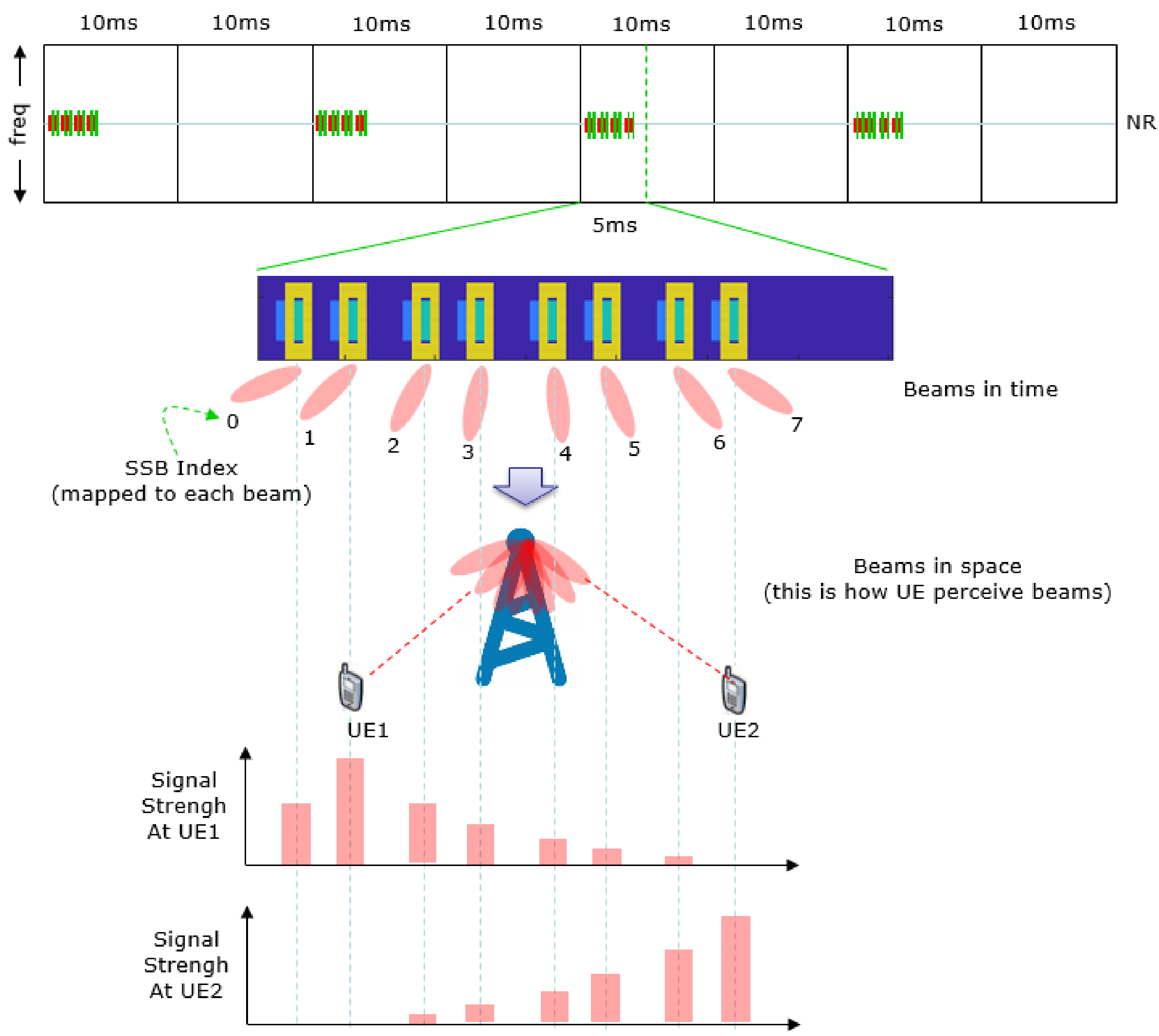

Fig 6 Mechanism by which UE measure and identifies the best beam

2.2.3 Beam Adjustment

When a UE has connected through an appropriate pair of beams. Various factors (e.g. movement, rotation, and blockage) of UE can slowly degrade it and there is a need to counteract them by adjusting the pair of communication beams. In addition, the sweeping structure of the TX beam in the gNB is relatively constant in IBE, which will be explained later in this chapter. Therefore, a relatively limited number of TX beams with a certain direction and width can only be selected by IBE. Beam Adjustment (BA) is the BM technique that adjusts the existing communication beam pair if necessary and possibly refines the beam pair to achieve a better link budget. BA offers more flexibility in the number of beams to choose from and their respective widths. It overcomes the limitations of IBE and continuously adapts the existing connection to the ever-evolving wireless environment where UE and gNB are located.

The procedures described previous sections, are used in an IBE context, and provided the UE with the essential parameters for a successful connection with the gNB, with the RRC status being changed from RRC IDLE to RRC CONNECTED. Basically, the BA methods are described with which the beams used for beam-formed communication are selected. In principle, the Beam Adjustment (BA) continuously adjusts the direction and width of the transmit and receive beams that are used on the gNB and UE side for UL and DL communication. For example, one can talk about beam refinement (the beam widths become narrower), beam tracing (the beams change direction), or a combination of these, among other things. The beams can also be broadened if necessary, for example, if a gNB has to cover several UEs with the same DL-TX beam. The basic structure of BA consists of:

- Programming of resources from the gNB side for sending reference signals.
- Reception of reference signals and measurement calculation. It can be carried out on the gNB or UE side, depending on the type of BA carried out.
- Measurement protocol. This step is optional depending on the type of BA performed.
- Beam adjustment

Measurements and reports can be carried out periodically, semi-periodically or aperiodically. Since Beam Adjustment does not occur simultaneously in UE and gNB, one Beam per procedure, identified by its index, is the result that can be used for the UL or DL communication. The gNB can use information and recommendations from the UE to improve the BA. The transmission of control signals and data can benefit from the beams selected in the process as BA aims to improve link quality based on changing radio channel conditions. gNB decides which UL RX and DL TX will be used, and tell UE about this. If the UE does not receive any prompts, it will accept them based on the configuration provided by the IBE. If the UE knows or assumes the beams used by the gNB, it can be able to select its own UL-TX and DL-RX beams. Even though they are not always aware of the beams that the other part is using, for example, that the gNB in DL wants to send with a specific TX and expects the UE to be received successfully, although the gNB does not know whether the RX beam that the UE will use is correctly receiving the DL transmission. The gNB can at most provide the information about which TX beam to be used for the UE. The information about the gNB's DL-TX beam is called the Beam indication. Therefore, it is expected that the UE will map the specified TX beam to an RX beam that is known, to establish a proper connection. If there is no indication, the UE receives a gNB-TX beam and selects a known corresponding RX beam to establish a proper connection.

2.2.4 Link Failure Procedure

With the introduction of beam establishment and beam adjustment procedures, it becomes possible to establish and maintain a connection between base station (gNB) and UE. Sometimes, the conditions of the radio channel may change so fast that the BA cannot cope with and withstand this change. Some techniques are used to re-connect the beam pair called Link recovery (LR) procedures. In order to apply these techniques, radio link failures must first be identified and then corrected. Among these aspects, a method that works one after the other is called "Beam failure detection" (BFD) and "Beam failure recovery" (BFR).

Chapter 3

Designing smart antenna array for beam management Procedures

One of the requirements of the IBE and BA are that the antenna array can realize beam forming and scanning so the point-to-point communication between a base station and UE could be optimized. There are several factors to consider when designing an antenna array. Typically an antenna array design includes parameters such as array dimensions, single element spacing, the spatial arrangement of the elements, and finally element tapering. In addition to this, the effects of mutual coupling between the elements are important to characterize before the final design is implemented. Once an initial configuration of the array design is complete, architectural partitioning can be iteratively evaluated against the overall system performance goals.

Moreover, the demand for efficient antenna performance has increased rapidly due to the rise in user density and high data rate requirements. Modern vehicular communication technologies now-a-days require wideband antennas that are capable of achieving stable radiation pattern and beam steering capabilities (in our case) with high gain. Millimetre wave spectrum provides a promising solution for the increasing user traffic. Because of the high free-space propagation losses of millimetre wave propagation, antenna array, which can increase the antenna gain and provide beam steering capabilities needs to be used. Since the antenna array behaves as a directional antenna, to establish point-to-point communication between mobile terminals and base stations, the phased array antenna should be adopted. On the other hand, the compact size of the array element is a growing demand to increase the isolation of adjacent elements. Hence, the Low Temperature Co-fired Ceramic (LTCC) technology is approached as the most adaptive way to realize compactness. However, the LTCC material exhibits high permittivity, which will make antenna bandwidth narrower.

3.1 Single Element Design and Analysis

In the first design, the radiating element is printed on a 0.84 mm thicker Rogers RT5880 substrate having a dielectric permittivity of $\varepsilon r=2.2$, and the microstrip feeding is fabricated on Rogers TMM4 substrate with $\varepsilon r=4.5$ and a thickness of 0.27 mm. In the second design, the microstrip feedline is fabricated on LTCC and then mounted on Rogers RT5880 of thickness 0.8 mm. The LTCC is made of Green Tape^{TM} 951 with $\varepsilon r=7.7$ and a thickness of 0.2 mm. The proposed broadband antennas are designed in three main steps. First, the microstrip feedline is optimized for 50 Ω for both the substrates. As a second step, the antenna patch is also optimized at the required impedance, and both the optimized feedline and the patch are put together to form a final single element. Layout and dimensions of the single antenna element for both the substrates are depicted in Fig.7 and Table I.

