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Radio Resource Management in a Coexisting 5G NR and Wi-Fi Vehicular Scenario

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Abstract

The recent and remarkable advances in the automotive industry are paving a new way to promote road safety and traffic efficiency, based on connected and autonomous vehicles. This potential can be fully exploited through Vehicle-To-Everything (V2X) wireless communications, which provide connectivity to and from base stations and among vehicles. Future driving applications will inevitably need higher performance than those currently supported by existing V2X technologies. This has sparked interest in developing novel necessary solutions to cope the challenges resulting from the high mobility of vehicles and the several requirements of the new use cases. Today, the two main access technologies are IEEE 802.11p and LTE-V2X that, however, fall short of fulfilling the foreseen increasing traffic demands, in terms of very high throughput, ultra low-latency and ultra-high reliability of future vehicular services. To overcome these limitations, IEEE 802.11bd and NR-V2X represent the new specifications for next generation vehicular networks, exploiting new communication technologies, such as beamforming, and new spectrum, such as the millimeter wave (mmWave) band, to improve performance from all points of view.

Starting from these considerations, in this thesis several techniques are applied together in a realistic vehicular scenario, realized thanks to a combination of simulation tools such as Wireless InSite and SUMO. In particular, we focus on a user selection algorithm based on Zero-Forcing Beamforming (ZFBF) and we analyze its performance in a real Infrastructure-to-Vehicles (I2V) scenario at mmWave. Furthermore, we exploit network slicing technique to enable the coexistence among different standards. Some other technologies utilized are MIMO systems, antenna arrays, orthogonally frequency division multiple access (OFDMA) and two different transmitted power allocation policies.

Our numerical results show that the environment's geometry significantly affects the propagation pattern and thereby reduces the efficiency of ZFBF in terms of multiplexing. On the other hand, this approach still takes advantage of multi-user diversity to improve the overall capacity.

Sommario

I recenti e notevoli progressi nel settore automobilistico hanno aperto una nuova strada per promuovere la sicurezza stradale e l'efficienza del traffico, basate su veicoli connessi e autonomi. Questo potenziale può essere sfruttato appieno attraverso le comunicazioni wireless Vehicle-To-Everything (V2X), che forniscono connettività da e verso le stazioni base e tra i veicoli. Le future applicazioni di guida avranno inevitabilmente bisogno di prestazioni più elevate rispetto a quelle attualmente supportate dalle tecnologie V2X esistenti. Ciò ha suscitato interesse nello sviluppo di nuove soluzioni necessarie per far fronte alle sfide derivanti dall'elevata mobilità dei veicoli e dai diversi requisiti dei nuovi casi d'uso. Oggi, le due principali tecnologie di accesso sono IEEE 802.11p e LTE-V2X che, tuttavia, non sono in linea con le crescenti richieste di traffico previste, in termini di throughput molto elevato, latenza ultra bassa e altissima affidabilità dei futuri servizi veicolari. Per superare queste limitazioni, IEEE 802.11bd e NR-V2X rappresentano le nuove specifiche per le reti veicolari di nuova generazione, sfruttando le nuove tecnologie di comunicazione, come il beamforming, e il nuovo spettro di frequenze, come la banda delle onde millimetriche (mmWave), per migliorare le prestazioni sotto tutti i punti di vista.

Partendo da queste considerazioni, in questa tesi diverse tecniche sono applicate insieme a uno scenario veicolare realistico, realizzato grazie a una combinzazione di simulatori come Wireless InSite e SUMO. In particolare, ci concentriamo su un algoritmo di selezione dell'utente basato su Zero-Forcing Beamforming (ZFBF) e analizziamo le sue prestazioni in un vero scenario di comunicazione fra infrastruttura e veicolo (I2V) a onde millimetriche. Inoltre, sfruttiamo la tecnica del network slicing per consentire la coesistenza tra diversi standard. Alcune altre tecnologie utilizzate sono i sistemi MIMO, gli array di antenne, l'accesso multiplo a divisione di frequenza ortogonale (OFDMA) e due diverse politiche di allocazione della potenza trasmessa.

I nostri risultati numerici mostrano che la geometria dell'ambiente influisce in modo significativo sul modello di propagazione e quindi riduce l'efficienza di ZFBF in termini di multiplexing. D'altra parte, questo approccio è comunque in grado di sfruttare la diversità tra gli utenti per migliorare la capacità complessiva.

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List of Abbreviations

- **3GPP:** Third Generation Partnership Project
- **5G:** Fifth Generation
- **5GAA:** Fifth Generation Automotive Association
- **AoA:** Angle of Arrival
- **AoD:** Angle of Departure
- **AP:** Access Point
- **BW:** Bandwidth
- **BWP:** Bandwidth Part
- **C-V2X:** Cellular V2X
- **CAVs:** Connencted and Autonomous Vehicles
- **CFP:** Contention-free period
- **CP:** Contention period
- **CSAT:** Carrier-sensing adaptive transmission
- **CSMA/CA:** Carrier-sense multiple access with collision avoidance
- **D2D:** Device to Device
- **DCM:** Dual Carrier Modulation
- **DSRC:** Direct Short Range Communication
- **eNB:** eNode-B
- **FDMA:** Frequency Division Multiple Access
- **gNB:** gNode-B
- **I2V:** Infrastructure-to-Vehicle
- **IoT:** Internet of Thing
- **KPI:** Key Performance Indicator
- **LBT:** Listen Before Talk

- **LOS:** Line Of Sight
- **LTE:** Long Term Evolution
- **LTE-LAA:** Long Term Evolution - Licensed Assisted Access
- **LTE-U:** Long Term Evolution - Unlicensed
- **MAC:** Medium Access Control
- **MCM:** Multi Carrier Modulation
- **MIMO:** Multiple Input Multiple Output
- **mmWave:** Millimeter Wave
- **MNO:** Mobile Network operator
- **MU-MIMO:** Multi-User MIMO
- **NFV:** Network Function Virtualization
- **NR:** New Radio
- **NR-U:** New Radio - Unlicensed
- **OFDM:** Orthogonal frequency-division multiplexing
- **OFDMA:** Orthogonal frequency-division multiple access
- **OSM:** Open Street Map
- **PCF:** Point Coordination Function
- **PRB:** Physical Resource Block
- **QoS:** Quality of Service
- **RAT:** Radio Access Technology
- **RRM:** Radio Resource Management
- **RSU:** Road Side Unit
- **SDN:** Software-Defined Network
- **SDVN:** Software-Defined Vehicular Networking
- **TDMA:** Time Division Multiple Access
- **UPA:** Uniform Planar Array
- **URLLC:** Ultra Reliable Low Latency Communication
- **V2I:** Vehicle-to-Infrastructure
- **V2N:** Vehicle-to-Network
- **V2P:** Vehicle-to-Pedestrian
- **V2V:** Vehicle-to-Vehicle
- **V2X:** Vehicle-to-Everything

Chapter 1

Introduction

The ability to support various vertical applications and use cases is an important feature of the 5G communication systems. Automotive industry is one of the main actors that will take benefit from novelties introduced by 5G technology and it has a great potential of enabling a variety of emerging applications for road safety, traffic optimization, infotainment and much more. In fact, vehicular communications promise not only safety, but also a more efficient and comfortable transport up to fully automated and connected vehicles. During the last years, they have evolved from a simple mechanical machine to a smart body of sensors which allow a significant improvement in both safety and experience for the driver and passengers. Motor vehicles are now safer and smarter than they have ever been.

World Health Organizations (WHO) estimates that in 2016 there were 1.35 million deaths on the roads worldwide [29]. Therefore, the first and essential purpose of vehicular communication is to prevent road accidents and thus reduce the number of deaths. Moreover, in 2014 traffic jams forced highway users in the U.S. to spend extra unnecessary 6.9 billion hours on the road and to consume additional 3.1 billion gallons of fuel, corresponding to an annual economic loss of $ 160 billion [30].

In addition to these improvements in terms of safety and and time savings, the impact of connected and autonomous vehicles (CAVs) will also extend to the economy at large. For examples, fewer collisions and more law-abiding vehicles will lower demand for auto repair, traffic police, medical, insurance, and legal services. Once CAVs are sufficiently reliable and affordable, they will penetrate markets and thereby generate economic ripple effects throughout industries, as investigated in [31]. Although CAVs may cause losses in some businesses, Morgan Stanley has estimated a combined potential value of $ 1.3 trillion annually, which is 8% of the entire US gross domestic product [32].

Futuristic applications, hence, will go beyond security and collision avoidance as they have been conceived so far: they will include real-time and remote control, integrated autonomous services and vehicle management [33].

Automotive industries, government agencies and academic institutions around the world have made great efforts in this direction, but unfortunately our transportation and telecommunication systems still suffer from serious issues.

Currently, there exist two major groups of vehicular communication approaches, based respectively on Wi-Fi and cellular solutions. So far, these technologies have been considered competitors, but are expected to coexist. In the near future, it is believed that a single technology can not support a big variety of applications for a large number of users. Hence, interworking between standards is needed for efficient vehicular communications. In addition, the performance results of both technologies suggest that one single technology is not able to to meeting the requirements of several use cases [34]. Thus, they will have to share on the same unlicensed frequency bands.

The access network should provide connectivity to all devices that require it in the cell. A critical aspect is therefore to allocate and utilize the available wireless network resources in an efficient manner. This issue is particularly crucial in a vehicular environment such as the one we are considering, as the impact of user mobility is much greater than in a traditional cellular network and, consequently, affects the channel. Some different approaches have been proposed to allocate radio resources, but they have some limitations and they do not focus on a millimeter wave (mmWave) vehicular scenario.

Our numerical results will show that the environment's characteristics significantly affects the propagation pattern and thereby reduces the efficiency of the proposed approach. On the other hand, some results will demonstrate the positive effect of multiuser diversity and the potentiality of network slicing to address the coexistence issue.

1.1 Purposes and contributions of the thesis

In this work, we try to find a way to increase performances, over different points of view, of a communication system in a vehicular scenario. Practically, to achieve this goal, we follow two main routes.

First, we want to explore and investigate the applicability of a classical scheduling algorithm in the context of vehicular communication by considering a real scenario and mmWave channel impairments.

Secondly, we aim to implement a network slicing technique, in order to enable the coexistence between users based on different standards: it is, in fact, an architectural solution that allows to provide an efficient network connectivity for networks with heterogeneous Radio Access Technologies (RATs). The main idea is to consider Wi-Fi as a slice of 5G network, as proposed in [12], and to handle simultaneously the two types of users guaranteeing to them a good degree of fairness and Quality of Service (QoS).

Most of the existing works lack or do not consider a realistic vehicular scenario with mmWave channel modeling. Our purpose is to fill this gap. The main contributions of this work are summarized as follows:

- Simulate a practical vehicular environment at mmWave. The scenario is simulated by using OpenStreetMap [35] and Simulation of Urban MObility (SUMO) [36] software to model the vehicle traffic over real road networks. The SUMO output is processed by Wireless InSite [37], which is a ray-tracing suite able to compute the mmWave channels.

- Investigate the potential of Zero-Forcing beamforming (ZFBF) as a multiplexing strategy where users streams are spatially separated. This selection process enables different users to be connected at the same time to the gNB with negligible level of interference.
- Exploit the semi-orthogonal user selection scheme proposed by Goldsmith *et al.* in [28] to construct a subset of users to be served with ZFBF.
- Apply two different power allocation policies following an unfair and a fair approaches, in order to maximize respectively the overall sum data rate and the number of served users.

1.2 Thesis structure and outline

The structure of the thesis is summarized as follows:

- **Chapter 2** gives a comprehensive overview of vehicular communications, by describing the existing and developing technologies and by focusing of the advantages of 5G and millimeter waves. At the end, the key aspects of this thesis are presented, namely the coexistence issue and the radio resources management in a vehicular environment.
- **Chapter 3** presents the state of the art regarding the coexistence between different technologies. Several developed approaches are illustrated, referring in particular to the two main group of standards: Wi-Fi-based one and cellular-based one. At the end of the chapter, the article we have taken as a reference and starting point for this thesis work will be depicted.
- **Chapter 4** introduces the principles of network slicing technique, by emphasizing its strengths and depicting its logical and physical architecture. SDN protocol is then briefly presented, focusing on its applications to V2X communications and slicing. The chapter ends with an in-depth analysis on the use of network slicing applied to a vehicular scenario.
- **Chapter 5** illustrates all the different hardware and software technologies exploited in this work, such as the multi-antenna systems, the beamforming and channel multiplexing techniques, and the antenna arrays. Each one is described with the help of related pictures and formulas.
- **Chapter 6** presents our proposed approach to manage the radio resources allocation and the coexistence of different technologies. It points out the implemented mathematical model and power allocation techniques, and explains the user selection algorithm based on zero-forcing beamforming. Then, the two employed scenarios are illustrated and an overview of exploited tools is given.
- **Chapter 7** shows the numerical results obtained from the various simulations. At the beginning, the user selection and power allocation processes behavior is investigated, both in a realistic and theoretical scenario, and a significant consideration is presented. Then, the results regarding the fair approach and the coexistence issue are shown.
- **Chapter 8** summarizes the work, deriving conclusions and suggesting forthcoming research directions.

Notation

Uppercase boldface letters stands for matrices and lowercase boldface for vectors. $||\cdot||$ represents the Euclidean norm operator, $(\cdot)^*$ stands for the conjugate transpose, $(\cdot)^+$ mean $\max\{\cdot, 0\}$, $\mathbf{H}^\dagger$ represents the pseudo-inverse of $\mathbf{H}$, and $|S|$ denotes the size of a set S.

Article publication

This work led to the realization of the article:

M. Haghshenas, M. D'Adda, F. Linsalata, L. Barbieri, M. Nicoli, and M. Magarini, **"On the performance of zero-forcing beamforming in a real I2V scenario at millimiter wave"**, *Fourth International Balkan Conference on Communications and Networking (BalkanCom21), IEEE, 2021*

Chapter 2

V2X communications

Our work is set in a vehicular environment, that is a very specific scenario with its own typical characteristics, such as the users mobility and speed, and with some particular performance requirements due to the peculiar use cases. these aspects make this type of scenario quite different from the classic ones. Therefore, a suitable and ad-hoc approach is needed to build a model that is as truthful and realistic as possible.

This chapter will start with a a general overview of vehicular communications. Hence, we will illustrate the existing and developing technologies, with a focus on the strengths and weaknesses of the two main approaches: Wi-Fi-based and cellular-based standards. Then, after a presentation of the main innovations and benefits introduced in this area respectively by 5G and millimeter waves, we will address the core of the thesis, i.e. the coexistence between technologies and the management of radio resources in the vehicular field, with an overview of the current state of the art and the related work.

Following sections are to be considered as background, with the reader referred to the references cited below for detailed considerations.

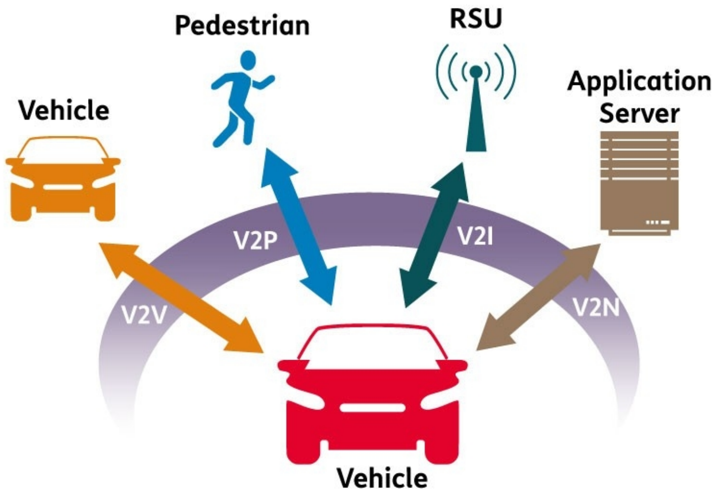


Figure 2.1: V2X use cases [1]

2.1 Overview

V2X (vehicle-to-everything) is a set of technologies that allow the communication between a vehicle and various elements of the Intelligent Transportation System (ITS), such as transport infrastructures (V2I), access networks (V2N), pedestrians (V2P), or other vehicles (V2V). In this way, all the participants of a road scenario (traffic lights, walking people, cars, etc) can be connected to each other. The main goals of V2X development are to improve traffic safety and management, limit traffic jams, increase the travel comfort, and reduce environmental pollution. With the progress of technology, the traffic systems will be smarter, safer, and more energy-efficient.

Requirements of V2X safety applications have been thoroughly researched in the literature regarding both computational complexity [38] and positioning accuracy [39].

As new application emerge, the existing protocols are not able to cope with the increasing demands such as lower latency, higher throughput and increasing density. These new use cases are intrinsically different from past ones because of their high degree of autonomy: fully autonomous driving requires a link reliability of at least 99,999% and a link latency of up to 3 ms, whereas lower levels of autonomy need 90%-99% and 100 ms respectively [40].