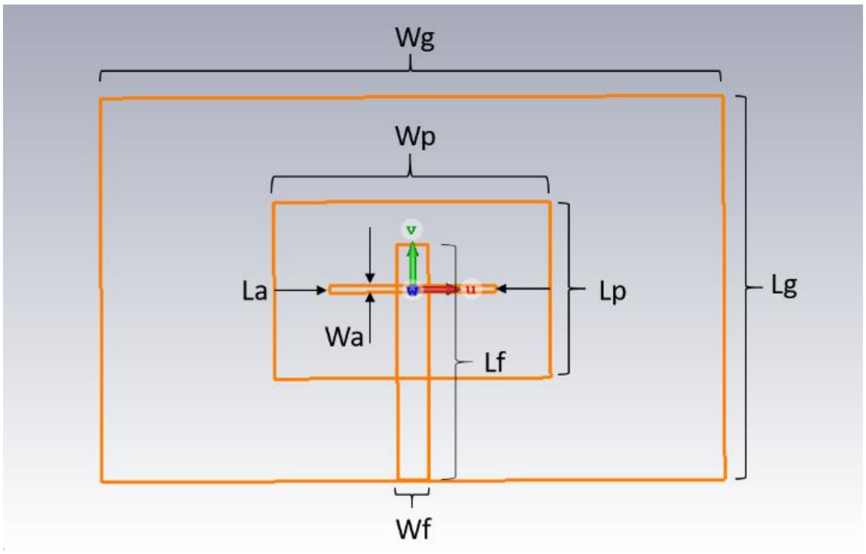

Fig. 7. Single element layout

TABLE I

Lengths	Values (Rogers TMM4)	Values (LTCC
Patch length (Lp)	2.76 mm	2.8 mm
Patch width (Wp)	4.3 mm	4.4 mm
Slot length (La)	2.65 mm	2.19 mm
Slot width (Wa)	0.11 mm	0.11 mm
Feed length (Lf)	3.75 mm	2.87 mm
Feed width (Wf)	0.5 mm	0.24 mm
Ground Length(Lg)	8.36 mm	8.36 mm
Ground Width(Wg)	9.8 mm	9.9 mm

The return loss of a single element in both designs is offering a bandwidth from 24.25 GHz to 29.5 GHz, as depicted in Fig. 8(a), 8(b).

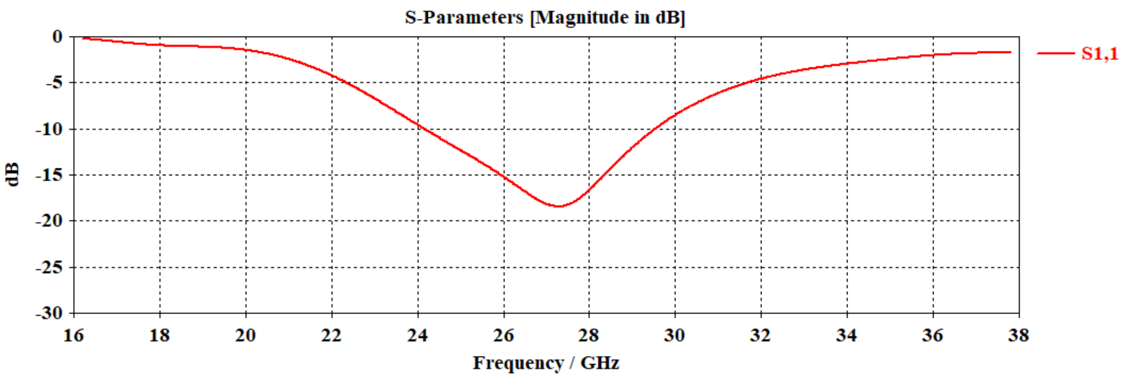

Fig. 8(a). S_{11} for a single element with Rogers TMM4 Substrate layer

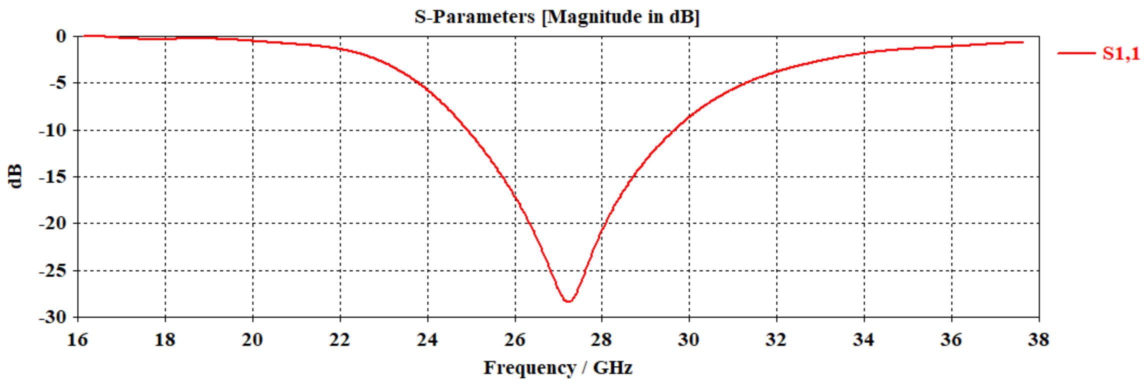

Fig. 8(b). S_{11} for a single element with LTCC Substrate layer

Hence, it can be seen that the antenna elements are properly matched at the proposed frequency bands. The three-dimensional Gain plots of the single antenna elements at the central frequency are illustrated in Fig.9 (a), (b).

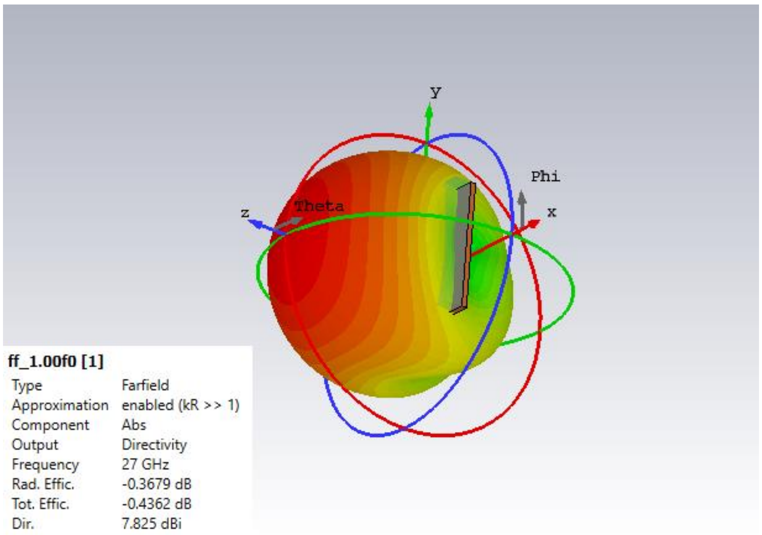

Fig. 9(a). Gain for a single element with Rogers TMM4 Substrate layer

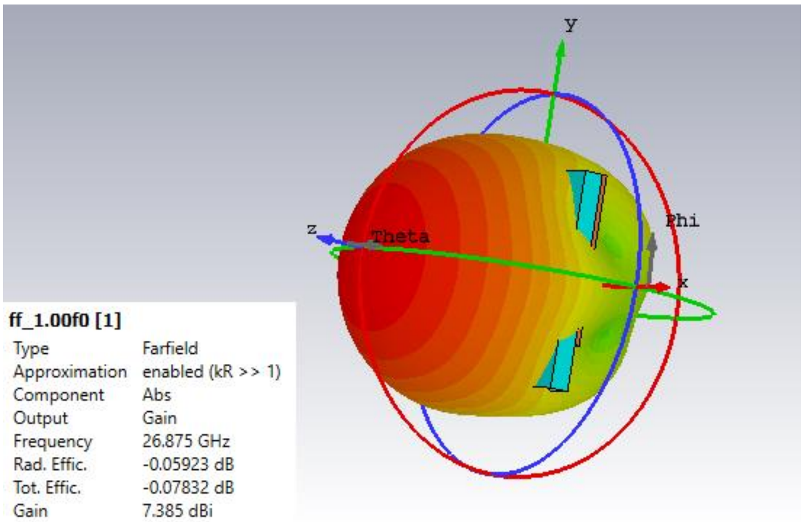

Fig. 9(b). Gain for a single element with LTCC Substrate layer

3.2 Antenna Array Design and Analysis

A first corporate subarray antenna was designed using four antenna elements. The inter element distance between any two adjacent elements of the array is ~0.6 λ_0 (λ_0, being the wavelength at the central frerquency of 27 GHz), that provides enough reduction of the mutual coupling between elements. In order to improve the matching conditions through all the frequency bands T junctions, miter bending's and quarter-wave transformers have been introduced. The dimensions for the corporate feed layout is presented in Fig.10 and Table II.

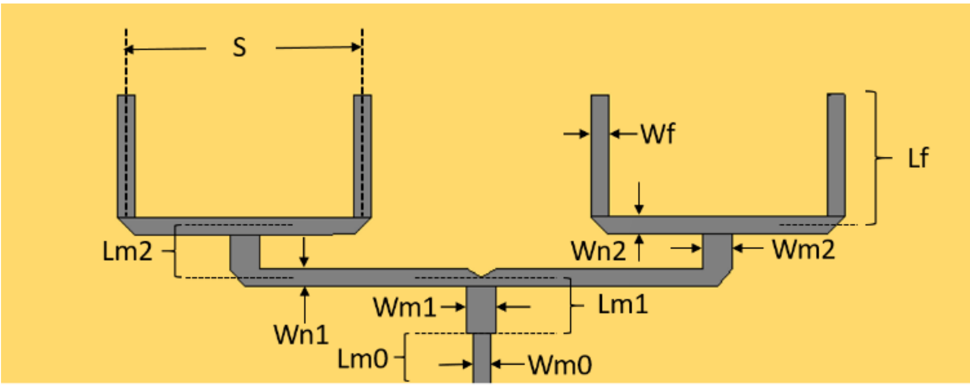

Fig. 10. Corporate feed layout

TABLE II

Lengths	Values for Roger TMM4	Values for LTCC
S	6.84 mm	5.8 mm
Lf	3.75 mm	2.87 mm
Wf	0.5 mm	0.24 mm
Lm0	1.53 mm	1.19 mm
Wm0	0.5 mm	0.24 mm

Lm1	1.48 mm	1.16 mm
Wm1	0.85 mm	0.44 mm
Lm2	1.48 mm	1.16 mm
Wm2	0.85 mm	0.44 mm
Wn2	0.5 mm	0.24 mm
Wn1	0.5 mm	0.24 mm

This compact antenna is designed to be mounted on the PCB of a mobile device. The S-parameters of the proposed antenna arrays for both substrates is shown in Fig.11 (a), (b).

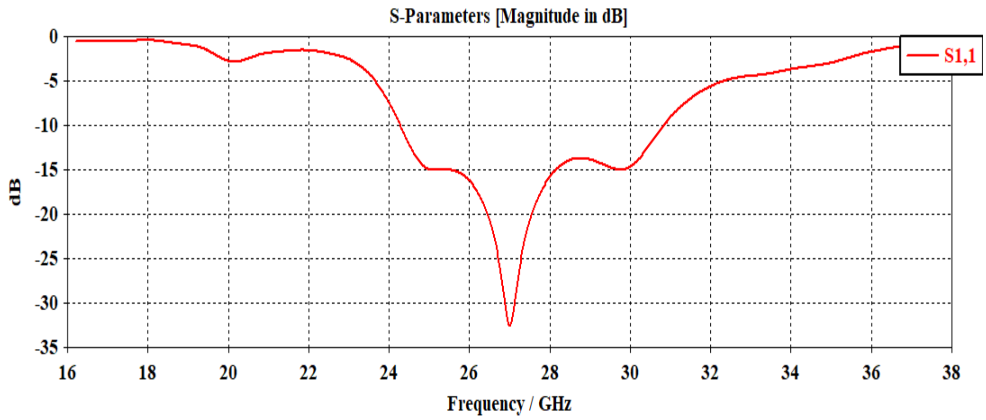

Fig. 11(a). S_{11} for array element with Rogers TMM4 Substrate layer

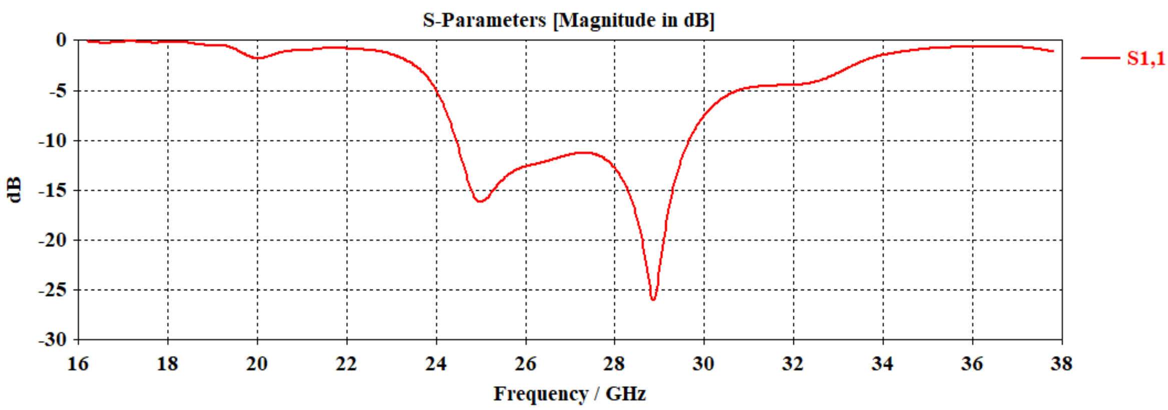

Fig. 11(b). S_{11} for array element with LTCC Substrate layer

It can be seen from Fig.10 that the antenna array has good performance within the entire frequency range of 24.25 GHz to 29.50 GHz. The three-dimensional Gain plots of the antenna arrays at the central frequency is illustrated in Fig.12 (a), (b).

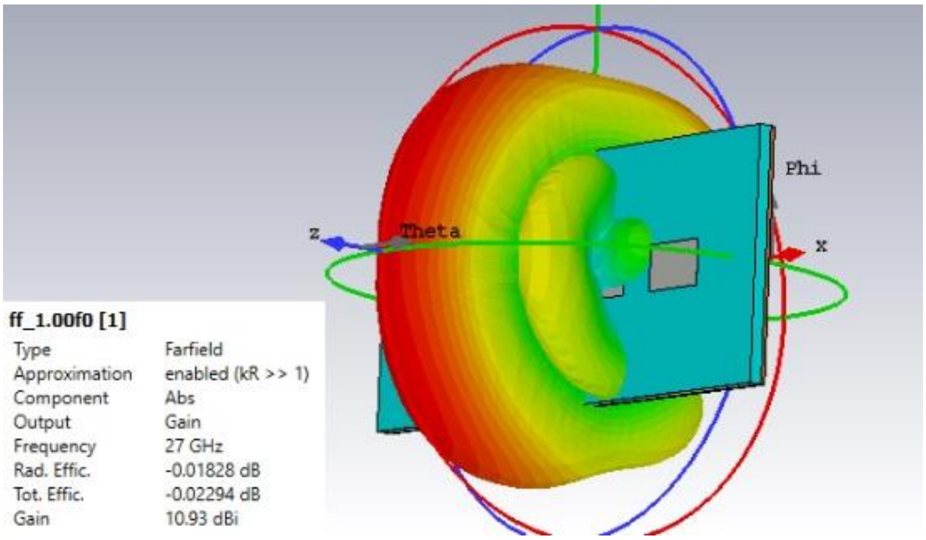

Fig.12 (a) Radiation Pattern for the array element with Rogers TMM4 substrate layer

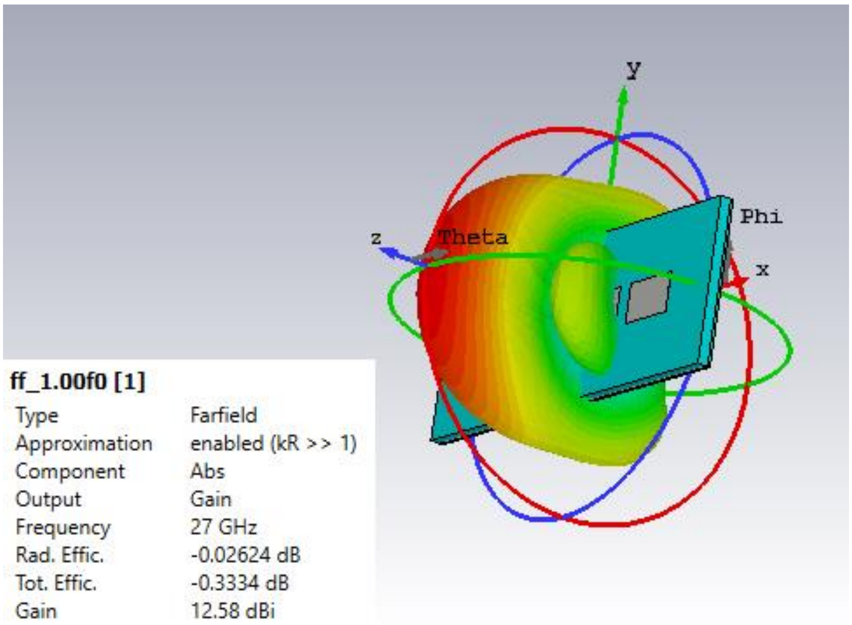

Fig.12 (b) Radiation Pattern for the array element with LTCC substrate layer

Hence, the base-antenna of the array behaves as a moderate directional antenna that could eventually be improved into the final array adding a back ground reflector. A very important criterion for evaluating the scanning property of the antenna array is to see if the side lobes of the 3D radiation patterns are small for bigger scanning angle. A scanning angle close to $\pm 20°$ have been obtained. Both designs (Rogers and LTCC substrates exhibit good S_{11} plots in the desired frequency range. But, when it comes to fabrication, the LTCC technique may be easier for fabrication. Moreover, it significantly cuts down the material and manufacturing costs.

3.3 Beamwidth as a Function of Antenna Elements

The beam width of uniform linear array (ULA) antenna can be formulated as $\Delta\theta_{3dB} = 1.772/N$. Where N is number of antenna elements in a row or column of a ULA. Fig. 13 shows the relation between number of antenna elements and beamwidth.