2.2 Standard and technologies

2.2.1 Fundamentals of technology implementation

All presented technologies implement the physical layer (PHY) and the Data Link Layer (DLL) according to the ISO/OSI 7-layer model (Fig. 2.2). The first one

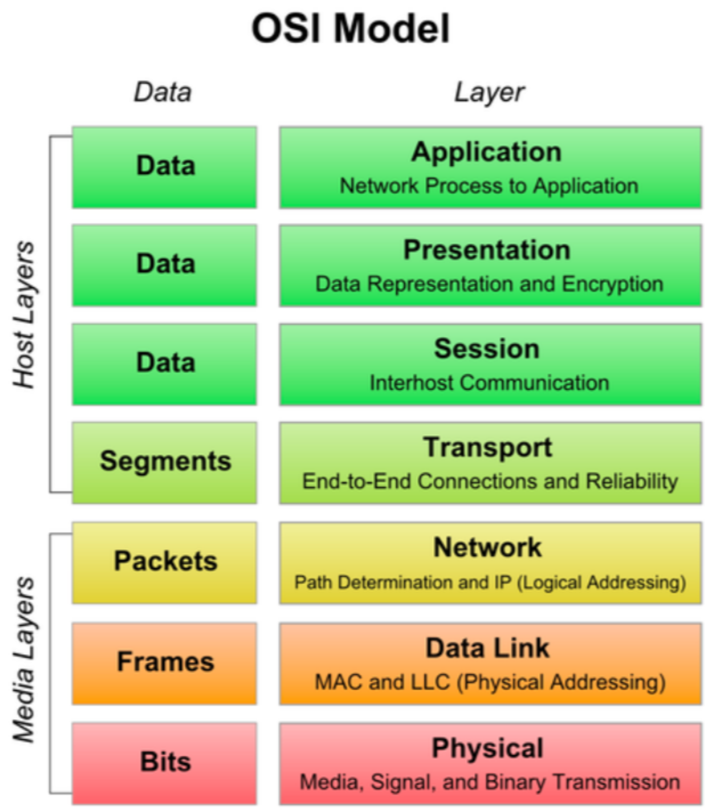


Figure 2.2: ISO/OSI model [2]

is responsible to transform the data into radio signals and vice versa. This layer defines physical characteristics such as channel access method, modulation scheme, maximum distances, signal timing and frequency, channel coding methods, etc. The DLL provides a direct link between two devices. It is in charge of the detection and correction of errors due to the physical layer. This layer is often subdivided into two sub-layers: Logical Link Layer (LLC) and Medium Access Control (MAC). The former controls upper layer errors and frame synchronization, while the latter is responsible for the medium access and the permission to transmit data [41].

2.2.2 Existing technologies

At present, there are two main technologies for vehicular communications:

- The first standard is **IEEE 802.11p**, introduced in 2013 as an amendment of WLAN (802.11a). It inherits the PHY from the original protocol, but the operation frequency is slightly shifted from 5 GHz to 5.9 GHz, which is the the spectrum allocated worldwide exclusively for V2X communication. This standard contains a set of protocols that enable the direct short-range communications (DSRC) for data exchange without the necessity of a basic service set (BSS).

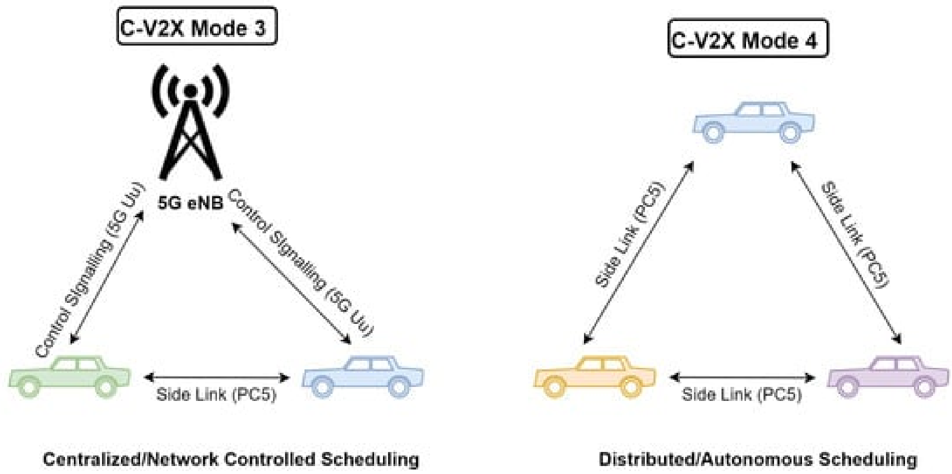


Figure 2.3: Transmission modes 3 and 4 of LTE-V2X communications [3]

- The second one, developed by 3GPP in Release 14 (2016) [42], is instead a cellular-based V2X standard (C-V2X) known as **LTE-V2X**. It introduced a new interface called PC5 that supports four different transmission modes. From vehicular communication's point of view, Mode 3 and 4 are relevant since they allow low-latency data transfer, enhanced handling for high data rates, and a new distributed channel access mechanism. As shown in Fig. 2.3, Mode 3 centralizes the resource allocation into the eNB, thus cellular coverage in needed, while in Mode 4 each device autonomously chooses its radio resources exploiting a distributed scheduling technique and a congestion control method.

Due to its technical advantages, DSRC has been the leading V2X technology for the past several years [43]. On the other hand, by and large the PHY of LTE-V2X is more advanced compared to 802.11p [41].

DSRC exploits a decentralized approach for the spectrum utilization, while C-V2X supports both centralized and decentralized strategy to allocate radio resources [44].

In literature, many studies show that both technologies are suitable for basic exchanges of information, with a latency of 100 ms and a low-density environment, but they do not satisfy the latency and reliability requirements of critical communications, like in autonomous driving [45], [46]. Results of [47] demonstrate that LTE-V2X is better in terms of data rates and reliability, while 802.11p has higher performance regarding transmission latency. Despite all its capabilities, however, LTE-V2X does not address all the stringent requirements of uRLLC, both in term of latency and bandwidth. In fact, Intel estimates that an autonomous driving vehicle may generate more than 4 terabytes of data per day [48].

The first limitation of 802.11p originates from the inherent "short range" characteristic of DSRC. So, to provide in-vehicle seamless Internet access, the vehicle should remain in the same small cell, but this is not realistic in a mobility scenario. Such limitation does not exist for C-V2X, where a BS covers a region much larger than one covered by a DSRC gateway.

Another major drawback of DSRC is the use of the CSMA/CA technique, that is the

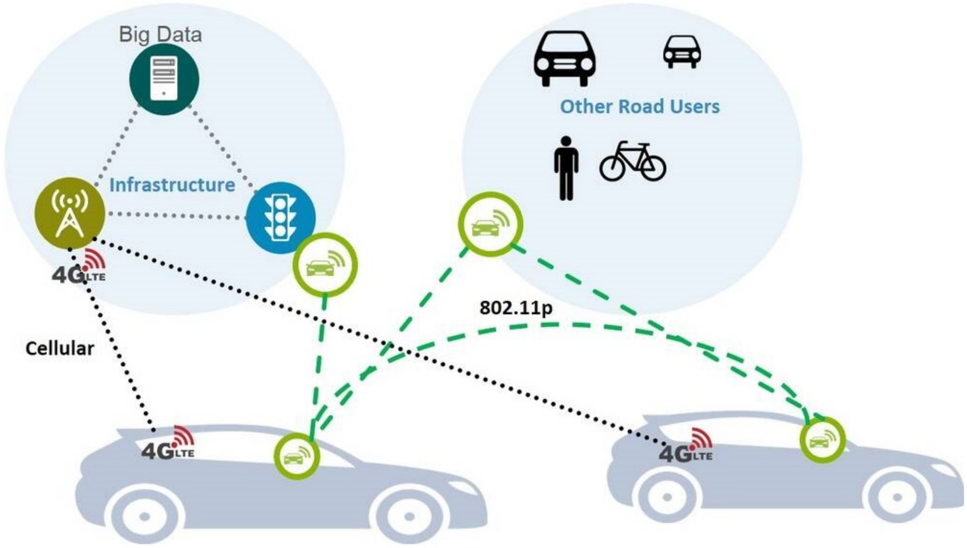


Figure 2.4: IEEE 802.11p and LTE-V2X connectivities. The key difference is the direct communications among 802.11p equipped devices. Cellular based services rely on the presence of the network. [4]

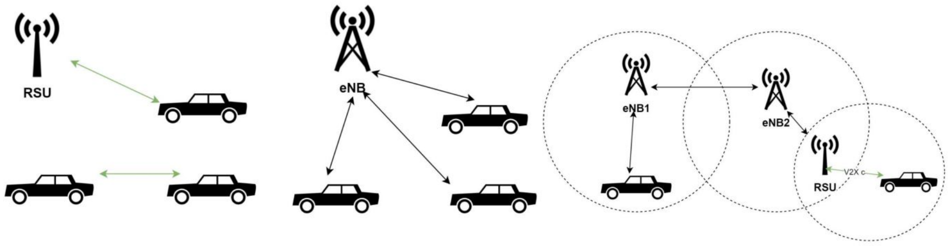
MAC scheme employed by 802.11 standards, and it is particularly noticeable in high-density traffic situations. In these scenarios, the intensity of channel contention among vehicles increases dramatically, causing a significant degradation of the performance, due to a huge number of collisions and a high delay.

The low performance of DSRC in a high-density scenario is even worse in delivering broadcast packets, due to the lack of handshaking and acknowledgment mechanisms, which are needed in an unreliable channel affected by the hidden terminal problem [49].

Furthermore, it is not expected to meet the high data traffic demand for in-vehicle Internet access, dominated by video applications. Although LTE-V2X is more advanced in terms of PHY and MAC, it still cannot meet the higher requirements on its own. So, these two already available technologies are fit only for basic applications.

5G Automotive Association (5GAA), in its paper [50], said there are several advantages in utilizing C-V2X compared to 802.11 standards. The main are:

- It can technically coexist with 802.11p-based RATs, in adjacent channels;
- It is scalable and evolvable, since it supports all V2X applications in an end-to-end way with the same technology;
- It has a proven evolutionary path from LTE to 5G, due to belonging to the 3GPP family of standards;
- It has higher performance in terms of direct communications;
- It offers a better degree of security.



(a) Direct (802.11p/PC5) (b) Full network assisted (c) Hybrid (5G+PC5/802.11p)

Figure 2.5: Different types of Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) scenarios [3]

In addition, the 5GAA also carried out a comparative experiment with real devices and it has obtained two important results: in C-V2X, the latency under congested scenario does not go beyond 100 ms and there is an improvement between 1.3x and 2.9x in terms of link budget respect to 802.11 [51]. Therefore, 5GAA's position is very clear that the best technology for V2X communications is 5G.

On the other hand, NXP in [52] has demonstrated that DSRC is 2 dB better in range compared to C-V2X, as opposed to what is claimed in the 5GAA report. Furthermore, the centralized nature of cellular networks limits their capability to support low-latency V2V communications, since data need to pass by the BS first.

Other papers in favour of IEEE 802.11p emphasize the fact that only the Wi-Fi technology is truly tested and reliable and C-V2X devices will not be ready in a short time [53].

2.2.3 Technology development in progress

Starting from the standards seen above, two new technologies are being developed:

- **802.11bd**, which is part of the 802.11 protocols family, also based on existing and verified Wi-Fi technologies;
- **NR-V2X**, the C-V2X standard applied to 5G-NR, which is the evolution of LTE-V2X developed by 3GPP in its Release 16 [54].

The first standard will introduce a new modulation mechanism with midambles: this brings great benefits in fast-varying and fading radio channels, which are typical in vehicular environment. In addition, as 802.11p derives from 802.11a, the features of 802.11bd originate from 802.11n/ac/ax: thanks to this, 802.11bd is able to operate on both 10 and 20 MHz bandwidth. Furthermore, this standard will support one or more retransmissions of a message, in order to increase the reliability of the communication. Another new feature is the Dual Carrier Modulation (DCM) technique, inherited from 802.11ax, which allows to transmit same symbols twice over far-apart subcarriers, and therefore, to take benefit from frequency diversity. In this way, modulation order increases (for example from BPSK to QPSK or from QPSK to 16-QAM) to achieve the same throughput. Finally, DCM can improve the block error rate (BLER) performance.

The second one, according to 5G philosophy, is designed to cover a wide variety of requirements. NR-V2X introduces a flexible numerology and some architecture improvements to support applications with varying degrees of throughput, reliability, and latency demands. Like LTE-V2X, it allows two operating modes: Mode 1 and Mode 2, which correspond respectively to LTE-V2X Mode 3 and 4. In the former, the resource allocation is completely delegated to the gNB, so cellular coverage is always necessary even if the communication takes place directly between the devices. On the contrary, Mode 2 does not need BS coverage and it implements an allocation mechanism similar to LTE-V2X. Thanks to its flexible numerology, NR-V2X supports 15, 30 and 60 kHz subcarrier spacing for sub-6 GHz and 60 and 120 kHz for frequency bands higher than 6 GHz: this higher subcarrier spacing leads to a further reduction in latency. Furthermore, this standard allows QPSK, 16-QAM, and 64-QAM modulation schemes. NR can aim achieving a better URLLC, while maintaining backward compatibility. NR-V2X is not intended to replace LTE-V2X, but to integrate it with improved services [55]. It is expected that they will coexist and the new vehicles will be equipped with both technologies.

Both standards are based on OFDM (Orthogonal Frequency Division Multiplexing), with an adaptive physical layer design to address different QoS, and are able to support communications both at sub-6 GHz and at millimeter waves (see Section 2.4) frequencies [56].

From the results presented in [57], it can be stated that NR-V2X has better expectations in terms of transmission latency and data rates.

2.3 5G for V2X

The 5G is the new disruptive technology that will enable a fully mobile and connected society. These networks will work on the New Radio, supporting technologies such as Wi-Fi, Wireless Gigabit (WiGig), LTE-A and mmWave [58]. The fifth-generation technology has a great potential that can be tapped: up to 100 billion of connections supported at any time, 1 ms of latency (compared to 50 ms of current 4G) and a throughput of 10 Gbps [59], [60]. As in all other contexts, also in the field of vehicular communications 5G has introduced significant improvements compared to previous technologies. In [61] the main strengths of 5G applied to vehicular communications are presented, both in Radio Access Network (RAN) and in Core Netowrk (CN). Regarding the radio access technologies and components, main aspects are:

- New Radio, which brings flexibility, a more agile frame structure, high frequencies and new multiple access techniques. Thanks to all of this, it is possible to meet the requirements of high capacity, low latency and massive connectivity;
- Millimeter Waves (mmWave), which enable wide bandwidth and high throughput;
- Non-Orthogonal Multiple Access (NOMA), which allows the same resource to be shared by multiple users, both in time and frequency;
- In-band Full Duplex (FD), another new technology that improves the spectral efficiency. Theoretically, it doubles the achievable throughput since it allows to transmit and receive simultaneously on the same band;

- More precise degree of positioning, exploiting the combination of traditional satellite systems, on-board sensors and infrastructure;
- Multi-RATs, because 5G supports several technologies very different from each other.

As for the network softwarization technologies, which make possible the efficient management of resources, the two main technologies exploited by 5G are:

- **Mobile Edge Computing (MEC)**, which consists in decentralizing of system intelligence. It has the goal to keep data streams near where they are generated and out of the core. In 5G, it is expected that physical infrastructure will be integrated with computing and storage resources in the edge of the network, in order to enable MEC. In this way, traffic that needs to be processed by an application can be processed on these resources, instead of sending it to the core, and a reduction in latency and load is achieved.
- **Network slicing**, which through SDN architecture and function virtualization enables a flexible configuration and a lot of advantages, detailed below (see Chapter 4).

In [62], many comparisons have been made between 4G (in particular, LTE-Advanced) and 5G and the results undoubtedly indicate that the latter clearly outperforms the previous generation in all aspects. In fact, 5G has ten times less delay, ten times greater download and upload speeds, improved availability, reduced power consumption, and more connected devices.

An important issue of 5G-NR V2X, in Release 16, is that it assumes that all connected devices can continuously sense the channel. There are, however, a lot of non-vehicular devices in a road scenario, such as smartphones or sensors, which are battery-constrained, and therefore, unable to implement an always-on sensing. Release 17 will introduce a power saving improvement to address this problem [63].

2.4 Millimeter waves in V2X communications

New V2X standards, 802.11bd and NR-V2X, will support communications at frequency up to 71 GHz, commonly called millimeter waves (mmWave), as shown in Fug. 2.6. In this portion of spectrum there is a large availability of bandwidth that could theoretically enable connections with data rates of multiple gigabit per second [64].

However, there are some downsides to take into account and critical issues to be resolved in order to guarantee reliability and robustness. First, the directional transmission, deployed by leveraging distributed antennas and beamforming technique, significantly increases the link budget, but requires an accurate alignment between transmitter and receiver and a greater control overhead. In addition, despite directionality ensures a good spatial isolation, the reflection caused by the metal of vehicles on the mmWave signals may produce strong interference to the nearby vehicles [65]. Directionality could also preclude broadcast communications, since different directions cannot be used simultaneously, but exploiting digital and hybrid

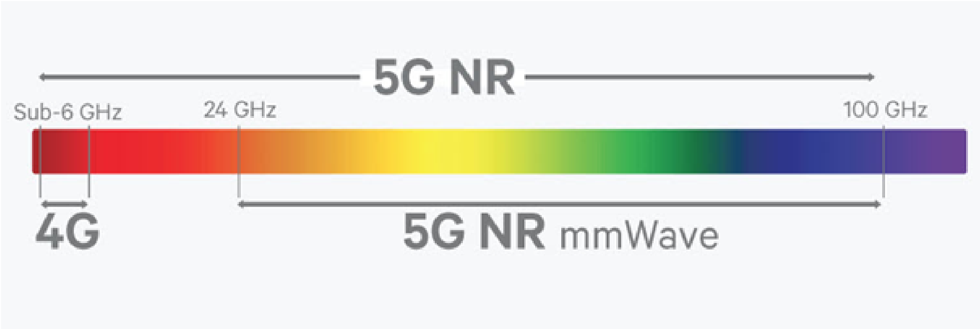


Figure 2.6: Spectra of frequencies of 4G, 5G NR and mmWave [5]

beamforming transceivers can transmit towards several directions, actually making multi/group/broadcast communications. Secondly, the inherently time-varying nature of the channel at these frequencies could prevent long-lasting connectivity, with serious consequences on the functioning of the entire protocol [66], [67]. Finally, signals that propagate in this segment of spectrum are affected by serious path and penetration losses, thus preventing long-range transmissions [68].