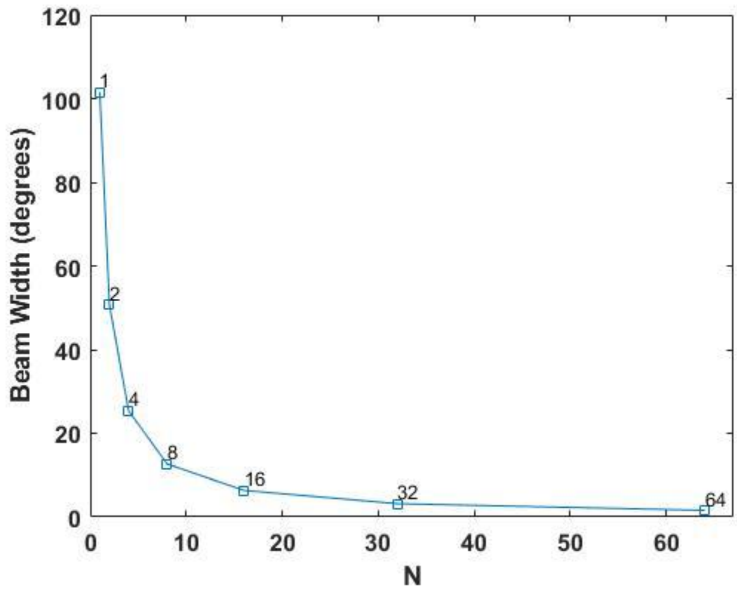

Fig. 13. Beamwidth as a function of N

An arrangement of 1000 elements is commonly used at gNB in 5G. Thirty-two elements in each direction i.e planar array provide an element count of 1024 and can produce a beam accuracy of less than 4° near the target. A 256-element planar array in general mass-produced at low cost can still have a beam pointing accuracy of less than 10° which can be quite acceptable for many vehicular applications. From Fig 14 we can see that increasing antenna elements can reduce the beam widths.

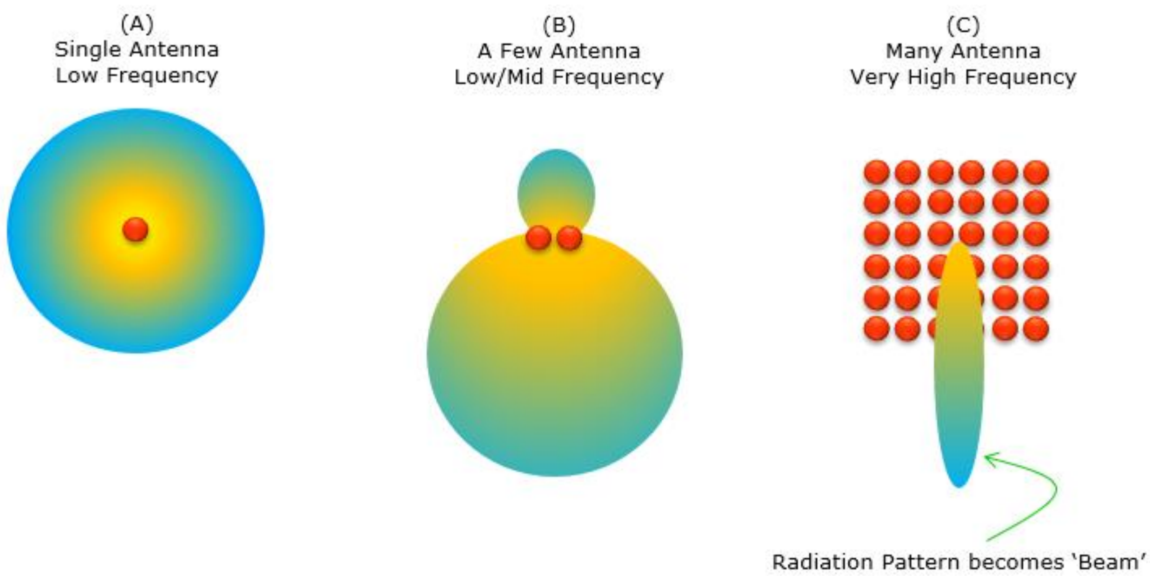

Fig 14 Antenna elements vs beam widths

3.4 Smart Antenna array design

The antenna design which we developed to study the beam management procedures in the chapter 4 consists of 4 x 1 subarrays and each subarray is a corporate array antenna implemented in the previous section. Beamforming techniques based on complex weighting vectors can be applied on the signals that feed each subarray. Beamforming allows control of the signal for both amplitude and phase evaluated at the subarray level. An Integrated Device Technology (IDT) chip will be used to apply the necessary subarray weights and perform the required beamforming through the chip's inbuilt SPI module which includes registers for each channel to control phase and gain biases. This chip is also integrated with On-chip Wilkinson combiners and a 5-bit DAC outputs to drive an (optional) external LNA or PA. Smart array architecture is presented in Fig.15.

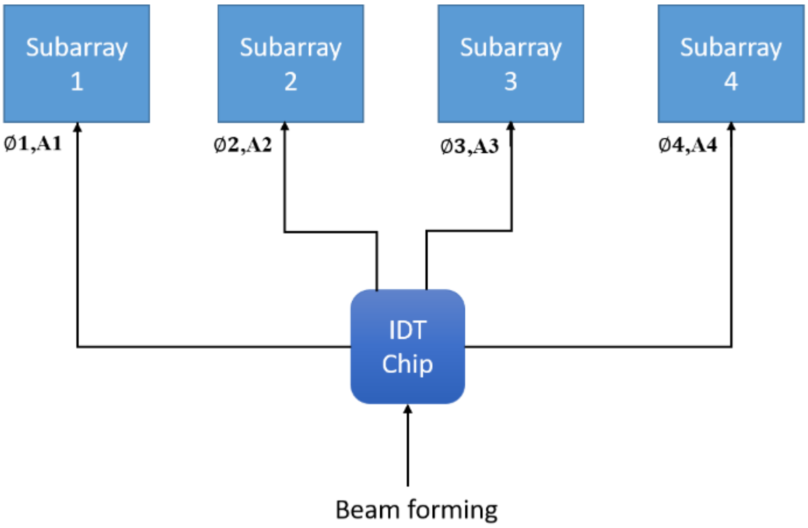

Fig.15 Smart array architecture

The distance between the sub arrays centers is ~2.4 λ_0 (borders of the sub-arrays is kept at ~0.6 λ_0) that provides enough reduction of the mutual coupling between subarrays. The three-dimensional radiation pattern plots of the total array considering tatt all the subarrays are excited with equal amplitudes (1, 1, 1, 1) and phases (0°, 0°, 0°, 0°) respectively at the central frequency is illustrated in Fig.16.

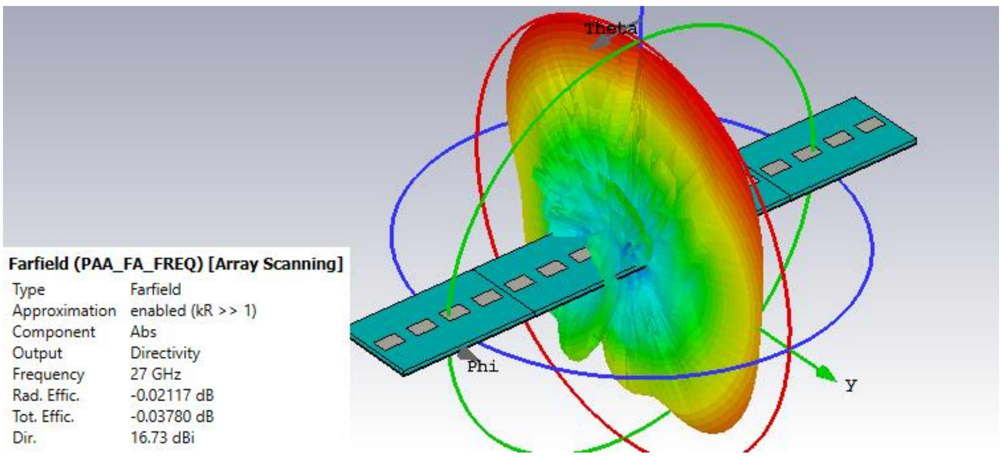

Fig.16 Gain for Smart array

The above plot in Fig.8 is highly directive and has a narrow angular beamwidth (3dB) of 5°. For the Smart handover application a wide angular beamwidth is required. Hence, we perform beamshaping by modifying amplitudes and phases as presented in Table III.

TABLE III

Modified weight	Amplitudes	Phases
Subarray1	1	0^o
Subarray2	2	60^o
Subarray3	2	60^o
Subarray4	1	0^o

The angular beamwidth (3dB) for the subarray, unmodified Smart array and the modified Smart array according weights in table 3 is 20^o, 5^o, 13^o respectively and is represented through gain vs elevation angle plots in Fig.17 (a),(b),(c).

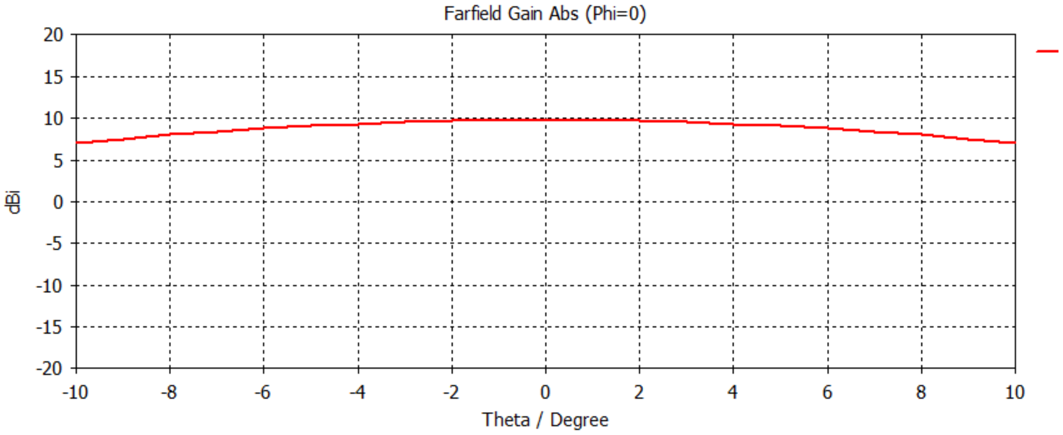

Fig.17 (a) Gain vs Elevation angle plot for Subarray

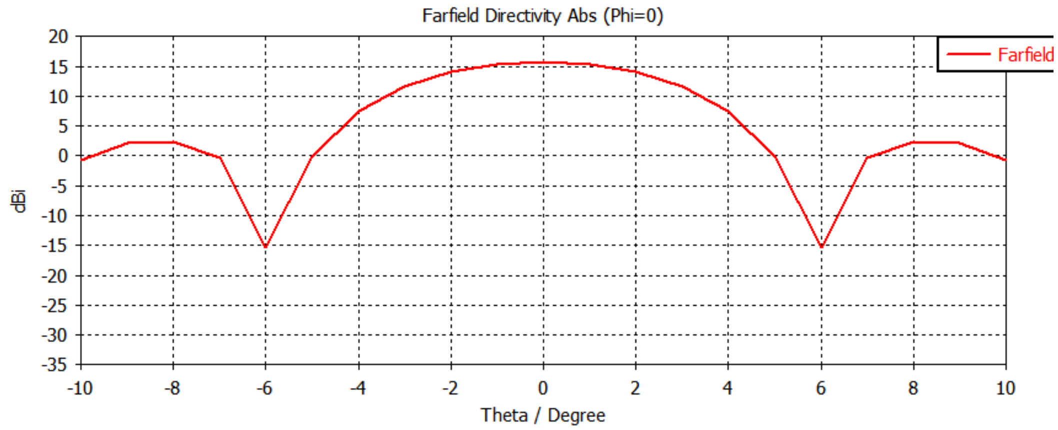

Fig.17 (b) Gain vs Elevation angle plot for Unmodified Smart Array

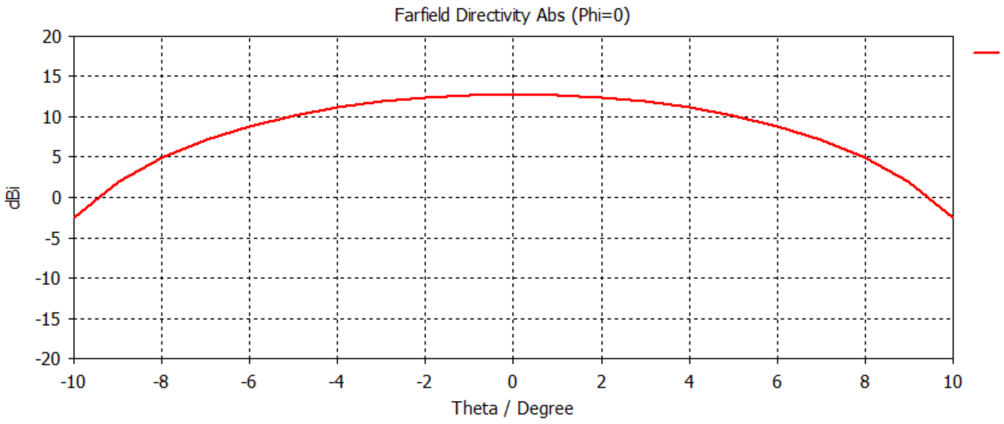

Fig.17 (c) Gain vs Elevation angle plot for Modified Smart Array

3.5 Design of Cosecant Pattern

Synthesisation of arbitrarily shaped radiation patterns using antenna arrays has a very significant importance in many applications. Various attempts based on analytical schemes are exerted for this application. Eventhough, these analytical methods are developed for specific problems, and usually synthesis of the radiation pattern is subject to only one restriction.Where as optimization algorithms are utilized for more general problems, eventhough, these algorithms require more computational time. In thesis we developed a Fourier technique for synthesizing arbitrary-shaped radiation pattern using the Smart antenna array described in the above sections. And the proposed Fourier synthesis algorithm can be applied to synthesis both the symmetric and asymmetric radiation pattern distributions with given number of antenna elements.

$$AF(\varphi) = \sum_{n=-\frac{N-1}{2}}^{\frac{N-1}{2}} a_n e^{jn\varphi} = DFT\{a_n\} \quad (1)$$

$$I_n = a_n e^{jn\alpha} \quad (2)$$

$$a_n = \frac{1}{2\pi}\int_{-\pi}^{\pi} AF(\varphi)\, e^{-jn\varphi}\, d\varphi \quad (3)$$

From a pattern specification $E_t(\theta)$ and the pattern of the basis element $E_o(\theta)$ and we obtain $AF(\theta) = E_t(\theta)/E_o(\theta)$. Then we finally compute a_n coefficients as Fourier series of $AF(\varphi)$.

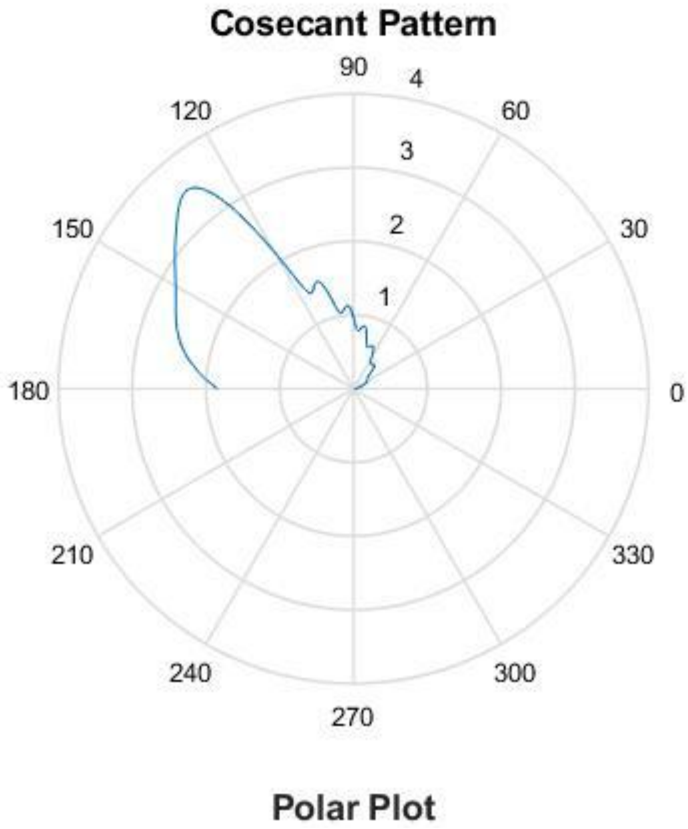

Fig. 18. Polar plot of cosecant linear array

The elevation pattern is a cosecant pattern with small secondary lobes towards ground, so the errors from ground reflection are minimized. The application of cosecant pattern in vehicular communications will be further discussed in chapter 4.

Chapter 4

Simulation and Results

4.1 Expense of Overhead on High Mobility Vehicular Tracking

Narrow beams as show in chapter 3 are key to establishing highly directional radio links which are desired for mmWave vehicular communications. However, they are limited to low mobility users, because vehicles moving at high speeds could suffer from a precise alignment of transmitter and receiver beams. So, to avoid beam pointing errors, the vehicle must always be in the radiation footprint (Rad_{ft}) of the gNB where the Rad_{ft} is expressed as a function of beamwidth and radial or relative distance (R_d) as represented in equation 1.

$$\mathrm{Rad_{ft}} = \Delta\theta_{3dB}\mathrm{R_d} \tag{4}$$

The gNB estimates the new position of a vehicle every T_{SS} period and if the moving vehicle position is correctly estimated then it falls in the radiation footprint. Hence, to be correctly estimated by gNB, the limits on vehicular velocities (V_{veh}) are calculated by equation 2 as a function of radiation footprint and SSB burst periodicity.

$$\mathrm{V}_{veh} < \mathrm{Rad_{ft}}/\mathrm{T_{SS}} \tag{5}$$

Using equation 5 we calculated the maximum limits on vehicular velocities for which N {16,32,64} elemental antenna array could be able to establish radio channel during IA procedure whereby default T_{SS} is 20ms and plotted on Fig. 19.

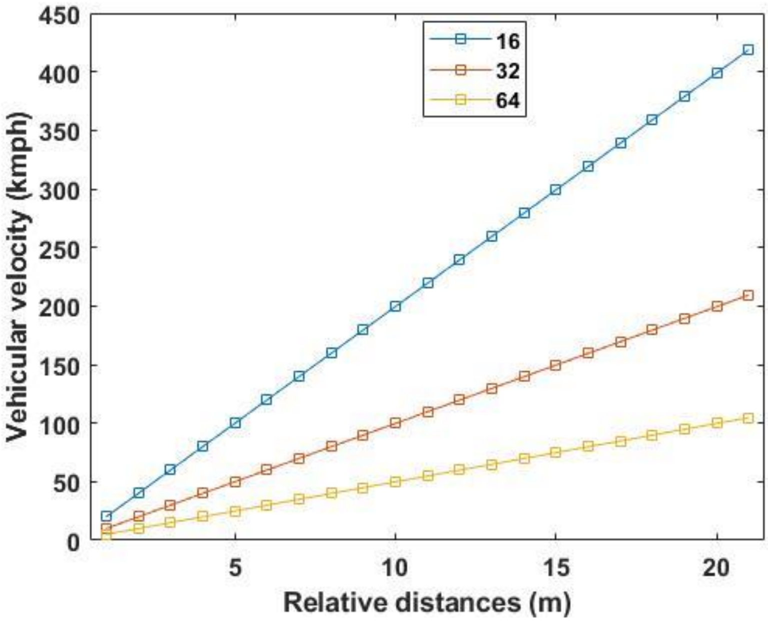

Fig. 19. Velocity as a function of relative distances that can be processed by different N-elemental arrays during the IA procedure

Moving from idle to connected mode mobility, if the gNB configures SSB burst periodicity of 5ms for better estimating the high mobility vehicles, it comes with the expense of high overhead. We characterize this overhead(ρ) for IA and beam tracking in terms of the ratio between the total time and frequency resources R_{total} that are allocated to SSBs with the duration of the SSB burst, or the entire T_{SS} interval.

$$\rho = \frac{R_{total}}{T_{SS}BW} \tag{6}$$

Where the R_{total} is scheduled for the transmission of N_{SSB}, each spanning 4 OFDM symbols and 240 (or multiple of 240) subcarriers

$$R_{total} = N_{SSB} 4 T_{OFDM} 240 N_{rep} SCS \tag{7}$$

T_{OFDM} is the OFDM symbol time and is expressed in μs. From equation 7 we could observe that overhead varies with the number of SSBs per burst (N_{SSB}) and SSB burst periodicities (T_{SS}) configured by gNB. Fig. 20 shows the increasing N_{SSB} per burst can result in a large overhead.