Due to their distinctive characteristics, in particular the high temporal and spatial resolution, the mmWave signals enable a very accurate positioning of vehicles [69], [70], a fundamental requirement for forthcoming applications, such as autonomous driving.

2.5 Coexistence in V2X communications

In this section, different vehicular coexistence scenarios are presented. For a complete investigation, it is worth to take a look also on the already existing coexistence solutions outside the vehicular applications. This topic will be addressed with more details in Chapter 3.

2.5.1 Coexistence of 802.11p and 802.11bd

During the design of 802.11bd, there were a number of requirements that were taken into account. In particular, both technologies must have:

- transceivers able to recognize both types of transmission;
- equal channel access possibilities, to ensure fairness;
- the capability of inter-operate with the other standard.

Obviously, these requirements negatively affect 802.11bd development, but this is a reasonable choice to avoid issues. So, since 802.11bd is designed to be backward compatible with 802.11p, the coexistence issue between these two standards can be considered to be solved.

2.5.2 Coexistence of LTE-V2X and NR-V2X

Unlike the previous case, the backward compatibility between the two C-V2X technologies is not available. So, there are two possible approaches.

The Frequency Division Multiplexing (FDM) does not need time synchronization between the two devices and can address regulatory transmission restrictions, if both modules work in the 5.9 GHz band. On the other hand, since LTE-V2X and NR-V2X operate at close bands, their transmissions will probably compromise the reception of the other module.

The Time Division Multiplexing (TDM), on the contrary, uses a strict time synchronization, so it does not allow simultaneous transmissions. Its main advantage is to enable the maximum transmission power on each module, but it introduces further latency that is not acceptable in several use cases.

2.5.3 Coexistence of C-V2X and Wi-Fi based technologies

Wi-Fi based and C-V2X technologies have different PHY and MAC, thus their simultaneously presence and activity in the same geographical region at the same 5.9 GHz frequency will result in an interference problem. To solve this issue, 5GAA proposed a simple spectrum sharing method [71], based on technology recognition and dynamic channel selection. In this approach, the spectrum is subdivided into three parts: the first and the last are each assigned to one of the two technologies, while the central portion is shared: both standards can access it using a mutual detect-and-vacate mechanism. This solution is very simple, but the algorithm has to be further elaborated.

2.6 Radio resource management

The Radio Resource Management (RRM) for V2X has been addressed in several papers and a number of scheduling algorithm have been proposed in the literature. The major parameters considered in designing resource allocation algorithms are throughput, spectral efficiency, fairness, and performance in term of error rate.

Numerous articles, such as [72], [73], [74], [75] and [76], illustrate the Dirty Paper Coding (DPC). It has been demonstrated that this is an optimal algorithm and it allows to reach the maximum sum-rate capacity. On the other hand, however, it is difficult to implement in practical system due to the high computational complexity, especially when the number of users increases. For this reason, this algorithm is not suitable for vehicular communications, which require very limited response times.

Authors in [77] provide a detailed comparison of the performance of some well-known downlink scheduling algorithms such as RR, B-CQI and PF. They conclude that each algorithm has its advantages and disadvantages and typically a trade-off has to be achieved in scheduler design. As illustrated in [78] and [79], PF with its many variations and adaptations, is probably the most popular scheduling algorithm and is the *de facto* standard in cellular networks. It is optimal for stationary channels and, in addition, it is able to consider and exploit the users' channel diversity. However, mo-

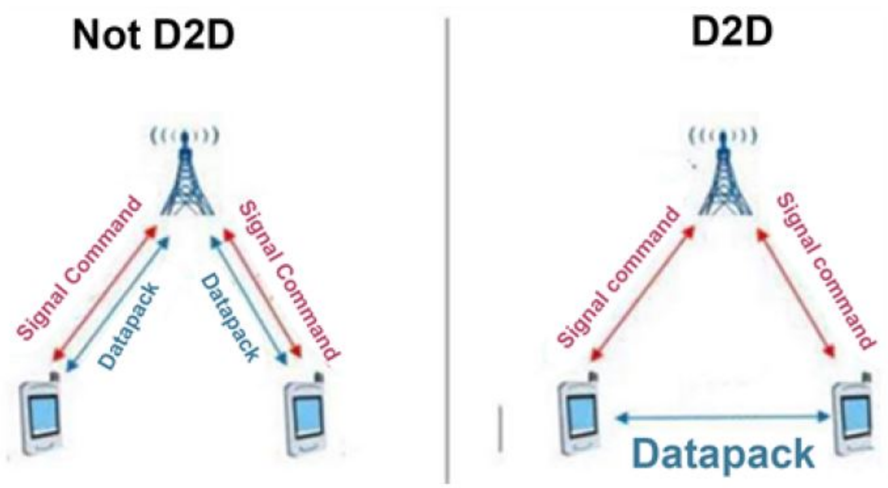


Figure 2.7: Difference between D2D and not-D2D communications [6]

bile users experience a non-stationary channel and are associated with gNB for short periods. Authors in [80] introduce a data rate prediction mechanism that exploits mobility information and is used by an enhanced PF scheduler. The performance is evaluated using a real dataset and shows a throughput increase of 15%-55% with respect to traditional PF scheduler.

In [81], authors propose an algorithm that maximizes the throughput by taking into account the channel conditions and without compromising the fairness criteria. Authors in [82] introduce an algorithm, called “Efficient Scheduling and Resource Allocation” (ESRA), that aims at maximizing sum rate and providing fairness in V2X. However, it is based on D2D communication, so it cannot support V2I and, hence, centralized resource management (see Fig. 2.7).

In [28], [12], and [83] the algorithm for user group selection with Zero-Forcing beamforming (ZFBF) is explained in detail. The used channels are assumed to be described by Rayleigh fading with i.i.d zeros mean complex Gaussian entities and unit variance. Therefore, the obtained results are not very realistic.

In [84] and [85], the authors propose an algorithm similar to the first part of ours for user subset selection in ZF, but it does not force semi-orthogonality among users. In their work, it is not necessary because any remaining interference will be cancelled by Dirty Paper Coding (DPC); in ZFBF, however, selecting a non-orthogonal user degrades the effective channel gains of other users.

A complete survey on resource allocation in vehicular networks is presented in [86], where they compare different existing algorithms applied to both Cellular-V2X and 802.11p-based standards. Authors in [87] tackle the problem of resource allocation in V2X by exploiting a centralized algorithm that maximizes the number of concurrent users. In their work, eNodeB centrally decides the resources reuse for vehicles in the network and a significant improvement in spectrum efficiency is obtained. In [88] an optimization problem is implemented to maximize the sum ergodic capacity of V2I links: the algorithm performs spectrum and power allocation and guarantees the latency violation probability (LVP) for V2V links.

Chapter 3

Coexistence between Wi-Fi and LTE/NR

In the previous chapter the issue of coexistence between different technologies was introduced in the specific case of a vehicular scenario, which is what we are studying in this thesis work. However, it is important to have a general knowledge of this question, even outside the particular application environment.

This chapter, therefore, will illustrate the state of the art regarding this issue. Coexistence between Wi-Fi and LTE will be initially introduced. Then, we will describe the two major approaches, i.e. listen-before-talk and duty cycling, and their implementation, with a focus on the fairness among different users. In the next section, after a deepening on the key aspect of the detection mechanism, two new proposed solutions will be presented. Finally, we will depict a work in which coexistence issue is addressed exploiting network slicing and spatial multiplexing techniques.

Starting from the general knowledge discussed in the following sections, and in particular from the last solution shown, we will take a cue and elaborate the approach to be applied to our specific scenario.

3.1 Overview

The increasing popularity of smart phones, tablets and other wireless devices leads to an exploding data traffic growth in wireless cellular networks. As a result, network capacity needs to be increased to meet the large and rapidly growing demand. One typical and straightforward approach is to increase spectrum resources in cellular networks. But licensed spectrum, though preferable, is limited and this scarcity is always the major bottleneck. There is, however, a large amount of available unlicensed spectrum. So, one solution is to allow mobile network operators (MNOs) to extend their operation into unlicensed spectrum, in particular in 5 GHz band. However, another different system, Wi-Fi, is already operating in this unlicensed band. Therefore, coexistence of LTE/NR (Long Term Evolution/New Radio) with incumbent Wi-Fi systems is a critical issue for mobile operators. The reason to adopt LTE in 5 GHz is not to unseat Wi-Fi, but to increase the spectral efficiency and capacity of this band. Both LTE and Wi-Fi have their own benefits and cannot be replaced by each other at the moment. The performance of either LTE or Wi-Fi should be maintained and not be affected by each other while deployed in 5 GHz spectrum together.

The features and procedures introduced for LTE are expected to play a key role in the design of future 5G New Radio Unlicensed (NR-U) [8], [89], [27].

3.2 Access Mechanisms: LBT Vs Duty Cycling

The main issue in coexistence between Wi-Fi and LTE is that of fairness among technologies, specially towards Wi-Fi devices.

This problem stems from the fundamental difference in the channel access mechanisms, since LTE and Wi-Fi systems use very different medium access control protocols. On one hand, Wi-Fi employs a distributed channel access protocol whereby each station senses the channel before its transmission. This is CSMA/CA, Carrier Sense Multiple Access with Collision Avoidance. On the other hand, LTE uses a centralized scheduling mechanism wherein the e-NodeB decides the time and the frequency at which each device in the network can transmit or receive. This is based on TDMA or FDMA, Time Division or Frequency Division multiple access. As a result, it is expected that when LTE and Wi-Fi operate in the same spectrum band, transmissions from LTE will dominate those of Wi-Fi devices, because they sense the channel always busy. Literature results show that without any coexistence schemes, Wi-Fi performance would drop significantly while LTE system performance is only slightly affected. There are several possible solutions to solve this problem, we will start looking at two of these: LBT, used in LTE-LAA, and duty cycling, employed in LTE-U [90].

3.2.1 Fairness

As said above, the most important aspect to take into account is the fundamental principle of fairness between coexisting technologies. In particular, it means that LTE should not impact Wi-Fi more than another Wi-Fi network, so a new node inserted should not cause any interference or degradation to a Wi-Fi network than adding

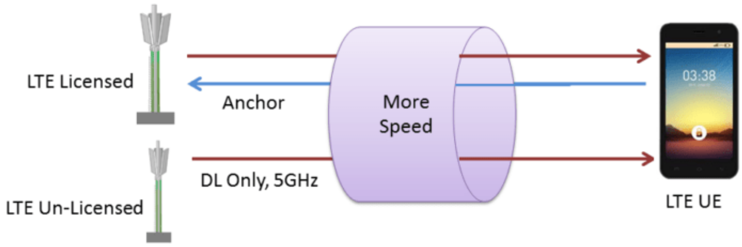


Figure 3.1: Primary and secondary carriers in LTE-LAA [7]

another Wi-Fi access point.

Some important aspects and guidelines to build upon [90]:

- The backoff time, defined below, plays an important role in how the traffic will be split between Wi-Fi and LTE-LAA and, hence, is a factor in how fair the coexistence will be.
- All technologies in unlicensed bands should have equal control for access to the medium. So, a purely duty cycling approach is unacceptable for unlicensed spectrum.
- LTE-LAA medium sharing algorithms should be dynamically designed and respond quickly to changing conditions. Like in Wi-Fi standard, unlicensed access algorithm should be able to respond to changes within a few packets transmission.
- An increase in the number and complexity of tests on fairness is desirable, specially in realistic scenarios, considering both uplink and downlink.
- Finally, the community should seek a balance between fairness and performance. As stated above, coexistence mechanism that increases fairness can have a negative effect on performance, like LBT.

3.2.2 LTE-LAA

LTE-LAA is an extension of LTE, a standard of wireless broadband communication for mobile devices. This technology allows LTE to use unlicensed band. The acronym LAA means Licensed Assisted Access and it's based on two carriers: the primary (or anchor) works on licensed portion of spectrum, while the secondary in the unlicensed spectrum, as shown in Fig. 3.1. It has been chosen LTE-LAA because it causes less interference to Wi-Fi compared to another Wi-Fi system. In other words, LTE-LAA is a better neighbour than another Wi-Fi system. On the other hand, if the coexistence is not sufficiently arranged, combined LTE-LAA and Wi-Fi can inevitably increase the traffic load and therefore the contention of spectrum resources and the congestion.

In order to understand in practice what we have discussed so far, let's look at the performance graph in Figure 3.2. We first consider LTE-LAA and Wi-FI coexistence scenario where there is one LAA eNB and one Wi-Fi AP. The graph illustrates the channel access probability and successful transmission probability for LAA and Wi-Fi

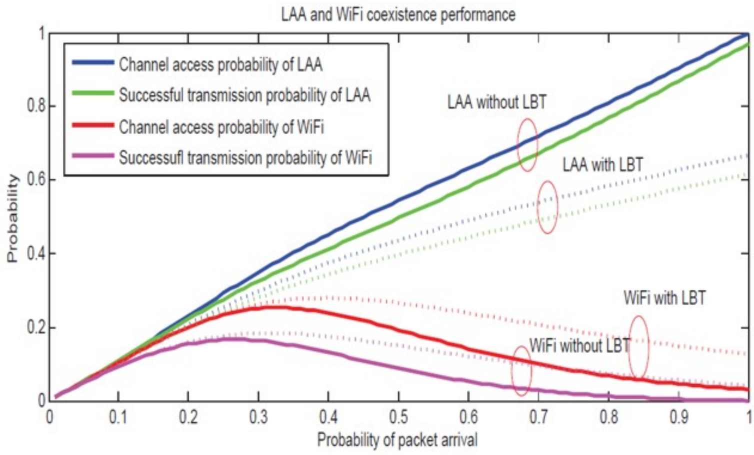


Figure 3.2: LAA and Wi-Fi coexistence performance with 1 AP and 1 eNB [8]

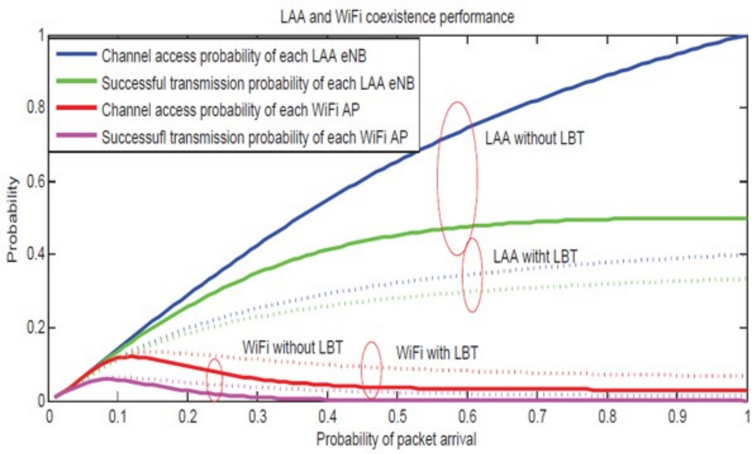


Figure 3.3: LAA and Wi-Fi coexistence performance with 3 APs and 3 eNBs [8]

with and without LBT scheme enforced on LAA. The constant contention window size for LAA is 2. The initial and maximum contention window sizes for Wi-Fi are 2 and 32, respectively. Solid lines correspond to case without LBT, while dashed lines correspond to case with LBT. We can observe that, when the traffic load is low, the two systems coexist well. When the traffic intensity goes high, Wi-Fi system would have little chance to access the shared channel and transmit a packet successfully, while LAA dominates the channel and only suffers slight interference from Wi-Fi. With LBT mechanism enforced on LAA, Wi-Fi performance would be improved a lot. However, its performance still drops significantly at high traffic intensity while LTE performance remains robust. When the number of LAA eNBs and Wi-Fi APs increases, coexistence becomes more challenging. One way to cope with this case is to increase the constant contention window size for LAA eNBs to create more chance for Wi-Fi APs to transmit [8].

In the scenario considered to get the results shown in Figure 3.3, we have 3 LAA eNBs and 3 Wi-Fi APs in the same area. The constant contention window size for LAA is

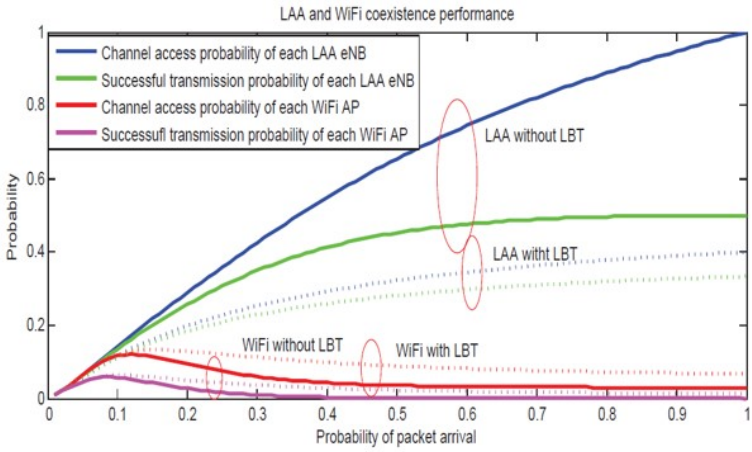


Figure 3.4: LTE-U duty cycles models [9]

increased to 4. Also in this case, we can see that with LBT scheme Wi-Fi system has more chance to access the channel. However, at high traffic load the interference from LAA eNBs is too strong. As a result, Wi-Fi APs have little possibility to successfully transmit a packet and almost every packet is involved in a collision [8].