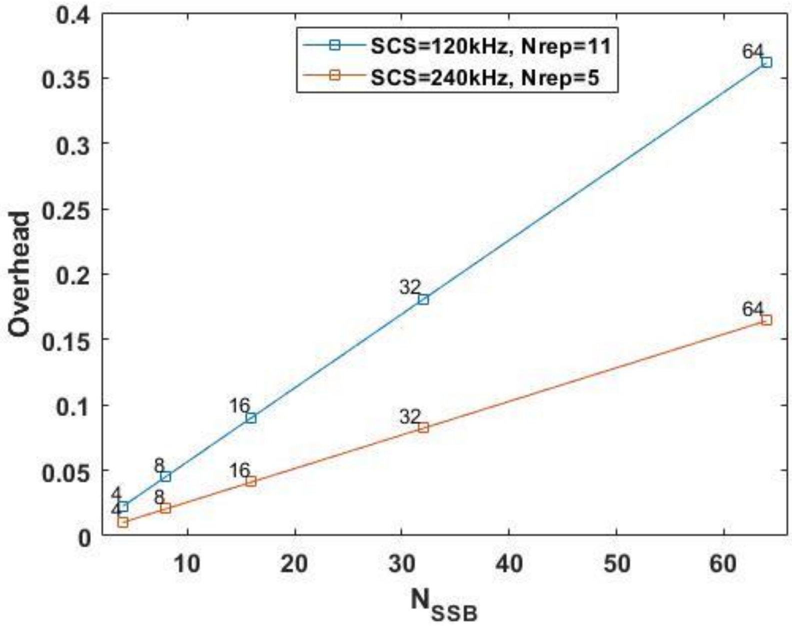

Fig. 20. Overhead as a function of N_{SSB} for different SCS and T_{SS} is set to 5ms

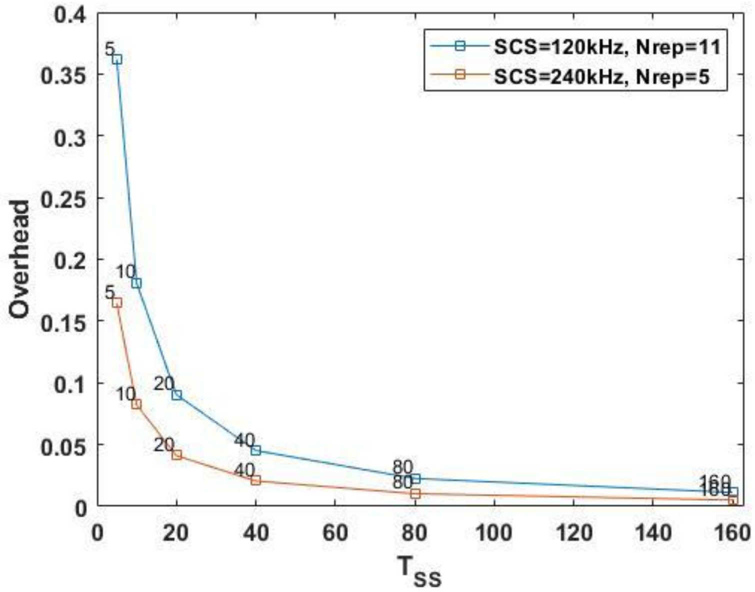

Fig. 21. Overhead as a function of T_{SS} for different SCS and N_{SSB} is set to 64

Fig. 21 shows the dependency of the overhead for tracking procedures with T_{SS}, which follows an inverse proportionality law. In particular, for very small T_{SS} (i.e., 5 ms) the impact of the SSB's with repetitions in frequency is massive, with up to 43% of the resources allocated to the SSB's. For $T_{SS} = 20$ ms or higher, instead, the overhead is always below 10%. Hence, the design and configuration of efficient IA and beam tracking procedures are of extreme importance in vehicular networks operating at mm-waves. In this paper, we propose that knowing the geo-locations (or GPS) of vehicles and their velocities beforre they arrival at a cell, can help the gNB to decide the beamswidths based on antenna array architectures to be used for the completion of the beam sweeping and reporting procedures in a single burst, so that it is possible to increase T_{SS} (e.g., to 20 or 40 ms), and reduce the overhead.

4.2 Modeling of a Realistic Urban Environment

To see the how the beam establishment procedure works we have to actualize realistic traffic simulations. So we approach Simulation of Urban Mobility (SUMO) [7] which is an open source traffic simulation package which includes net import and demand modelling components. SUMO helps to investigate several research topics e.g. route choice and traffic light algorithm or simulating vehicular communication. Therefore the framework is used in different projects to simulate automatic driving or traffic management strategies.

SUMO is not only a traffic simulation, but rather a suite of applications which help to prepare and to perform the simulation of traffic. As the traffic simulation "sumo" requires the representation of road networks and traffic demand to simulate in an own format, both have to be imported or generated using different sources. SUMO road networks can be either generated using an application named "netgen" or generated by importing a digital road map. The road network importer "netconvert" allows to read networks from other traffic simulators as VISUM, Vissim, or MATsim. It also reads other common formats, as shapefiles or Open Street Map. Due to the lack of applications, the support for TIGER networks was dropped. But TIGER networks are also available as shapefiles and were included in the OSM data base. Besides these formats, "netconvert" is also capable to read less known formats, as RoboCup network format, or openDRIVE.

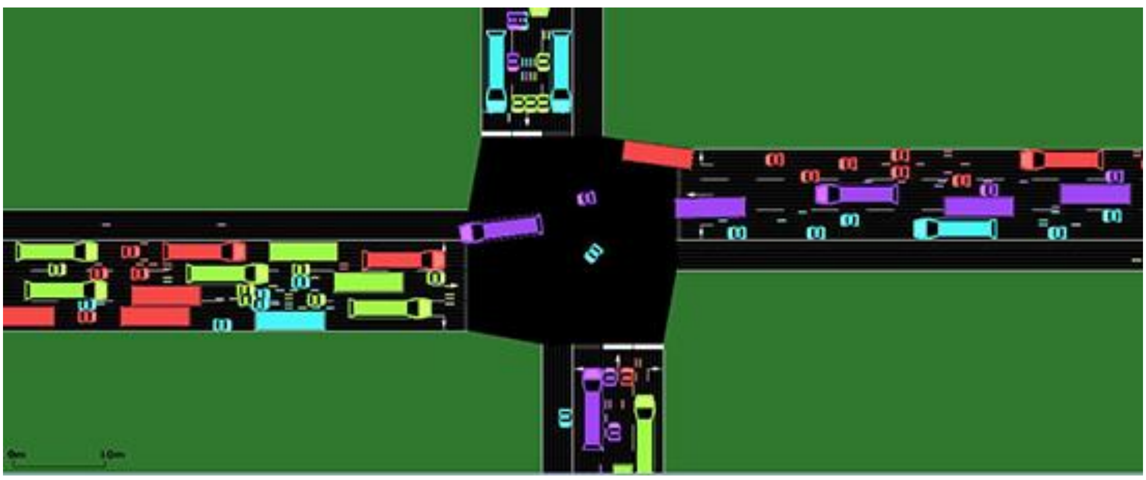

Fig. 22. Birds eye view of the cars and buses in the graphical user interface of SUMO

It is space-continuous and internally, each vehicle's position is described by the lane the vehicle is on and the distance from the beginning of this lane. When moving through the network, each vehicle's speed is computed using a so-called car-following model. SUMO uses an extension of the car-following model developed by Krauß. Changing the lane is done using a model developed during the implementation of SUMO. And in SUMO two versions of the traffic simulation exist. The first is a pure command line application for efficient batch simulation. The second version is a graphical application which renders the performed simulation using openGL.

4.3 Vehicular clustering & Beam management zones

We used the smart array designed in Chapter 3 to study the beam management procedures in different vehicular mobility scenarios. The SUMO simulation output file consists of the vehicular types (car, bus, etc.), their IDs, and respective GPS positions at every time step. The simulation we computed gives 45 minutes of traffic data and the GPS positions of vehicles are noted every 100 ms.