3.2.3 LTE-U

Another protocol used in LTE unlicensed band is LTE-U. As per standard, LTE-U base station does not employ any carrier sensing techniques such as LBT or CSMA/CA. In order to ensure a fair coexistence in the unlicensed spectrum, LTE-U employs the duty cycle mechanism, which limits its usage of the spectrum and protects the incumbent users. In this protocol, base stations operate in a cycle of on and off, active and idle state. According to the LTE-U specification, the cycle can set a maximum of 20 milliseconds active time and a minimum of 1 millisecond idle time, which corresponds to a 95 % duty cycle.

In order to improve the coexistence with Wi-Fi, LTE-U is equipped with a duty cycle optimization mechanism. It allows a base station to observe air medium during the idle period. It's called CSAT, carrier sense adaptive transmission, and it allows to dynamically adjust the duty cycle based on the presence and the number of detected Wi-Fi basic service sets. Like in Figure 3.4, if there is no Wi-Fi systems, duty cycle can reach the maximum value of 95 %. In case of one Wi-Fi network, duty cycle is set at 50 %, in case of two Wi-Fi it drops to 33 % [9].

3.3 Detection Mechanisms

A very important issue in coexistence between LTE/NR and Wi-Fi devices is the choice of the mechanism by which devices will detect each other. There are two main mechanisms: preamble detection and energy detection. Both are already used in 2.4 and 5 GHz bands, in particular the first one in Wi-Fi devices and the second one in

ZigBee and LTE-LAA. Preamble detection allows power saving mechanism, because thanks to the preamble we can know in advance the duration of transmission. Since this mechanism is used in all Wi-Fi devices, it is impossible forget it in order to allow all devices to continue working. However, this preamble contains several fields that are unnecessary for the coexistence and its transmission decreases performances. Energy detection, instead, is very simple to implement and it is technology neutral. It does not need any ability to transmit or decode any fixed signal (like preamble). In this case, without preamble, you can't know in advance the duration of transmission and so you can't implement a power saving mechanism. An interesting alternative is to use an hybrid solution, using both preamble and energy detection. This approach is already used in 5 GHz bands by Wi-Fi and LTE-LAA. It is very flexible, but it's complex to implement [91].

About detection, the most significant parameter influencing the coexistence performance is the detection threshold, used by devices to detect each other. It has a direct impact on the performance of the two radio access technologies, Wi-Fi and LTE/NR, when they coexist, but also has implications on which mechanism is chosen by devices to detect each other (preamble or energy detection). For example, if the detection threshold is too low (such -82 dBm), the only suitable mechanism is preamble detection. On the other hand, if the chosen detection threshold is higher (-72 or -62 dBm), also energy detection can be used.

If preamble detection is used, there will be an additional problem: a suitable common preamble must be chosen. There are some criteria to satisfy for design of preamble, like the accuracy of detection in both technologies and the spectral efficiency, because it must consume the minimum possible amount of resources.

3.4 Other proposals

So far, we have seen two standards for LTE operating in the 5 GHz band: LTE-LAA, based on LBT, and LTE-U, based on duty cycling. There are several other studies to ensure fair sharing and coexistence between LTE and Wi-Fi.

3.4.1 Direct communication

LTE-U seen before works fine where the other users' usage do not change frequently. But we know that practically Wi-Fi usage changes frequently over time. So, the duty cycle needs to be adjusted often, based on the actual usage information of Wi-Fi. This problem can be solved by using direct communication to share information between Wi-Fi access points and LTE eNode-B. This exchange can take place either on wired or wireless channel.

Figure 3.5 shows the result of simulation of this model, compared with LTE-LAA. In case of coexistence based on LTE-LAA, we can observe that there is a huge gap between two systems, and in particular Wi-Fi dominates over LTE. In the proposed model, LTE starts with a low duty cycle and adjusts it based on Wi-Fi throughput, the directly received information. After some time, LTE and Wi-Fi throughput gradually become similar and the total throughput is higher. In Figure 3.6 we can observe the comparison of the results [10].

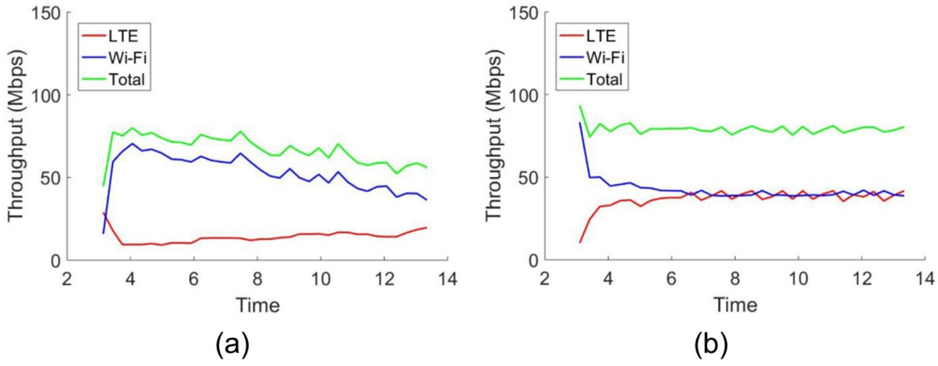


Figure 3.5: Simulation results on LTE and Wi-Fi coexistence. (a) LTE-LAA and Wi-Fi. (b) LTE-U direct communication and Wi-Fi. [10]

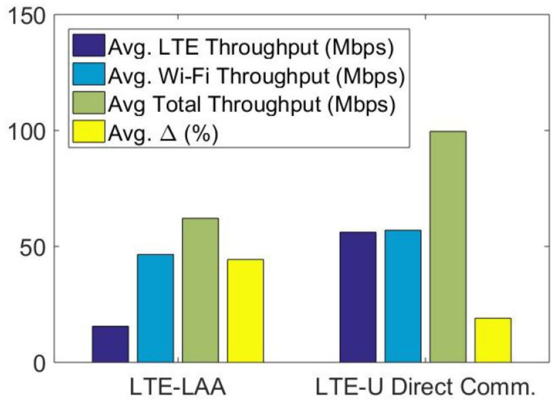


Figure 3.6: Overall comparison between LTE-U direct communication and LTE-LAA [10]

3.4.2 Virtual network entity

Another proposal for coexistence between Wi-Fi and LTE systems in unlicensed spectrum is based on a coordinated structure. In this way, the control of spectrum access is governed by virtualized network entities and higher level management. There are three main benefits. First, the interference between Wi-Fi and LTE is avoided. In this way, the unlicensed spectrum utilization can be improved. Second, no LBT operation is required for LTE-U systems. Third, since the central entity has the authority to control over both systems, Wi-Fi throughput requirement can be kept satisfied. More specifically, in this proposed model, the central network entity facilitates separation of LTE and Wi-Fi transmissions in two different phases, like in Figure 3.7. In the first segment LTE users can access using TDMA, while in second one Wi-Fi users can transmit their packets using CSMA. This architecture allows each network to use its current deployed MAC protocol. Thus, the model leads to minimal modification requirement for both systems. It also eliminates the LBT requirement for LTE network. Specifically, it facilitates uplink transmissions for LTE network, since in the uplink scenario the user has to perform the LBT operation.

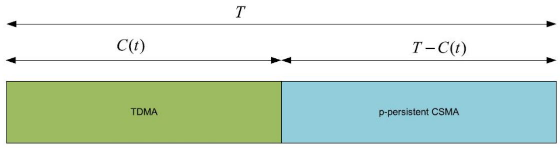


Figure 3.7: Duty-cycle-based structure for Wi-Fi and LTE-U coexistence in virtual network entity approach [11]

To realize this model, we deploy point coordination function (PCF) mechanism for the Wi-Fi. In this mechanism, each superframe consists of a contention-free period (CFP) followed by a contention period. Thus, by activating the PCF, the CFP can be used by LTE users, while the contention period can be assigned to the Wi-Fi users. To facilitate the coexistence between Wi-Fi and LTE and increase the spectral efficiency, the central controller dynamically divides each duty cycle between two slices. Although the length of each duty cycle is fixed, the length of each phase assigned to Wi-Fi or LTE-U network varies over different cycles. This would be done in a way that the overall throughput is maximized, but there are two constraints to be respected. First, it has to guarantee that Wi-Fi throughput does not fall below a required threshold (denoted by η). Furthermore, to keep LTE users satisfied, we add the second constraint to reserve at least C_{min} time-slots for LTE users. The values of η and C_{min} are fixed based on the service level agreements of Wi-Fi and LTE-U systems [11].

The hybrid TDMA-CSMA scheduling algorithm can satisfy a minimum requirement for Wi-Fi throughput at each duty cycle. However, also the LTE users may have quality assurance constraints. Therefore, it is important to admit a precise number of LTE users such that their QoS requirements such as delay constraints can be satisfied. Thus, our objective is to study the number of LTE users that can be admitted to operate in unlicensed spectrum, while their delay requirements can be satisfied. As mentioned above, we assume that at each duty cycle, C_{min} time-slots are dedicated to LTE users to derive an upper bound on the delay. These time slots can be assigned in two ways: a user can obtain one either on demand, sending a pickyback request in the previous duty cycle, or as free assignment, waiting for its turn to be served.

In Figure 3.8, we can see how increasing the number of users in LTE and Wi-Fi systems can affect the throughput. We consider two scenarios: with and without fixed number of LTE time-slots. Packet delivery ratio (PDR) is defined as the ratio of number of transmitted packets to the number of generated packets. We can observe that, in this proposal, increasing Wi-Fi users number does not affect the total overall throughput, while increasing LTE users causes decreasing of throughput. It is shown that the developed algorithm can ensure a minimum throughput requirement for Wi-Fi while maximizing the total throughput. Furthermore, we obtain an upper-bound for average delay of LTE users. Using this analysis, we can derive minimum number of LTE users that can be admitted by the network while their delay requirements are met [11].

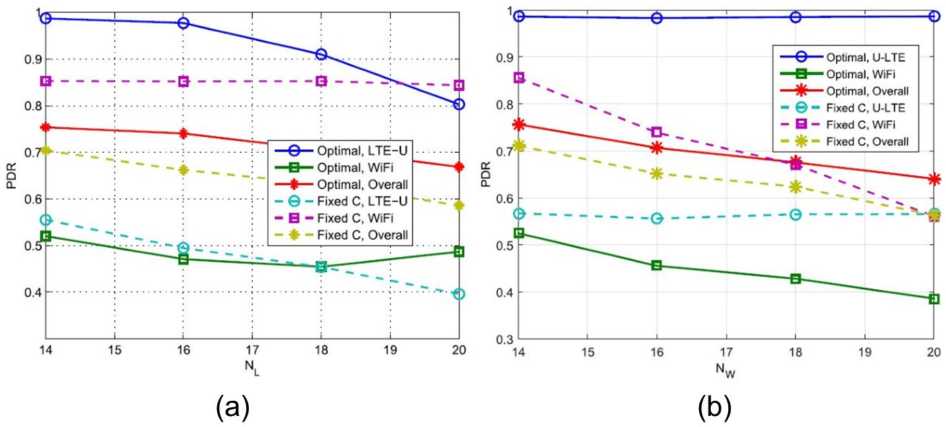


Figure 3.8: Effect of increasing number of Wi-Fi (a) and LTE (a) users on PDR [11]

3.5 Coexistence based on Network Slicing and Spatial Multiplexing

In [12] a coexistence approach based on network slicing and spatial multiplexing is presented. In their work, authors focus on a synchronous radio access technology (RAT) for both Wi-Fi and cellular users in NR-U network. It has been proposed a new networking framework by integrating Wi-Fi and NR-U networks into one logical network through network slicing. The main targets are to provide efficient network connectivity among heterogeneous users and to protect Wi-Fi performance. They consider a network slicing based NR-U framework consists of a gNB and several cellular and Wi-Fi users. In this framework, Wi-Fi has been integrated into NR-U as a slice, as shown in Fig. 3.9. Furthermore, cellular network has been divided into several slices according to their specific requirements.

They assume that gNB can support to connect multiple users with heterogeneous radio access technologies simultaneously. The gNB is connected to a central baseband unit. In addition, with NR-U technology, gNB can support both licensed and unlicensed spectra.

Their results demonstrate that the performance of both Wi-Fi and cellular users can be improved according to the proposed approach. They also show that their scheme provides flexibility to satisfy different user requirements [12].

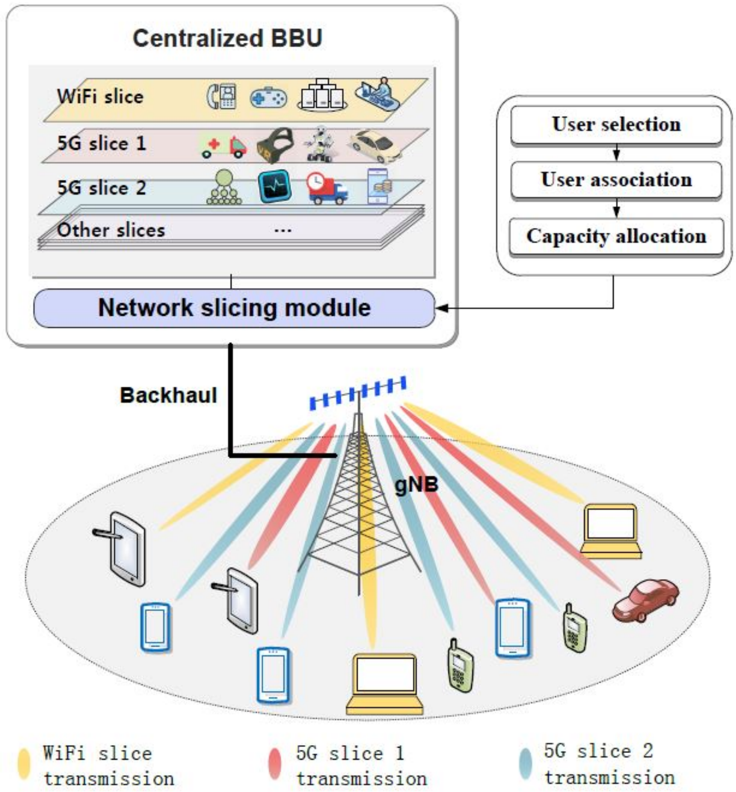


Figure 3.9: Network slicing based NR-U framework [12]

3.6 Implementation choice for our work

After having studied and evaluated the different existing techniques that enable coexistence, we have chosen the latter just presented for this thesis work.

In fact, we started from the work illustrated above and described in detail in the article [12]. We will follow their approach based on network slicing and spatial multiplexing. These two techniques will be explained in deep in Chapter 4 and in Sec. 5.1, respectively.

While they have performed their work in a generic environment, we will apply this pattern to a realistic V2X scenario, realized with a combination of simulation tools as depicted in Chapter 6.

Chapter 4

Network Slicing in Fifth generation

In addition to the two main aspects presented in the previous chapters, i.e. the V2X scenario and the coexistence, another milestone of this thesis is the network slicing, a relatively new feature that promises to offer a great variety of potentials and benefits.

In this chapter, this innovative technique will be described in details, pointing to the numerous improvement compared to the previous approach. Both the logical and physical architecture on which network slicing is based will be illustrated, emphasizing the role of the different physical and virtual components. Then, the SDN protocol will be presented, focusing on its application to V2X communications and network slicing, and the next section will propose the three main slices most commonly implemented. Finally, we will try to apply 5G network slicing to vehicular communications, that is one the mail goal of this thesis.

Like the previous chapters, this too is to be considered as a background knowledge that will serve, in the next chapters, to lay the foundations for realizing our system model.

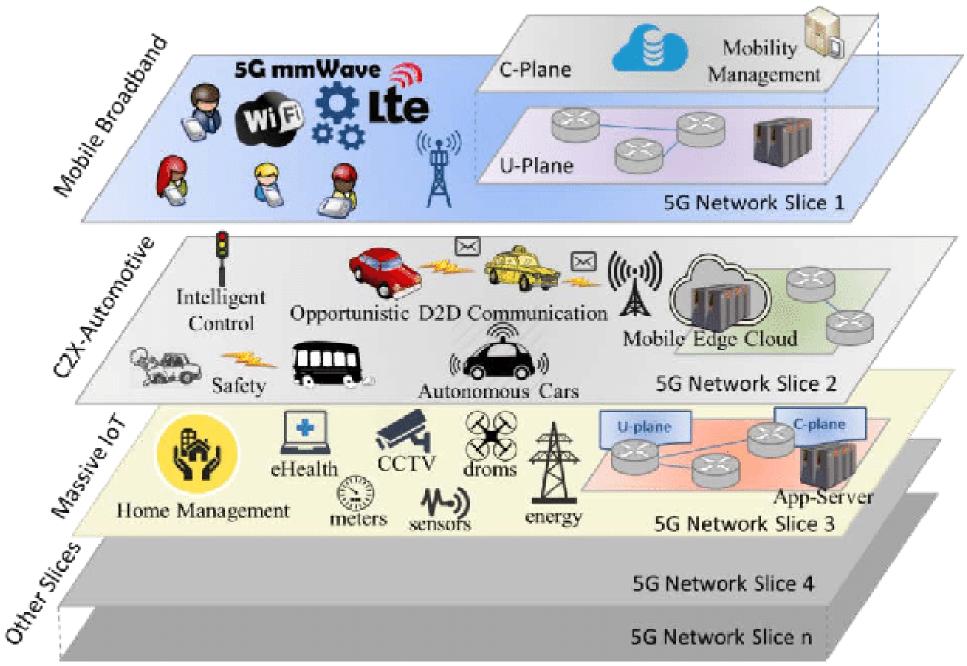


Figure 4.1: An example of slices [13]

4.1 Overview

In the pre-5G communications world, the network was like a large pipe carrying all traffic under roughly the same conditions. If the pipe is flooded, all traffic moves more slowly and it is not possible to guarantee any kind of prioritization based on the type of communication or the level of QoS required by the user. This also limits the network operators' opportunity to monetize the network and therefore to make a profit [92].

The previous generations of mobile networks do not offer much flexibility to the vertical industries which need to connect their devices. These companies therefore have to adapt their connectivity requirements in order to meet the one-size-fits-all mobile network, but this often involves a great deal of time and money. So, the central question is how to design an efficient network to provide guaranteed QoS while balancing data services among users and towards other applications. To meet the several demands of 5G networks, mobile broadband networks will need to be parcelled up into many virtual networks tailored to meet varied users' requirements. That's the concept of network slicing. It consists of sharing of MNO's resources among multiple logical networks, which uses the same physical resources, but serve different business use cases and thus have to meet different requirements. The fundamental principle of network slicing is to provide a network specifically customized and optimized for a use case, instead of requiring use cases to adapt to networks. This design must also have the capability to adapt itself to meet the changing requirements. It uses Network Functions Virtualization (NFV) and Software Defined Networking (SDN) to divide a larger network into smaller slices, all of which supported by one common physical infrastructure. Each network slice can be tailored to a different use case and its requirements including latency, speed, reliability, connection, device battery life and cost. The performance of a single slice should be isolated from each other, so it's not affected by activities on other slices. In this way, it is guaranteed that all slices appear to their own connected devices as isolated physical networks [93].

Network slicing is therefore one of the essential technologies for the development of 5G, since it allows dynamic allocation of available resources in a more flexible and efficacy way and it provides a tailored service to the users. [14] It is a technique that enables running of multiple logical networks on a common physical infrastructure. Each slice represents an independent and virtualized end-to-end network. [94] By the NGMN Alliance [95], network slicing is considered as a necessary means for allowing the coexistence of different verticals over the same infrastructure. [96] The key concept of this technology is that network resources are virtualized and managed in a centralized way. This solves the resource allocation process complexity due to the large diversity of types of network supported by 5G.

Network slicing has however some security concerns, due to new vulnerabilities caused by physical infrastructure sharing.

4.2 Logical architecture

The architecture of 5G networks is composed of a software control structure and a hardware infrastructure, which must cooperate closely. This approach is based on SDN, that allows decoupling control plane (CP) from the data plane and logically centralizing network intelligence, thanks to introducing network programmability. SDN also makes possible the creation of a unique and common infrastructure that supports multiple client instances efficiently [97]. NFVs replaced the traditional network components - such as MME (mobility management entity), PCRF (policy and charging rules function) and P/S-GW (packet/service gateway) - both in RAN and CN, with a set of virtual machines installed on servers which implement also functions of dedicated physical infrastructure. The Core Network is the central part of the infrastructure that connects all the access networks together and contains datacenters, which are hardwares able to provide computing, storage and memory resources. The conventional centralized architecture of CN became a Core Cloud, in which CP is divided from UP. The Core Cloud implements some fundamental functions of CP, like the management of mobility, resources and interferences. Other RAN functions are situated in the Edge Cloud, a set of resources that are in charge of manage some virtualized functionalities. The User Plane functions are also moved to the Edge Cloud, in order to reduce latency times and the load on the backhaul network. Thanks to SDN, 5G networks are able to connect all VMs allocated both in the Core and Edge Cloud, creating a map among them. In this way, SDN controllers can handle network slicing in a centralized manner [14].

4.3 Physical architecture

An end-to-end slice is a set of functions and modules isolated from other slices. In the slicing management section, in addition to SDN controllers there are some other elements in collaboration with each other (see Fig. 4.2):

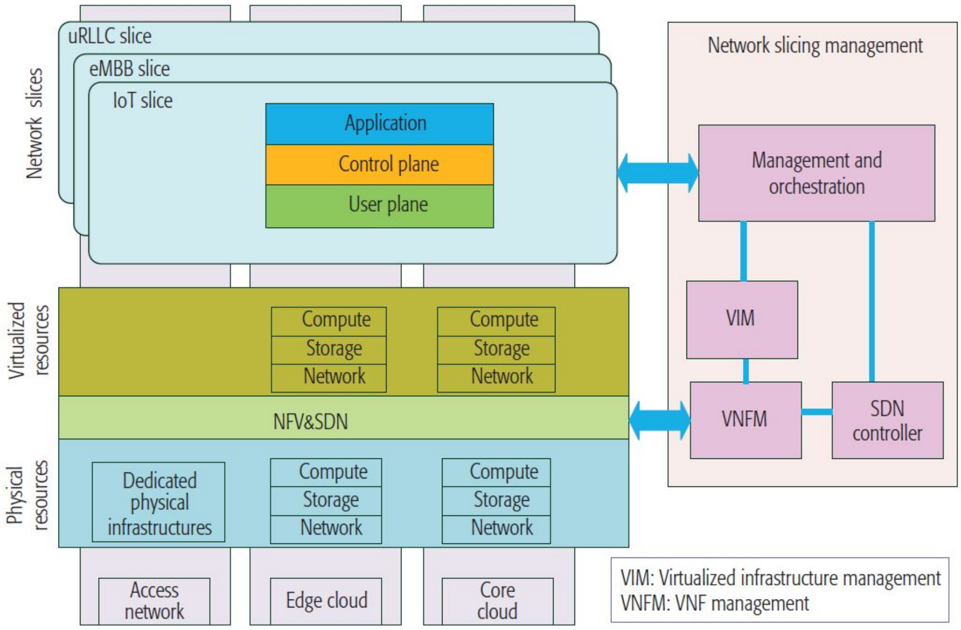


Figure 4.2: Network-slicing-based 5G system architecture [14]

- VNFM (virtualized network function management), that coordinates the whole virtual network;
- VIM (virtualized infrastructure management), that allocates resources to the VMs based on their utilization state;
- MANO (management and orchestration unit), that is the core of slicing because it takes care of creation, activation and cancellation of slices based on users' requirements.

This slicing-based 5G architecture is drastically changing the conventional models of network design and deployment. Slicing is oriented and adapted to network application and user requirements. Since it avoids mapping each application to a single physical channel, 5G networks are able to offers end-to-end tailored services matching applications' requirements [14].

4.4 SDN protocol

Software-defined networking (SDN) technology is a cloud computing approach to network architectures, which facilitates their management and configuration in order to improve their performance and facilitate their monitoring. The key concept is to separate the network control (control plane, CP) and the forwarding process (data plane, DP) for a better user experience. This segmentation brings numerous advantages in terms of network flexibility and controllability. It allows first to combine the advantages of system virtualization and cloud computing, and then to centralize network intelligence to have clear visibility across the entire network and, therefore, enable greatly improved management, maintenance, control and responsiveness.

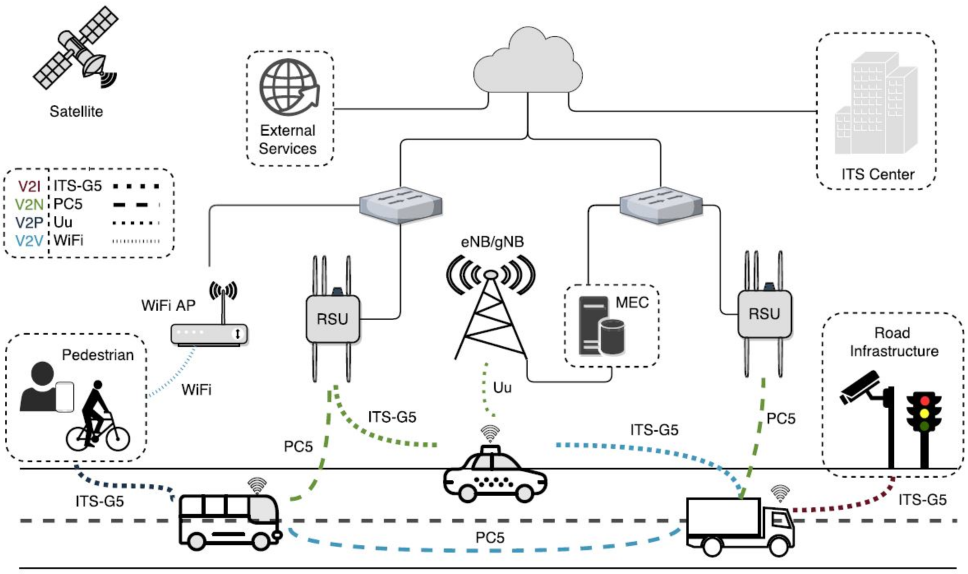


Figure 4.3: Overview of a heterogeneous V2X scenario [15]

This approach overcomes the well-known limitations of traditional networks, where the CP (which determines how to handle network traffic) and the DP (which forwards traffic based on to the decisions of the CP) are grouped inside the networking devices. SDN breaks the vertical integration by separating the CP from the DP. In this way, switches and routers become simple forwarding devices and the control logic, which establishes how the traffic flows must be handled, is implemented in a logically centralized controller that has a global vision of the network [98].

Practically, SDN separates the routing and forwarding decisions of networking elements, such as routers and switches, from the DP. In doing so, the network administration and management become easier because the CP only deals with the information related to logical topology and the traffic routing. On the other hand, the DP handles the network traffic according the established policies in the CP. In this paradigm, the control operations are centralized in a controller that dictates the management guidelines [99].

4.4.1 SDN in V2X applications

The open programmability and logically centralized control features of the SDN paradigm, through control and data plane separation and centralized intelligence, is considered a key technology to handle communication and networking resources in the flexible and programmable vehicular networks and promise improved performance. Several works proposing novel software-defined vehicular networking (SDVN) architectures and solutions can be found in the literature [16], [98], [100].

The standard SDVN architecture is composed of the same layers as the SDN paradigm. As shown in Fig. 4.4, the data plane is in charge of collecting and forwarding data and it includes, in addition to vehicles and user devices, switches and routers in conjunction with the wireless access infrastructure, i.e. Road Side Units (RSUs),

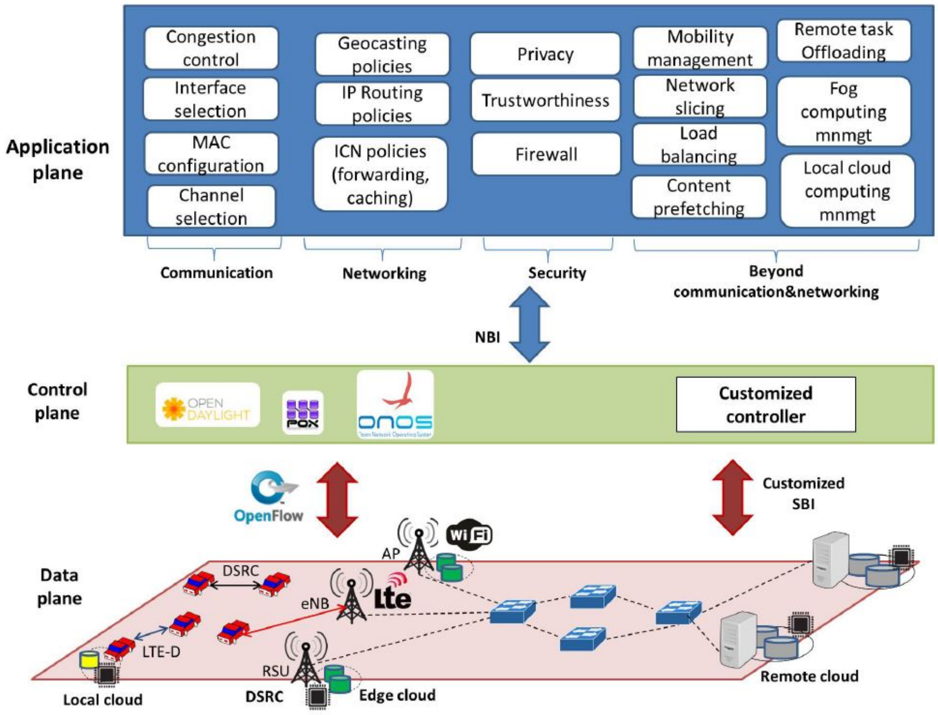


Figure 4.4: Software-Defined Vehicular Networks architecture [16]

WiFi access points (APs), eNBs, and gNBs. The control plane is responsible for getting and distributing control instructions and is composed of the SDN controller, while the application plane is accountable for the rules in the SDVN structure.

4.4.2 SDN for network slicing

Network slicing exploits virtualization techniques to support different services with heterogeneous requirements over a shared common physical network infrastructure. With SDN, slicing can be implemented via software, thus adapting to the dynamic vehicular environment. Thanks to its global vision, SDN can enable the management of multiple applications in an isolated way, guaranteeing their performance requirements [16].

In literature, several network slicing approaches exploiting SDN have been proposed [101]:

- in [102], authors implement an efficient scheduling algorithm, based on centralized SDN architecture, to provide a real-time allocation of bandwidth to different slices according to their requirements.
- in [103], developers propose an architecture to enable autonomic slice networking.
- in [104], authors introduce a management structure based on SDN and NFV to provide flexible orchestration and optimal workload allocation.

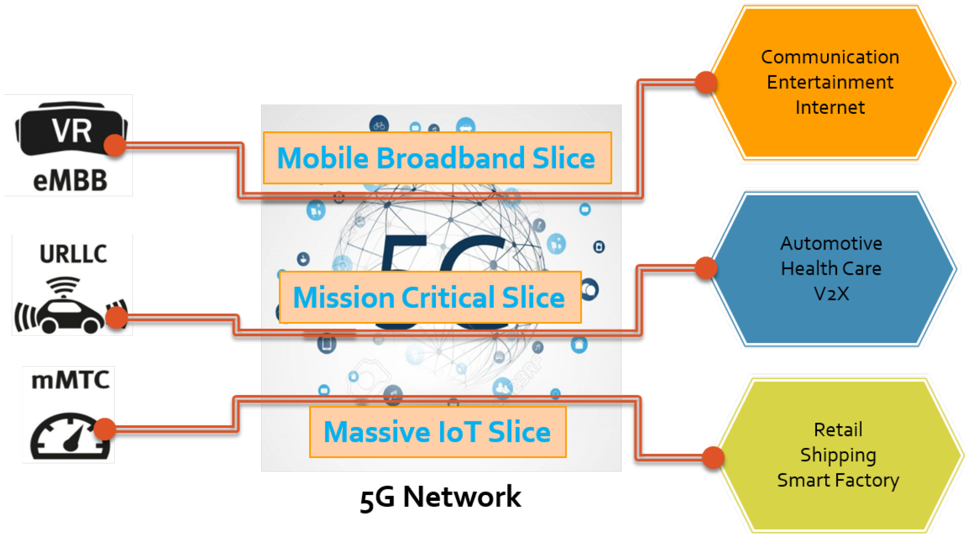


Figure 4.5: Types of slices in 5G network [17]

4.5 Slices for use cases

In literature ([14], [97], [93]), three typical categories of applications' requirements and, therefore, three conventional slices are indicated, as in Fig. 4.5:

- **eMMB (enhanced mobile broadband)**: it requires large bandwidth, high mobility, security and coverage, to support high-data-rate communications used in services like video streaming and augmented reality;
- **uRLLC (ultra-reliable and low-latency communication)**: it needs high reliability, availability and security and ultra-low latency, because services supported are extremely sensitive to latency, for example in autonomous driving or emergency communications. In this slice, all functions must be implemented at the edge cloud, in order to be very close to the UE and reduce delays;
- **mMTC (massive machine type communication)**:its main feature is the very high density of devices, whose requirements are low-cost, low-power, long range and broadband connectivity. Transmissions of this slice are characterized by low volume of data that is not sensitive to delay, for example IoT sensors.

Each slice has its proper characteristics, customized on applications and users demands. Different requirements need different new technologies. eMBB applications require new RATs such as Massive-MIMO and mmWave, to increase the data rate, and context awareness of the device such as location and battery information, for a customized QoS. uRLLC slice should have wireless backhaul and meshed networks, to provide more reliable communications. Finally, to meet mMTC requirements, the overall traffic load of base stations should be lightened. This goal can be achieved reducing the range of cells and enabling D2D communication, that allows devices to communicate with each other without passing through the base station.