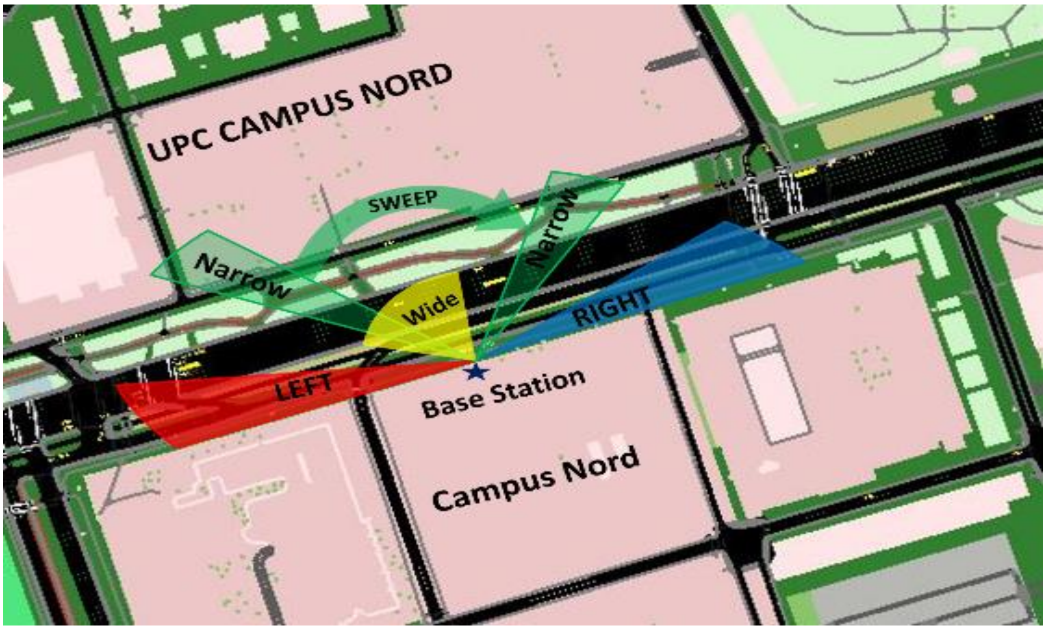

Fig. Beam Management Zones

This data is then processed to extract 3 feature vectors. The decision boundaries to group the data into different clusters were set based on the conditions to reduce the overhead in high mobility and to establish directional links in low mobility scenarios. These conditions are formulated based on the relation between vehicular velocities and their relative distances from the base station for the smart array and they are defined as follows: 1) Vehicles moving closer to base station with high velocities are allocated wide beams or lower elemental array configurations 2) Vehicles moving at lower speeds are associated with narrow beams or higher array configurations and finally 3) Vehicles entering from acute left or right to the base station are assigned with a cosecant pattern as shown in Fig.18 which have small secondary lobes towards ground, so the errors from the ground reflection are minimized.

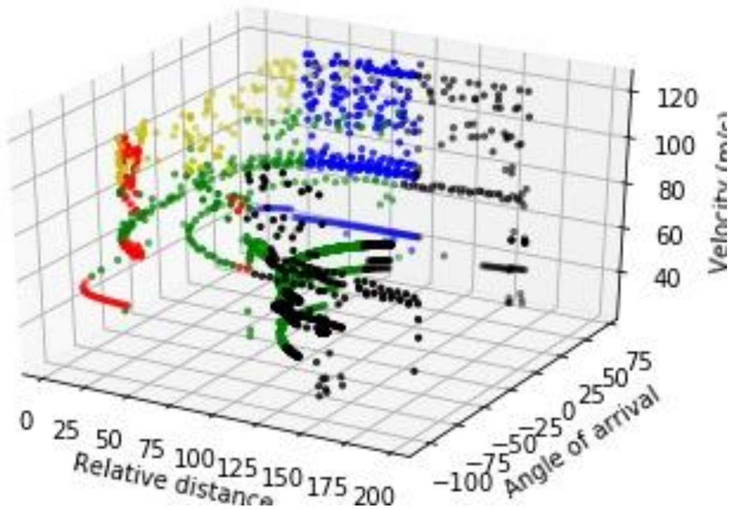

Fig. 23. 3D scatter plot

Fig. 23 is a 3D scatter plot between relative distances, velocities, and Angle of arrival (AOA) of vehicles to the base station that showcases different clusters based on the decision boundaries. The yellow data points in the scatter plot are defined from condition 1 that represents a wide beam. And the green data points in the plot are defined from condition 2 that represents a narrow beam. Whereas left and right data points are defined from condition 3 which represents the cosecant pattern beams. Finally, the label out in the figure represents that there are beyond the range of serving cells. To further clarify the conditions explained above in Fig.19 and Fig.23 for beam assignment, a vehicle moving at a speed of 100 kmph and driving in a lane within the relative distance of 12m or less from the base station is assigned with the wide beam. Whereas, a vehicle with the same speed driving in a lane farther than 12m is allocated with the narrow beam.

To better represent and for better understanding of the clusters, a 2D plot, Fig. 24, a top view of the scatter plot in Fig. 9 between the AOA in the y-axis and relative distance from a base station in the x-axis is created.

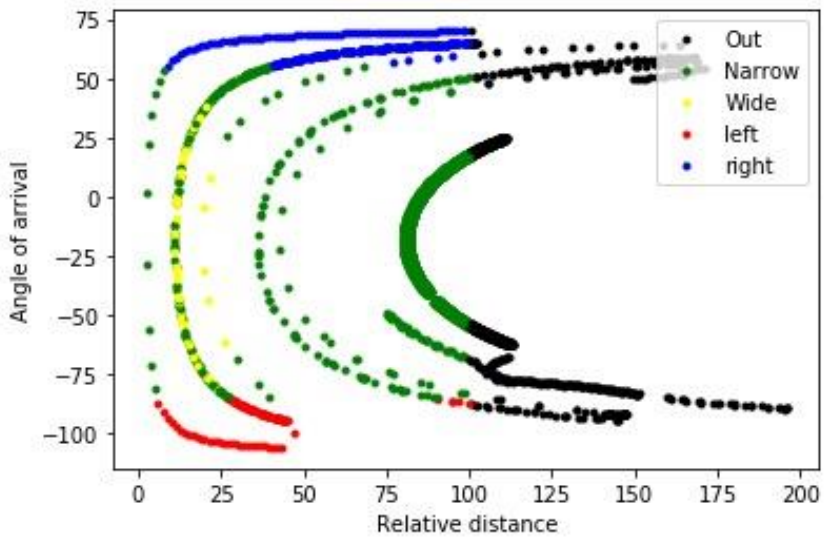

Fig. 24. 2D plot between angle of arrival and relative distance form base station

4.4 ML classification

Classification is a supervised machine learning process that matches input data with predefined groups or classes. The main condition for using the classification method is that all data objects must be assigned to one class, and each data object can only be assigned to one class. The distance-based classification algorithm is a technique used to classify data objects by using a distance function to calculate the distance between the test pattern and all training patterns. A distance-based algorithm was originally proposed to process a type of data with distance-based measurements to determine the similarity between the data. These algorithms have been developed to be able to handle heterogeneous data, because real-world data sets usually have different types, formats, content, and quality, especially when they come from different sources.

In general, when classifying heterogeneous data using distance-based algorithms, there are two categories of methods: the first category converts values from one data type to another (e.g., grouping data, interpolating, or projecting data), and then, distance-based algorithms can use a measurement can be used to classify the data.

However, this method is ineffective because the similarity measure of the transformed data does not necessarily represent the similarity of the original heterogeneous data consistently, especially if the transformation is not completely reversible. In addition, data conversion can fundamentally change the values to make them more equidistant, which means that there is no guarantee that the data will be interpreted correctly, which will cause the risk of losing or changing important information in the process of deciding the classification task is designed to support. The second category extends distance-based algorithms to compare different data. This can be done through distance metrics that can handle heterogeneous data. A common classification method based on the use of distance metrics is nearest neighbour (KNN). The traditional KNN classification algorithm finds the nearest neighbour (s) and classifies the numerical data records by calculating the distance between the test sample and all training samples using the Euclidian distance. The focus of the KNN classifier is the data set with purely numerical features. However, KNN can also be applied to other data types including that contain categorical data. Several studies were conducted to find suitable classification measures for such data. In addition, it can also be used to classify data described by both numbers and categorical features.

4.4.1 K-nearest neighbor classifier (K-NN)

In this section, we examine a classification method that uses the concept of distance to classify data objects. The KNN classifier [6][14][15] is one of the simplest and most widely used classification algorithms of its kind. KNN was proposed by Fix and Hodges in 1951 and modified by the cover and hard. The technique can be used for both the classification and the regression. The main concept of KNN is based on calculating the distances between the test and training data samples to identify their closest neighbours. The tested sample is then simply assigned to the class from your closest neighbour.

In KNN, the value k represents the number of nearest neighbours. This value is the central decision factor for this classifier since the value k decides how many neighbours influence the classification. If k = 1, the new data object is simply assigned to the class of your nearest neighbour. The neighbours are taken from a set of training data objects for which the correct classification is already known. Moreover, KNN works with numerical data. Various numerical measures are used, such as the Euclidean, Manhattan, Minkowsky, City block, and Chebyshev distances; among these, the Euclidean is the most widely used distance function with KNN. The main steps of k-NN algorithm are shown in Fig. 25.