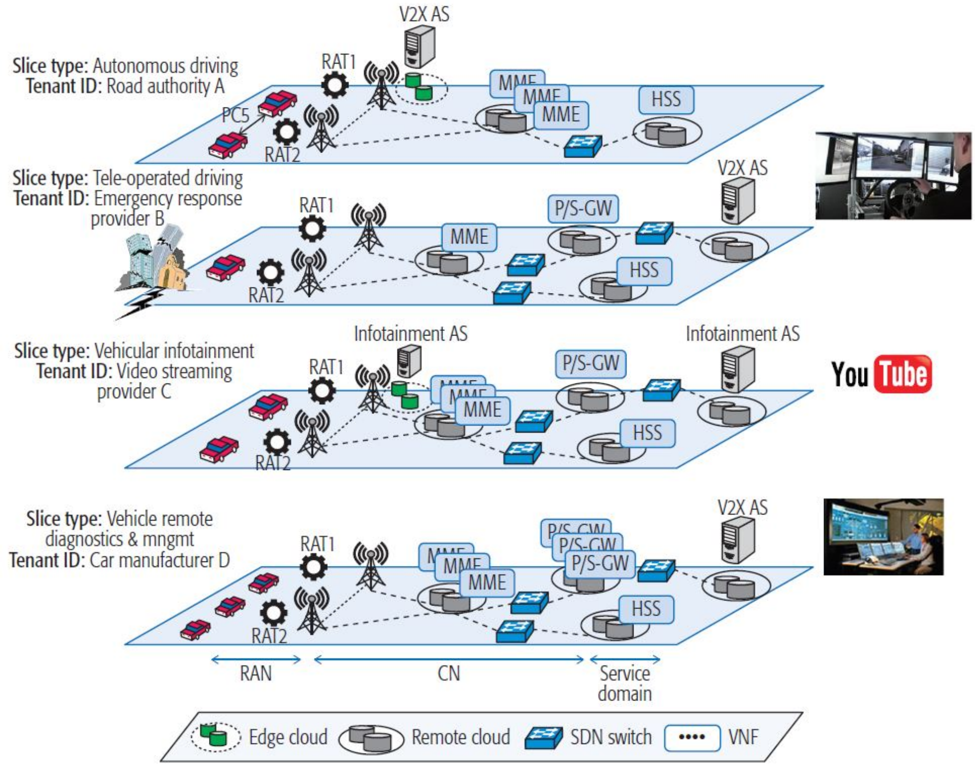


Figure 4.6: Overview of the proposed slices [18]

4.6 5G slicing for V2X

In V2X communications world, the network slicing can really cope with a large variety of use cases by leveraging the 5G infrastructure. Network slicing is the technique that allows to split a physical network into multiple logical networks each of which can be optimized for a certain type of application.

In [18], based on KPIs and requirements of typical use cases, the following four slices are proposed (Fig. 4.6):

- **Autonomous driving and safety-critical services.** It requires ultra-low latency connectivity for both V2V connections and network functions, such as mobility, authentication and subscription. For this reason, AS are collocated in the edge cloud close to the UEs, typically in the eNode-B;
- **Tele-operated driving.** It should guarantee an ultra-low latency and high reliable end-to-end connection between the remote operator, who is usually hosted outside the CN, and the controlled vehicle;
- **Vehicular infotainment.** It should support everything that can be done in a vehicle, such as watching a video, reading news, web browsing, files downloading, etc. It consists of the traditional use of a smartphone, so using an already existing technology, but considering being on board a vehicle. An MME instance will be created for each requested service;

- **Vehicle remote diagnostic and management.** It must support the not frequent exchange of small amounts of data between vehicles and remote server, situated outside the core CN.

Since network slicing allows logical network separation and individual management of each segment, each slice works in an independent way and handles autonomously its services. In this way, vehicles, infrastructures and all traffic participants could become more reliable, faster and safer depending on the requirements. In some cases, however, some common CN functions can be shared to improve resources allocation process. Similarly, the vehicle will have to be conceived as a multi-slice device, because it should be able to be connected with multiple slices at the same time. For instance, autonomous driving function can be activated while children in back seat are watching a streaming cartoon and diagnostic information is exchanged in a background process.

Another characteristic of V2X environment is to be multi-tenancy. Different services, in fact, can be offered by several providers over an infrastructure of multiple owners and operators. This issue could involve complexity in subscription and mobility operations [105].

The last aspect that needs to be considered is the multiplicity and diversity of various users that can request the slice activation: they can be smartphones, embedded car systems or intelligent traffic light, each one with its technology.

Based on literature results, we can state that 5G network slicing is one of the most promising technologies for the future of V2X communications. In [106], in fact, it is shown that network slicing greatly improves the performance compared to the direct RSU communication method, both in term of throughput and reliability.

Chapter 5

Implemented technologies

After having presented the theoretical bases and the state of the art of the key aspects of this thesis, we now proceed with the analysis of the used techniques.

In this chapter we will illustrate the different technologies exploited in our work, in terms of both hardware and software implementation. We will start with the description of multiple antenna systems and the beamforming technique, which greatly improve the performance of multi-user communications. A specific paragraph will be dedicated to the Zero-Forcing beamforming, which will be the method used in our algorithm. Then we will describe the antenna arrays with a focus on the uniform planar arrays, which are the basis of our physical architecture. The next sections will present the water filling optimization method, exploited during the power allocation step, and the multiplexing techniques used in our system. In Sec. 5.6, an general introduction of multipath concept and its statistical characterization will be given. Finally, we will take a look at the benefits provided by bandwidth part and multiuser diversity, and the 5G New Radio in unlicensed band will be introduced.

A comprehensive overview of the specific technology will be provided in each of the following sections, with a focus on the aspects we will need most for the implementation of our approach. We will analyze the pros and cons of each technique, then trying, in the next chapter, to combine them in such a way as to obtain the greatest advantages in the V2X coexistence scenario we are interested in.

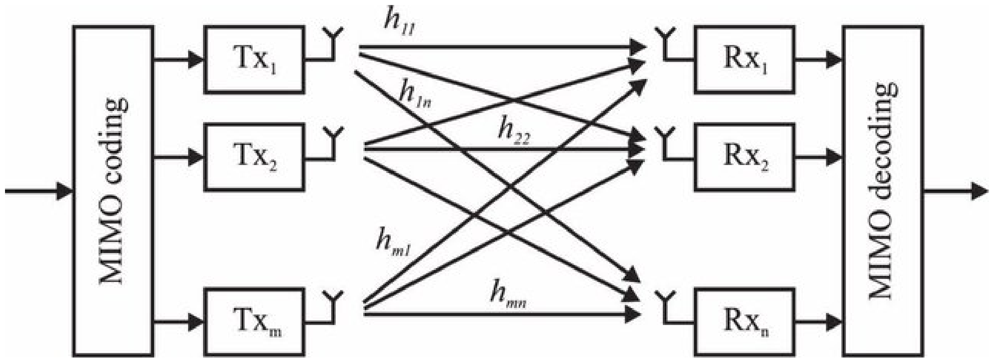


Figure 5.1: Scheme of a MIMO system [19]

5.1 MIMO systems

Multiple-input multiple-output (MIMO) communication systems make use of communication links with multiple transmit and receive antennas and provide considerable improvements in terms of rate and reliability. MIMO systems also offer a significant capacity gain through an increased spatial dimension [107], [108]. These benefits are obtained thanks to the spatial multiplexing and diversity [109].

Let us consider a MIMO system, characterized by M antennas at the transmitter and N at the receiver, as in Fig. 5.1.

Spatial multiplexing is a technique in which data is multiplexed across the transmit antennas. In this way, a MIMO link can be split into a parallel of r SISO (Single Input Single Output) links, where $r = min(M, N)$. This means that, under certain conditions, the capacity could be increased of a factor r respect to an equivalent link with just one antenna at the transmitter and one at the receiver. Therefore, spatial multiplexing can be exploited to increase the throughput of a wireless system for a single user or to create more channels in order to serve simultaneously more users. In cellular systems, however, the benefits from spatial multiplexing are limited by fading and interference [110].

Spatial diversity is the means to obtain an higher SNR at the output of the receiver combiner, in order to decrease the error probability accordingly. In general, a MIMO system can reach a maximum diversity order that is equal to $M \times N$, since this is the maximum number of independent channel links.

Multiple antennas will be applied at both receiver and transmitter side to exploit spatial diversity and multiplexing and, therefore, to achieve an higher reliability and throughput.

In a MIMO system, the equivalent lowpass channel impulse response between the j-th transmitting antenna and the i-th receiving antennas is usually denoted as $h_{ij}(t)$. So, the randomly time-varying channel is characterized by a $N \times M$ matrix:

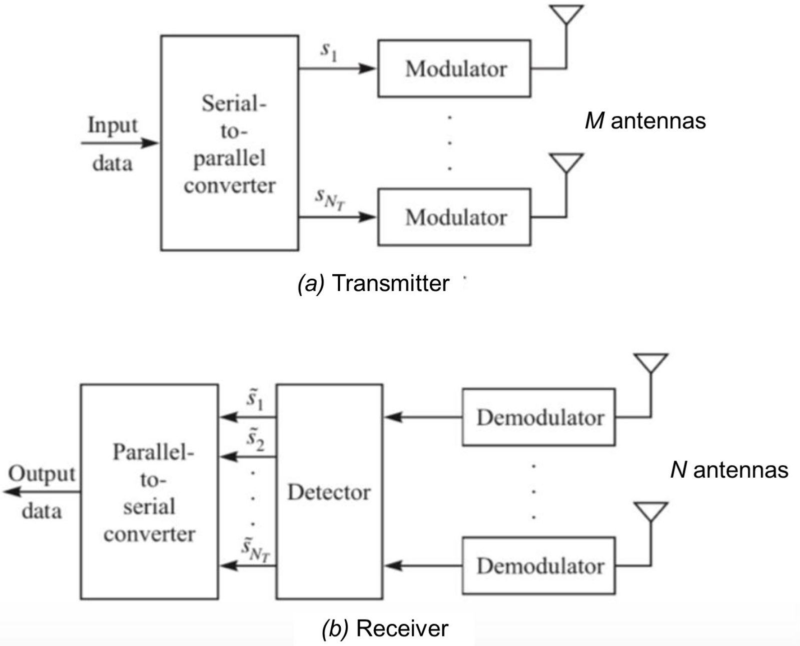


Figure 5.2: MIMO system transmitter (a) and receiver (b) schemes with M transmitting antennas and N receiving antennas [20]

$$\mathbf{H}(t) = \begin{bmatrix} h_{11}(t) & h_{12}(t) & \cdots & h_{1M}(t) \\ h_{21}(t) & h_{22}(t) & \cdots & h_{2M}(t) \\ \vdots & \vdots & \ddots & \vdots \\ h_{N1}(t) & h_{N2}(t) & \cdots & h_{NM}(t) \end{bmatrix} \tag{5.1}$$

and the received signal is given by

$$\mathbf{y}(t) = \mathbf{H}(t)\mathbf{x}(t) + \mathbf{n}(t), \tag{5.2}$$

where $\mathbf{x}(t)$ is the transmitted signal and $\mathbf{n}(t)$ represents the noise.

If we assume $h(t)$ as a Rayleigh fading channel with i.i.d. zeros mean complex Gaussian entities with unit variance, we can consider $\mathbf{n}(t) \sim \mathcal{N}$ as a white Gaussian channel noise.

If the time variations of the channel impulse response are very slow within a symbol interval, $\mathbf{H}(t)$ can be considered constant $\mathbf{H}$.

In addition to multiplexing and diversity, the least feature of MIMO systems is the beamforming, a technique that realizes a spatial filtering by applying specific weight vectors to arrays of antennas (see Section 5.2). This method can be used to increase SNR and/or to allow coexistence of multiple channels for users enough separated in the space. However, there is a fundamental difference between the previous two solutions and this one: in diversity and spatial multiplexing, it is necessary to achieve a sufficient degree of uncorrelation among the signals, while in beamforming signals need to be highly correlated for obtaining the angular selectivity effect by changing the phases, so antenna spacing is surely narrower (typically $\lambda/2$).

It is important to point out that the choice between these three techniques is not exclusive, as combinations and trade-offs between spatial multiplexing, diversity and beamforming are possible.

Despite the significant advantages, however, MIMO systems inevitably also have some critical issues to take into consideration, such as increased hardware cost, power consumption and computational complexity. But the benefits of this technology undoubtedly greatly outweigh the downsides.

5.2 Beamforming

Beamforming (BF) is a particular technology that allows to direct and concentrate a signal in one direction rather than another. The effect is to be able to steer the main lobe in a given direction and/or rejecting interfering signals coming from specific directions. In more technical terms, BF is a wave processing technique that allows directional transmission and reception of the signal. This is made possible by the combined use of particular transceivers that allow to create constructive or destructive interferences, according to the necessity. BF is also known as spatial filtering. For achieving spatial directivity, this technique is utilized at both transmitting and receiving terminals [111]. BF is a suboptimal strategy that can serve multiple users at a time, but with reduce computational complexity respect to Dirty Paper Coding (DPC). In this technique, each user stream is coded independently and multiplied by a weight vector $\mathbf{w}$ for transmission through multiple antennas. An accurate choice of $\mathbf{w}$ allows to reduce, or even eliminate, mutual interference among different streams by leveraging spatial separation between users and, in this way, to support multiple users simultaneously [28]. Furthermore, in [112] it has been demonstrated that if $\mathbf{w}$ are selected optimally, when number of users goes to infinity the BF sum rate approaches that of DPC. Finally, results in [68] demonstrate that appropriate beamforming design is able to reduce the impact on interference and enhance the efficiency thanks to reusing of the available resources, thus guaranteeing better communication performance.

In a MIMO $M \times N$ system, as discussed in Sec. 5.1, the channel matrix $\mathbf{H}$ can now be modeled as

$$\mathbf{H} = \mathbf{V}^T\mathbf{U}\mathbf{W} \tag{5.3}$$

where $\mathbf{V}$ and $\mathbf{W}$ represent respectively the transmitter and receiver beamforming matrixes, while $\mathbf{U}$ is the channel gain matrix between transmitting and receiving antenna arrays in beamspace [113].

The main benefits of beamforming are:

- Enhanced spectral efficiency, leveraging the improvement in the signal quality and the power controlling of signals, both in uplink and downlink;

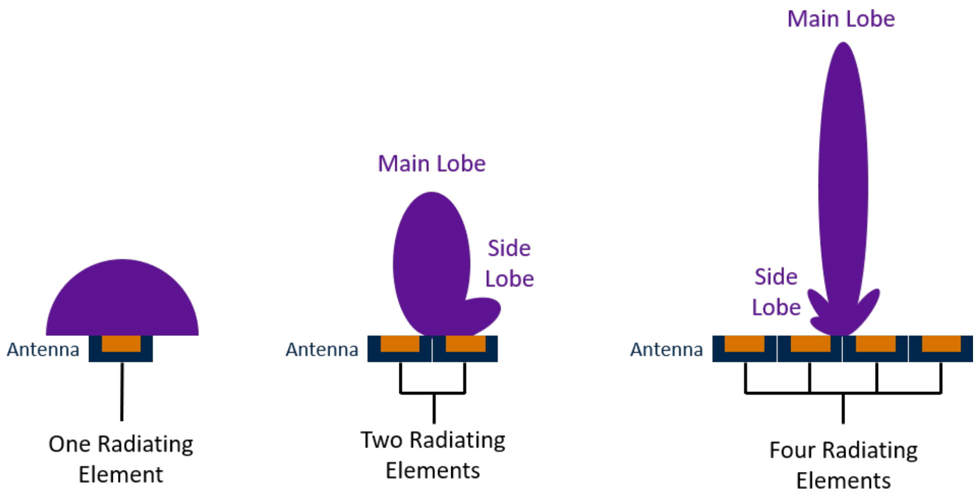


Figure 5.3: Main and side lobes in beamforming with two and four radiating elements [21]

- Improved energy efficiency, since the power required for transmitting a signal through a beamforming antenna is quite low;
- Applicability for mmWaves, because beamforming support high bandwidth at these frequencies;
- Improved system security, since the signal is guided until the receiver.

Depending on the configuration of the antennas, beamforming is classified in the following types:

- Static beamforming, with fixed number and configuration of antennas that produce a fixed radiation output
- Dynamic beamforming (or beamsteering), similar to static one, but with adaptive adjustment of radiation and directivity capability; available only at transmitting station
- Transmit beamforming, in which multiple phase-shifted signals are transmitted in-phase towards receiver place.

Another classification of beamforming is based on how the signal is transmitted to the antennas:

- Analog beamforming, that sends the same signal to multiple antennas, but with different phases using phase shifters
- Digital beamforming, that sends different signals for each antenna
- Hybrid beamforming, that is a combination of the previous two

Zero-forcing beamforming

In this work, following [28], we exploit a particular type of BF, *zero-forcing beamforming* (ZFBF), where the weight vectors are chosen to avoid interference among user streams. The ZFBF, in fact is a sub-optimal solution to determine weight vectors $\mathbf{w_j}$ such that they satisfy the zero-interference condition $\mathbf{h_k}\mathbf{w_j} = 0$ for $j \neq k$. These weights can be simply calculated by inverting the channel matrix of the users as

$$\mathbf{W} = \mathbf{H}^{\dagger} = \mathbf{H}^{*}(\mathbf{H}\mathbf{H}^{*})^{-1}, \tag{5.4}$$

where $\mathbf{H}$ is the channel matrix presented in (5.1).

In general, this approach is not power efficient since weights are not matched to user channels. In [114] and [115], however, it has been demonstrate that when the number of users is high, its sum-rate performance approaches that of DPC, thanks to *multiuser diversity* effect (see Section 5.8).

This approach exploits the *Gram-Schmidt orthogonalization*, in order to evaluate the orthogonality between channels. It is a procedure that allows to obtain a set of orthogonal vectors starting from a generic set of linearly independent vectors in a space with a definite positive scalar product.

Practically, the ZF algorithm calculates the orthogonal projection of a channel vector over another one. Then, it computes the vectorial product v between the channels and the subspace and we can have three different results:

- $v = 0$ means that the channels are perfectly orthogonal, so we are avoiding any interference;
- $v = 1$ stands for the absolute lack of orthogonality, and therefore we experiment the maximum of interference;
- $0 < v < 1$ indicates that we are in a *semi-orthogonality* condition.

5.3 Antenna arrays

In telecommunication systems, there are different types of antennas.

- An **omnidirectional antenna** has equal gain in all directions and is also called *isotropic*.
- **Directional antennas**, on the other hand, have more gain in certain directions and less in others.
- A **phased array antenna** is made up of a set of simple antennas and combines the signal sent to these antennas to form the desired output. Each antenna is known as an element of the array. The direction of maximum gain is controlled by adjusting the phase between different elements.
- A phased array is called **adaptive antenna** when its gain can be changed in a dynamic fashion, depending on the need. In this way, the array is able to adapt itself to the situation, and the adaption process can be managed remotely in a processing step.

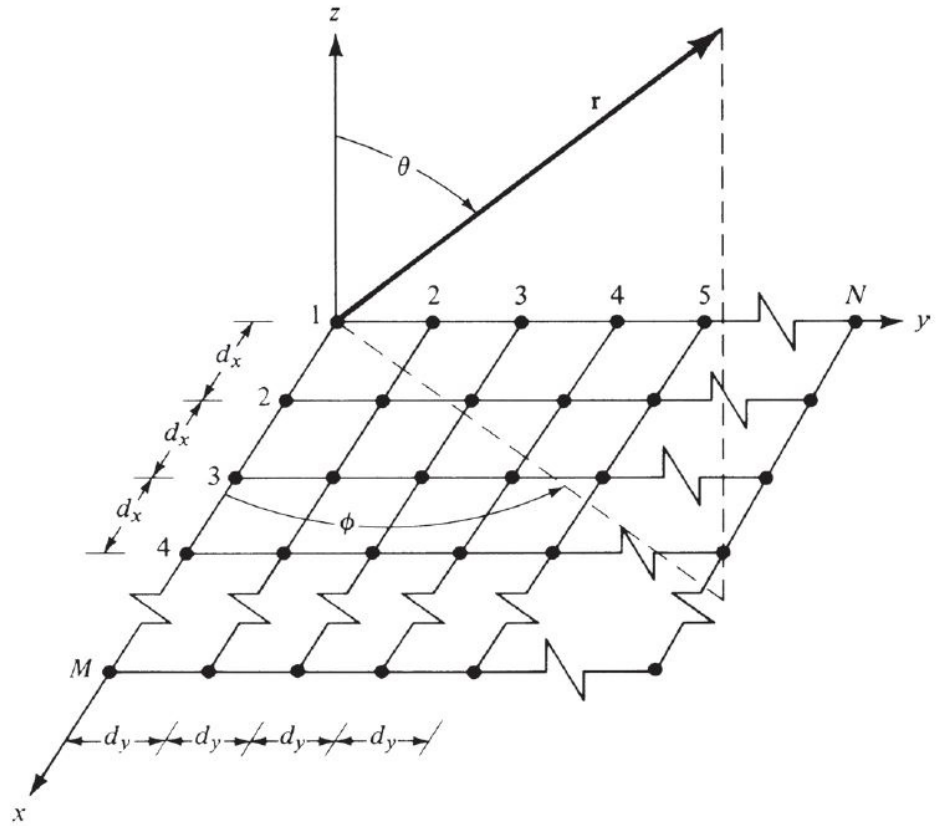


Figure 5.4: UPA geometry [22]

Antenna arrays are widely used in mobile communications systems to overcome the problem of limited channel bandwidth. It has been demonstrate that they allow to improve the system performance by increasing channel capacity and spectrum efficiency, extending range coverage, and tailoring beam shape [116].

An array of antennas mounted on vehicles, ships, aircraft, satellites, and base stations is expected to play an important role in fulfilling the increasing demand for channels. Array signal processing involves the manipulation of signals induced on the elements of an array [117].

The high path loss of the mmWave bands can successfully be improved by adaptive beamforming using antenna arrays; the alignment of transmit and receive beams in direction can result in high beamforming gains [118]. Therefore, one of the key architecture features of mmWave is the use of large antenna arrays at both the transmitter and the receiver.

Uniform planar array

For uniform planar array (UPA) antennas, individual radiators are located along a rectangular grid, as shown in Fig. 5.4. Planar arrays provide additional variables which can be exploited to control and shape the pattern of the array, hence they are

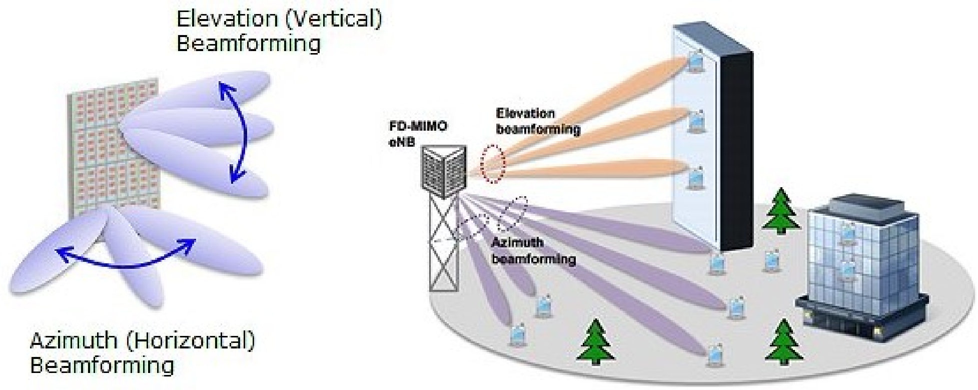


Figure 5.5: Azimuth and elevation angles in beamforming MIMO system [23]

more versatile and can provide more symmetrical patterns with lower side lobes [22].

The array has A and B elements on y and z axes, respectively. Since the arrangement is Cartesian, or matrix-like, it is useful to use two indices to refer the position of the elements: a row index a and a column index b, corresponding to y and z indices of an antenna element, respectively. Therefore, the array response vector is given by [119]:

$$\begin{aligned}\mathbf{a}(\vartheta, \phi) = \frac{1}{\sqrt{I}}[1, \cdots, e^{jld(a \sin\vartheta \sin\phi + b\cos\phi)}, \cdots, \\ e^{jld((A-1)\sin\vartheta\sin\phi + (B-1)\cos\phi}]^T,\end{aligned} \tag{5.5}$$

where $l = 2\pi/\lambda$, λ is the wavelength, d is the inter-element spacing, and ϑ is the azimuth while ϕ is the elevation angle (see Fig. 5.5). Accordingly, (ϑ_R, ϕ_R) and (ϑ_T, ϕ_T) represent, respectively, Angle of Arrival (AOA), and Angle of Departure (AOD) of the specific propagation path.

UPAs are widely used in tracking and search radar, remote sensing, communications, etc.

5.4 Water Filling

Water Filling is a numerical optimization technique that gives an approximate solution after a finite number of iterations. In communication systems, it stems from a class of the problems of maximizing the mutual information between the input and the output of a channel with parallel independent sub-channels.

This algorithm is widely used in power allocation problems. In fact, it distributes the available power among various users according to their channel quality, i.e. the user with higher noise level will be allocated less power [120]. Practically, more power is allocated to “better” subchannels with higher signal-to-noise ratio (SNR) and vice-versa, in order to maximize the sum of data rates in all subchannels or the capacity of all the channels. The solution to this class of the problems can be interpreted by a vivid description as pouring limited volume of water into a tank, the bottom of which has the stair levels determined by the inverse of the sub-channel gains [121].

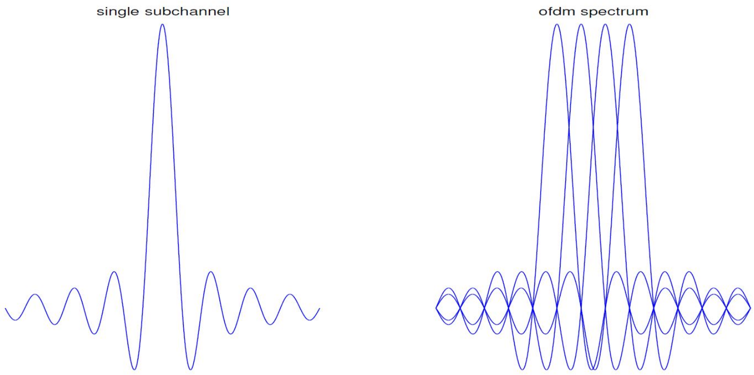


Figure 5.6: Difference between traditional MCM and OFDM [24]

The conventional water filling problem has a sum power constraint under non-negative individual powers. The core of the problem is to obtain the water level such that the power constraint is satisfied with equality. This leads to a non-linear system in one parameter, the water level, that is determined by the sum power bound (for the calculation, see Sec. 6.2.1).

For simple water filling problems with a single water level and a single constraint (typically, a power constraint), some algorithms have been proposed in the literature to compute the solutions numerically. On the other hand, some other optimization problems require more complicated water filling solutions that include multiple water levels and multiple constraints [122].

By denoting γ_i as the channel gain, the amount of power P_i allocated to each user i is obtained from

$$P_i = (\mu\gamma_i - 1)^+, \tag{5.6}$$

in which the water level μ is calculated by solving

$$\sum_{i \in S} \left(\mu - \frac{1}{\gamma_i} \right)^+ = P, \tag{5.7}$$

where P is the total available power of the transmitter.

5.5 OFDM and OFDMA

Orthogonal Frequency Division Multiplexing (OFDM) is a multiplexing technique that splits the available bandwidth into several orthogonal frequency sub-carriers. The input data stream is subdivided into multiple parallel sub-streams of reduced data rate and each sub-stream is transmitted on a distinct orthogonal sub-carrier.

Unlike traditional Multi Carrier Modulation (MCM) system, where subcarriers are non-overlapping, OFDM uses subcarriers that are mathematically orthogonal. These properties help to reduce interference caused by neighboring carriers and makes OFDM based systems more spectrally efficient as shown in Fig. 5.6 [24].

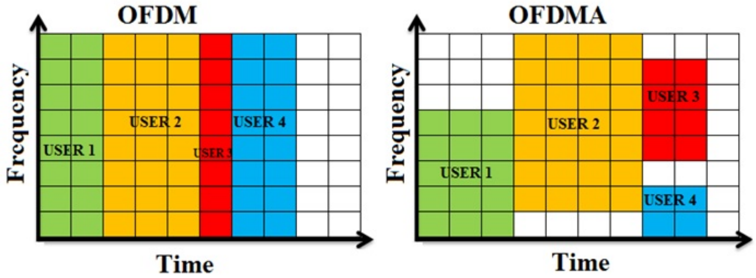


Figure 5.7: Difference between OFDM and OFDMA [25]

The orthogonality between two carriers, regardless the phase, is guaranteed by a frequency spacing Δf equal to $1/T$, where T is the duration of the single rectangular baseband pulse. The overall OFDM signal in the time domain is given by:

$$s(t) = \sum_{k=0}^{N-1} a_k \cdot g_k(t) \tag{5.8}$$

where a_k is the constellation point (i.e. M-QAM, M-PSK) and

$$g_k(t) = \begin{cases} \frac{1}{\sqrt{T}} \exp^{j2\pi kt/T}, & 0 \leq t < T \\ 0, & elsewhere \end{cases} \tag{5.9}$$

normalized to unitary energy by the factor $\frac{1}{\sqrt{T}}$.

Therefore, the resulting set of N pulses $g_k(t)$ forms a set of orthonormal signals, such that:

$$\int_0^T g_k(t) \cdot g_i^*(t) dt = \begin{cases} 0, & \text{for } k \neq j \\ 1, & \text{for } k = j. \end{cases} \tag{5.10}$$

This is a fundamental feature that ensures the possibility of transmitting and receiving the N overlapping symbols a_k without performance degradation [123].

In other words, OFDM divides one high-speed signal into numerous slow signals to be more robust at the receiver's end so that the sub-channels are then able to transmit data without being affected to the same multipath distortion faced by single carrier transmission. The numerous sub-carriers are then collected at the receiver and recombined to form one high-speed transmission. In this way, the available bandwidth is used very efficiently. Practically, OFDM is a block modulation scheme where a block of N information symbols is transmitted in parallel on N sub-carriers [124].

In OFDM systems, however, only a single user is allowed to transmit on all of the sub-carriers at any time. To adapt to multiple users, a strictly OFDM system must make use of either TDMA or FDMA, which exploit respectively separate time frames and separate channels. Both of the two techniques are time or frequency inefficient.

Orthogonal Frequency Division Multiple Access (OFDMA) is the multi-user OFDM technology where users can be assigned according on both TDMA and FDMA where a single user does not necessarily need to occupy all the sub-carriers at the same time. So, while OFDM support multiple users (Multiple Access) via TDMA basis only, OFDMA is able support either on TDMA or FDMA basis or both at the same time. In this way, only a subset of sub-carriers is assigned to a specific user, as shown in Fig. 5.7. This allows simultaneous low data rate transmission from several users and a dynamic allocation to the best channels.

The main advantages of OFDMA are:

- scalability and flexibility, since it can support a wide range of bandwidth;
- robustness to multipath, thanks to the sub-channels orthogonality;
- high MIMO spectral efficiencies;
- improved downlink multiplexing capacity, because OFDMA has one more dimension of flexibility to allocate power and sub-channels to different users in the same time slot.
- higher uplink capacity, due to the elimination of intra-cell interference through orthogonal sub-channels multiple access.

Authors in [125] conclude therefore that OFDMA is a superior access technology for broadband wireless data network compared with traditional access technologies such as TDMA and CDMA.

5.6 Multipath channel

In wireless telecommunications, multipath is the propagation phenomenon that results in a combination of more signal components (reflections or echoes) reaching the receiving antenna with different delays and amplitude.

As shown in Fig. 5.8, several possible versions of the transmitted signal can arrive at the receiver, mainly due to atmospheric ducting, ionospheric reflection, refraction and presence of obstacles, such as buildings, trees or any type of reflecting surfaces. They can sum each other determining a constructive or destructive interference. Many multipath models have been proposed to describe the observed statistical nature of a specific radio channel, such as: shortwave ionospheric radio communication in the 3–30 MHz frequency band, tropospheric scatter radio communications in the 300–3000 MHz frequency band and ionospheric forward scatter in the 30–300 MHz frequency band [126].

In order to develop a simple and effective model, the carrier frequency $f_c$of the signal $x(t)$ can be neglected, at least formally, so that it is represented by its low-pass equivalent $x_l(t)$:

$$
\begin{aligned}
x(t) &= Re x_l(t) e^{j2\pi f_c t} \\
x_l(t) &= a(t) e^{j\theta(t)}
\end{aligned}
\tag{5.11}
$$

where $a(t)$ and $\theta(t)$ are the envelope and the phase of the signal.

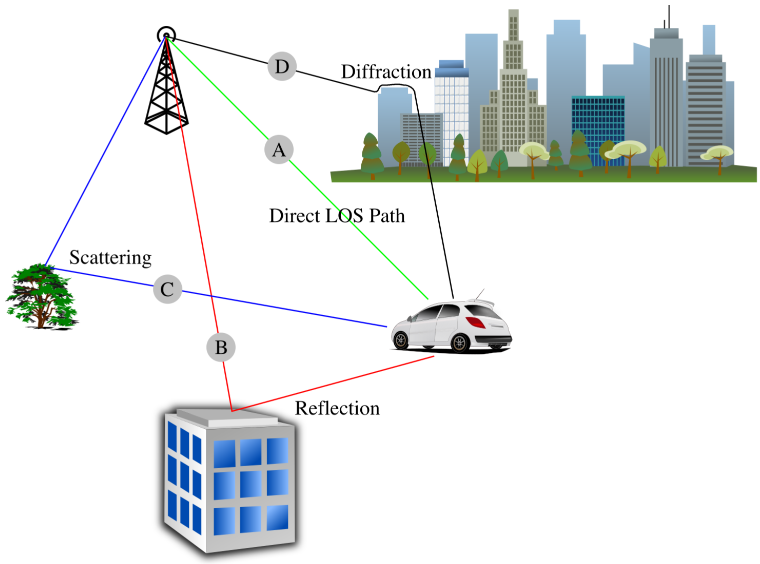


Figure 5.8: Different effects of wireless communication environment over a signal going from the BS to the User, in case of LoS condition and with the presence of obstacles [26]

As known, the received signal can be expressed by the convolution between $x_l(t)$ and the channel impulse response $h_l(\tau)$:

$$y_l(t) = \sum_n a_n e^{-j2\pi f_c \tau_n} x_l(\tau - \tau_n) \tag{5.12}$$

$$h_l(\tau) = \sum_n a_n e^{-j2\pi f_c \tau_n} \delta(\tau - \tau_n) \tag{5.13}$$

or in frequency domain by the product between $H_l(f)$ and $X_l(f)$ [20].

Statistical characterization

An important characteristic in the structure of the physical channel is its time variations, since the nature of the multipath can vary with time.