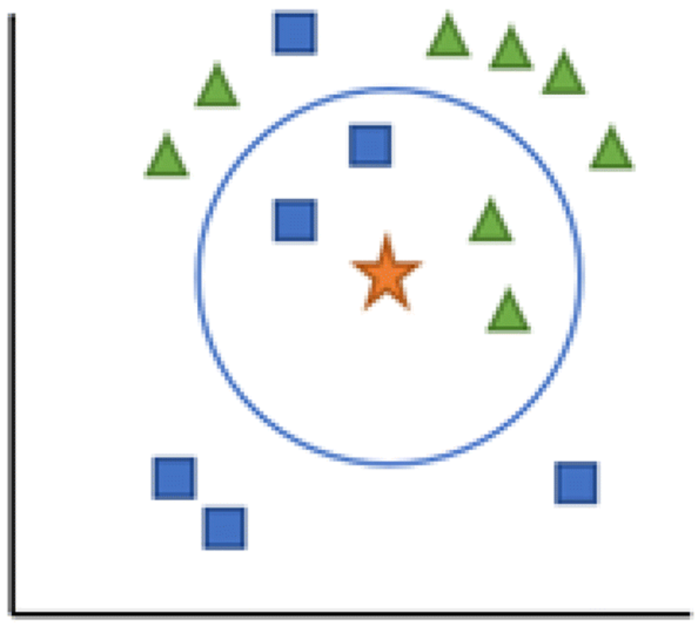

Fig. 25 k-Nearest neighbour classification (for k=4)

1. Determine the number of nearest neighbours (which are the K values).
2. Compute the distance between the test sample and all the training samples.
3. Sort the distance and determine nearest neighbours based on the K-th minimum distance.
4. Assemble the categories of the nearest neighbours.
5. Utilize simple majority of the category of nearest neighbours as the prediction value of the new data object.

4.5 Performance metrics of classifier

According to, the k-NN classifier can be used to classify new data objects using only their distance to labelled samples. However, some works consider any metric or non-metric measures used with this classifier. The most widely used technique for summarizing the performance of a classification algorithm is the Confusion Matrix. Fig.26 shows the confusion matrix for the case of binary classification with the following elements:

		Prediction	
		Positive	Negative
Actual	Positive	TP	FN
	Negative	FP	TN

Fig.26. A confusion matrix for binary classification

1. *True Positives (TP)* is defined by the total number of accurate outputs when the actual class of the data object was True and the predicted is also a True value.
2. *True Negatives (TN)* is defined by the total number of accurate outputs when the actual class of the data object was False and the predicted is also a False value.
3. *False Positives (FP)* when the actual class of the data object was False whereas the output value was the True value
4. *False Negatives (FN)* when the actual class of the data object was True whereas the output value was the False value.

4.5.1 Metrics computed from a confusion matrix

A confusion matrix provides useful information about how well the model is working; however, its elements can be used to compute many key performance indicators to obtain even more information [15]. The most popular are:

1. *Accuracy* is the most intuitive measure of performance and is defined as the ratio of the number of correctly classified objects to the total number of objects evaluated.
2. *Precision* it is simply the ratio of correctly predicted positive data objects to the total predicted positive data objects.
3. *Recall* it is defined by the number of correct positive results divided by the total number of relevant samples (all samples that should have been identified as positive).
4. *F-score* it can be defined as the weighted average of the precision and recall. An F-score can be considered perfect when it reaches its best value at 1, while the model is considered a total failure when it reaches the 0 value.

This information is used to train the Kernel Nearest Neighbors (KNN) algorithm to implement the beam patterns for vehicular channels as discussed above. The KNN algorithm is used to predict new data based on the above-mentioned decision boundaries. This KNN algorithm shows 99% accuracy in detecting the 1) high mobility vehicles and assign them wide beam widths, 2) vehicles arriving from left and right corners of the base station and allocate the cosecant pattern, and 3) assigning narrow beams for low mobility users. Further information about the performance metrics of the KNN algorithm for each condition or cluster is shown in Fig.27.

	precision	recall	f1-score	support
Narrow	0.99	0.99	0.99	720
Out	0.99	0.99	0.99	336
Wide	0.70	0.88	0.78	8
left	0.88	0.93	0.90	15
right	0.93	0.99	0.96	67
accuracy			0.99	1146
macro avg	0.90	0.95	0.92	1146
weighted avg	0.99	0.99	0.99	1146

Fig. 27. Classifier evolution metrics

Finally, the detailed breakdown of the beam allocation process for vehicular networks using ML is shown in Fig.28.

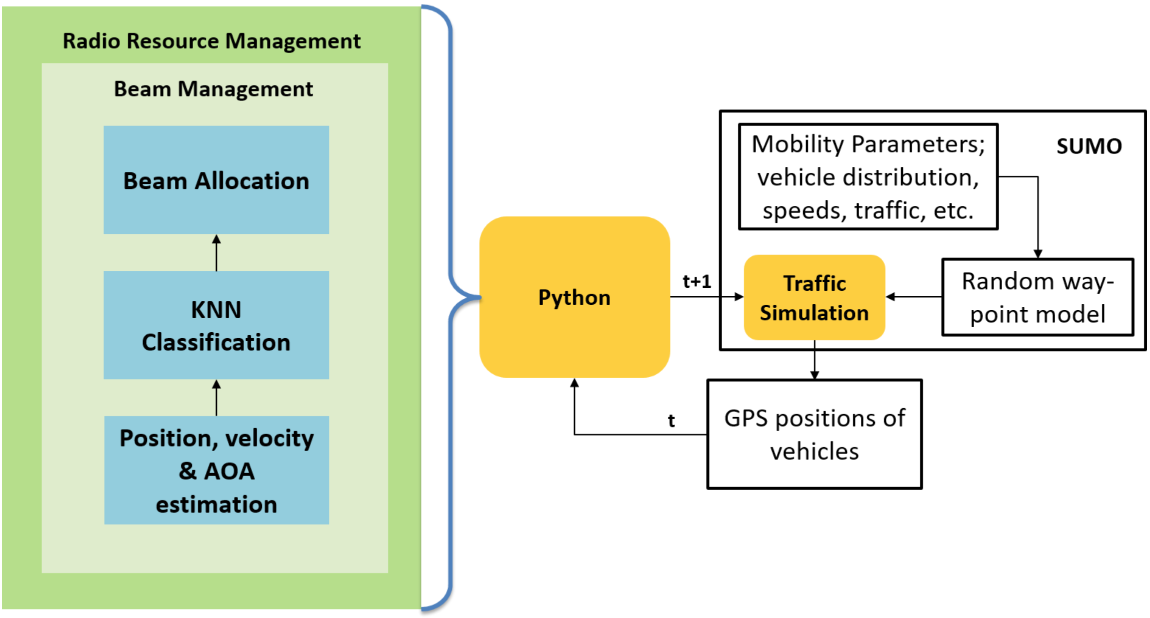

Fig. 28. Block diagram of smart beam management procedure

By this classification of vehicular traffic using KNN, we can assign the best beam pairs to vehicles in high mobility scenarios which in turn reduces, misalignment errors during the IA procedure in idle mode mobility and frequent overhead usage to maintain the connectivity in connected mode mobility.

Chapter 5

Conclusions

In this thesis, several aspects of next generation vehicular communications have been discussed. The main conclusions that can be extracted from the work developed in previous chapters are summarized in the following lines.

After a brief overview of the literature on beam management at mmWave frequencies in chapter 2, we described the frame structure and reference signals in 3GPP NR, focusing on the settings for communication at mmWave frequencies. Then, we described beam management procedures according to different network architectures and signal transmission directions (downlink or uplink). We also evaluated the impact of several parameters (specified by 3GPP for NR) on their performance. In chapter 3, we showed that there exist trade-offs among better detection accuracy, and reduced overhead and provided the insights and guidelines for determining the optimal initial access and tracking strategies. Finally, in chapter 4, we proposed a KNN based machine learning approach to solve the beam management problem by leveraging the information about the vehicle's mobility before it arrives at the base station.

To summarize, mmWaves are widely studied to enhance the capacity of future vehicular networks. The harsh propagation at mmWave frequencies requires the implementation of directional transmissions supported by beamforming techniques to increase the link budget. Therefore, control procedures such as initial access must be updated to account for the lack of an omnidirectional broadcast channel, and the optimal beam pair with which a base station and a UE communicate should be tracked when needed. Consequently, the design and configuration of efficient IA and tracking procedures is of extreme importance in vehicular networks operating at mmWaves.

In this thesis, we have presented smart beam management frameworks for mmWave vehicular communications in 3GPP NR V2X. The benefits of our proposal are particularly useful for the high mobility vehicular use cases envisioned for NR-V2X and beyond. Our approach incurs a considerable reduction of beam tracking overhead.

5.1 Future Work

The work previously presented is just the starting point of a more ambitious project regarding the design of future smart beam management systems for next-generation vehicular networks. In addition, some of the proposals have to be optimized and evaluated before extending the work to other topics. The measurement campaign is expected to be carriedout in short term and some outdoor experiments need to be scheduled as well. The UWB antenna has to be fully tested up to the mmWave band, between 24 and 28 GHz at least. Correlation measurements of multi-antenna geometries are also required to characterize the system.

In a mid-long-term period, there are several proposals to extend this thesis and coveradvanced topics of NR V2X networks. The consideration of massive antennas is mandatory to improve the efficiency and introduce spatial multiplexing techniques, which seem to be crucial in future vehicular systems. It also leads to larger bandwidths and higher frequencies in the mmWave region. The management of several users and the design of appropriate antennas are the most important challenges in this direction.

In conclusion, the close horizon of the next generation autonomous vehicles is speeding up antenna designers to provide innovative and feasible solutions to create a new era of efficient, green, ultra-fast and massively deployed vehicular networks. This thesis tried to cover some aspects and introduce others for future research lines.

5.2 Research Outcome

The following articles have been published as a consequence of the workpresented in this thesis and closely related topics:

- G. Bharath Reddy, G.A. Ramirez, J. Molins, M. Fernando-B, J. Romeu, and L. Jofre-R "Vehicular mm-Wave Array for Smart Handover", XXXV URSI National Symposium, Málaga, September 2020.
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