In fact, repeating the transmission of a short pulse over the channel, it could be observed variations in the received pulse train, in the amplitude and numbers of the individual pulses and the relative delays. Therefore, it is reasonable to characterize the time-variant multipath channel statistically, for example treating $h_l(\tau)$ as a complex valued random variable with normal (Gaussian) distribution according to the Central Limit Theorem [20].

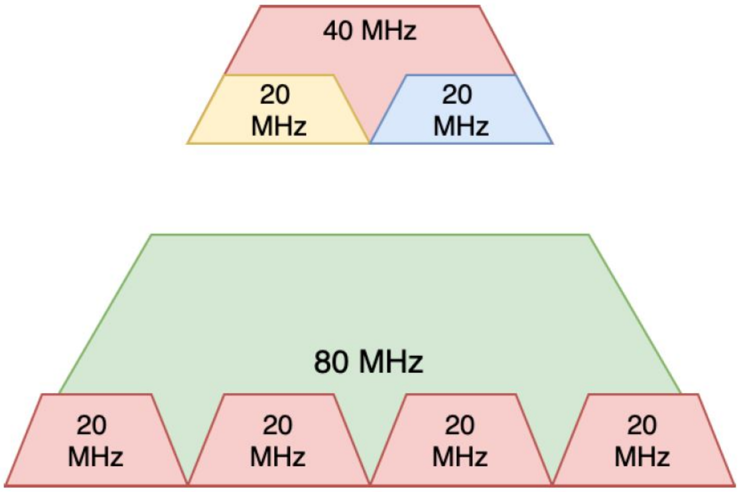


Figure 5.9: Associated bandwidth parts to a wide band channel [27]

5.7 Bandwidth Part

An important goal of 5G New Radio is to enable spectrum flexibility, by introducing flexible carrier size. It means that UEs are able to utilize a carrier BW smaller than the one utilized in the network cell, as shown in Fig. 5.9. To achieve this goal, 3GPP (Rel-15) introduced a new feature called Bandwidth Part (BWP) for 5G NR. This allows to configure the UEs in order to work in BWs which are narrower than the carrier BW and which fit the service requirements regarding throughput, delay and energy efficiency.

Each BWP is made up of contiguous PRBs (physical resource blocks) that share some common numerology and are allocated by a gNB to a UE according to its requirement [127].

5.8 Multiuser diversity

As we saw in the section 5.1, MIMO systems offer significantly advantages in terms of rate and reliability. In cellular systems, however, the gain from spatial multiplexing is limited by fading and interference.

One potential solution to cope this issue and, therefore, to increase the throughput of multi-user systems is to leverage on multiuser diversity to take advantage of the independence of the fading and interference statistics of different users. It leverages the fact that, in a system with many users whose channels fade independently, at any given time some users will have better channels than others. In a multiuser diversity system, hence, a packet scheduler utilizes instantaneous knowledge of the SNR of each channel to allocate resources to the user according on channel quality. By transmitting only to users with the best channels at any given time, radio resources are allocated to the users that can best exploit them, thus allowing a better capacity and/or performance of the system [128].

This approach is suitable for high-speed data transmission since data packets are more tolerant to scheduling delays than constant bit rate services such as voice [110].

5.9 5G New Radio in the Unlicensed Band

New Radio in the Unlicensed band (NR-U) is a new operating mode that has that has the ability to offer the technology needed by cellular operators to integrate the unlicensed spectrum into 5G networks.

The unlicensed spectrum plays a crucial role in achieving the goals of industrial 5G communications, by providing ultra-high-speed, low latency, high capacity, and improved reliability of wireless communications, which are essential to address future massive-scale and highly-diverse enterprise requirements [129].

NR-U considers different unlicensed bands or shared bands such as 2.4 GHz, 3.5 GHz, 5 GHz, 6 GHz, 37 GHz, and 60 GHz. The first four are classified as sub-7 GHz bands, while the last two are part of the so-called millimeter waves (mmWave). The 5 and 60 GHz bands are the most attractive candidates for NR-U, since they are currently not very crowded as 2.4 GHz and can offer a large amount of contiguous bandwidth [130].

Chapter 6

Proposed approach for resource and coexistence management in a realistic V2X scenario

In the previous chapters, we have introduced the motivations, the theoretical background, and the different techniques of this thesis work. Now, we will illustrate in detail our approach and the algorithm implemented.

This chapter starts with the description of the model of our system, focusing on the mathematical formulas utilized to calculate the channel gain, the received signal and the overall data rate. Then, the used two power allocation polices are depicted, with an example of application of each one. In Sec. 6.3, we will describe the user selection algorithm based on ZFBF, while the next section will illustrate the two followed approaches, the theoretical one and the simulated one. Finally, a general overview of the exploited tools and software will be given.

At the end of this chapter, we will be ready to run the different simulations and obtain the results, which will be presented in the chapter 7.

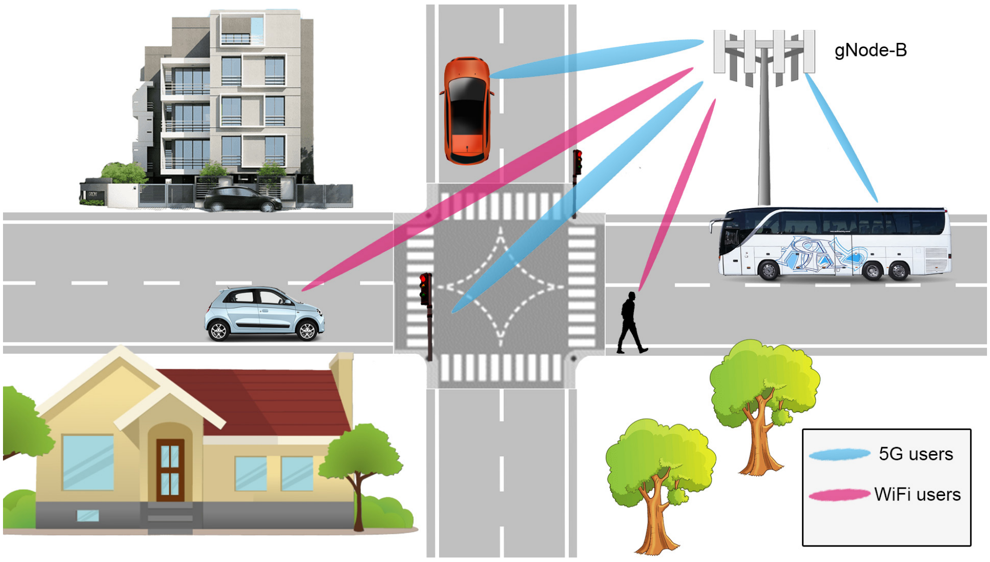


Figure 6.1: Scheme of our scenario

6.1 Overview

In this thesis, we started from the work illustrated in Sec. 3.6 and described in detail in the article [12], and we followed their approach, but applying that to different context. In fact, we want to evaluate its performance in a realistic V2X scenario, with its typical characteristics, as discussed in Chapter 2. This environment is realized thanks a combination of simulation tools as depicted in Sec. 6.4.2.

This approach exploits several concepts and techniques we talked about in previous chapters. In particular, it is based on network slicing and zero-forcing beamforming, explained in deep in Chapter 4 and in Sec. 5.2, respectively.

In our model, like in [12] WiFi users in WiFi-dedicated slice communicate with gNB according to IEEE 802.11 standard, while cellular users in various 5G slices follow the 3GPP protocol. Both technologies support MIMO and OFDMA, illustrated in detail in Sec. 5.1 and in Sec. 5.5.

Fig. 6.2 depicts the block scheme implemented in our BS. Based on this proposed framework, there are three main operations to be performed:

- We should first select an eligible group of users, that can be synchronously connected to the gNB with negligible interference, and we should associate these cellular and Wi-Fi users to the gNB, with different access protocol (see Sec. 6.3).
- Secondly, we should allocate an amount of power to each of these selected users. This quantity is assigned according to two different allocation policies, as detailed below in Sec. 6.2.1 and 6.2.2.
- Finally, the ZFBF illustrated in Sec. 5.2 is implemented before the transmission.

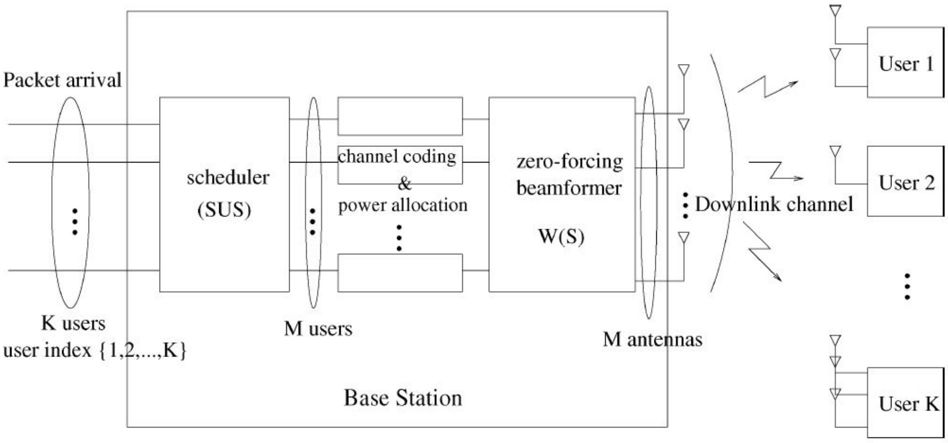


Figure 6.2: MIMO downlink system with M transmit antennas and $K > M$ users. Plot shows proposed downlink strategy of ZFBF combined with selection algorithm (see Section 6.3) [28]

6.2 System Model

We focus on a single cell with K user terminals receiving data from the gNB, which needs to orchestrate the resource allocation to guarantee a high level of downlink connectivity at each time instance. In the developed system model we assume that all the receiving vehicles are equipped with a single antenna. The gNB, instead, has an array of I antennas such that it can support multi-user, multiple-input, multiple-output (MU-MIMO) transmissions. In this way, the gNB can transmit up to I independent streams via spatial multiplexing. In particular, the gNB is equipped with a uniform planar array (UPA), described in Sec. 5.3, arranged along the yz-plane, with A and B elements on y and z axes such that $A \times B = I$.

According to the array response vector given by (5.5), the $1 \times I$ channel vector for each user k is

$$\mathbf{h_k} = \sum_{n=1}^{N_{path}} \alpha_n \mathbf{a}_R(\vartheta_{R,n}, \phi_{R,n}) \mathbf{a}_T^*(\vartheta_{T,n}, \phi_{T,n}),\ k = 1, \cdots, K, \tag{6.1}$$

where α_n denotes the path gain of the nth path and N_{path} is the total number of physical path between gNB and user k. Denote by $\mathbf{H} = [\mathbf{h}_1^T, \cdots, \mathbf{h}_K^T]^T \in \mathbb{C}^{K \times I}$ the overall channel matrix between gNB and K users, the matrix representation of the Multiple Input Single Output (MISO) system is presented as follows

$$\mathbf{y} = \mathbf{Hx} + \mathbf{n}, \tag{6.2}$$

where $\mathbf{y} \in \mathbb{C}^{K \times 1}$ is the received signal vector, $\mathbf{n} = [n_1 \cdots n_k]^T \in \mathbb{C}^{K \times 1}$ is the additive white Gaussian noise, with each element independently drawn from $\mathcal{N}(0, \sigma_n^2)$, and $\mathbf{x} \in \mathbb{C}^{I \times 1}$ is the transmitted signal from gNB at each time instance. Let s_k, $\mathbf{w}_k$, and P_k be the transmitted symbol, beamforming weight vector, and associated power to user k, respectively. Therefore, the transmitted signal is $\mathbf{x} = \sum_{k=1}^{K} \sqrt{P_k} \mathbf{w}_k s_k$.

Accordingly the received symbol for user k is

$$y_k = (\sqrt{P_k}\mathbf{h}_k\mathbf{w}_k)s_k + \sum_{j\neq k}\sqrt{P_j}\mathbf{h}_j\mathbf{w}_j s_j + n_k. \tag{6.3}$$

The user selection is an important criteria for the performance of the ZFBF method. In particular, if the channel matrix of the selected user $\mathbf{H}(S)$ is poorly conditioned, then the effective channel gain (6.5) tends to zero. Thus, the system does not gain from multiplexing. To avoid such a condition, in section 6.3 we present a semi-orthogonal user selection algorithm to choose a group of users nearly orthogonal to one another.

Once the eligible user group has been selected, we proceed with the allocation of radio resources. The main purpose is to achieve an optimal power distribution, in order to maximize the overall sum rate:

$$R(S) = \max_{P_i:\sum_{i\in S}\gamma_i^{-1}P_i\leq P}\sum_{i\in S}\log(1+P_i), \tag{6.4}$$

where P is power budget, $\gamma_i^{-1}P_i$ is the power assigned to user i, and

$$\gamma_i = \frac{1}{||\mathbf{w}_i||^2} = \frac{1}{[(\mathbf{H}(S)\mathbf{H}(S)^*)^{-1}]_{i,i}} \tag{6.5}$$

is interpreted as the effective channel gain for the ith user.

We follow two main approach to allocate power among the users, explained in the next two sections.

6.2.1 Allocation with Water Filling

The first technique we implement for power allocation is the Water Filling, that is illustrated in detail in Section 5.4.

Fig. 6.3 shows an example of power allocation scheme in a 10 users scenario. The procedure takes in input the total power P and the noise level of each channel, represented by the blue bars. The red line at the top is the water level μ obtained from 5.7. The output of the procedure is represented by the red bars, which indicate the amount of power allocated to each channel. In Table 6.1 input and output values of previous example are listed. The calculated value of μ is equal to 5.2 dBm. Looking at both graph and table, it is easy to understand the simple concept behind this approach.

This technique provides a good solution for power allocation, but it is *unfair*. In fact, as can be seen in the Fig. 6.4, some users (the best ones) can achieve a very high rate thanks to both the good quality of the channel and the consequent large amount of power assigned. On the other hand, some other users who already have noisy channels are further penalized, due to the low power assigned to them, and therefore they will not be able to reach a good rate.

Table 6.1: Example of Water Filling procedure input and output

Channel ID	1	2	3	4	5	6	7	8	9	10
Noise (dBm)	1	4	0.5	2	3.5	1.5	4	1.5	3	1
Power (dBm)	4.2	1.2	4.7	3.2	1.7	3.7	1.2	3.7	2.2	4.2
Rate (Mbps)	1.6	0.8	1.7	1.4	1	1.5	0.8	1.6	1.2	1.6

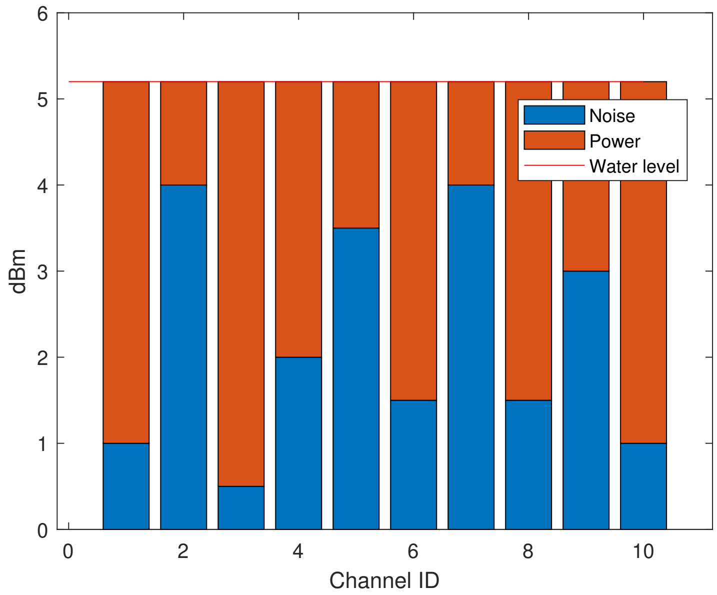


Figure 6.3: Power allocation in Water Filling

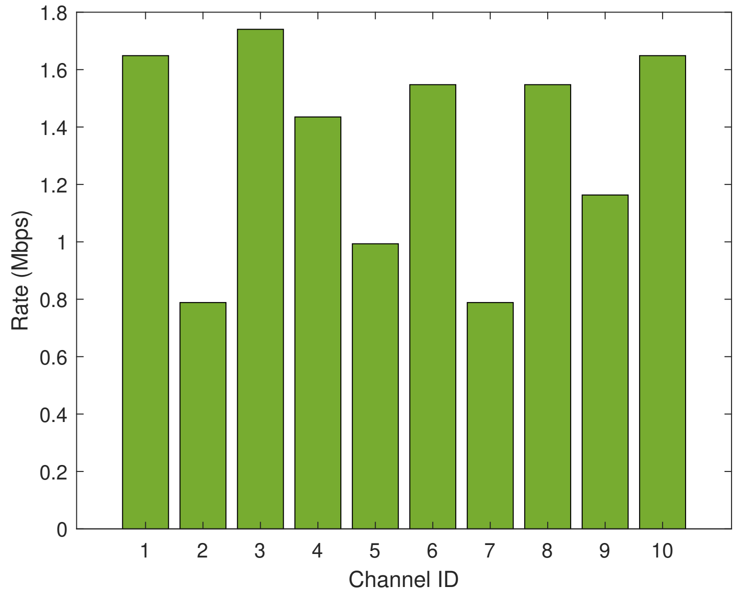


Figure 6.4: Channel rate in Water Filling

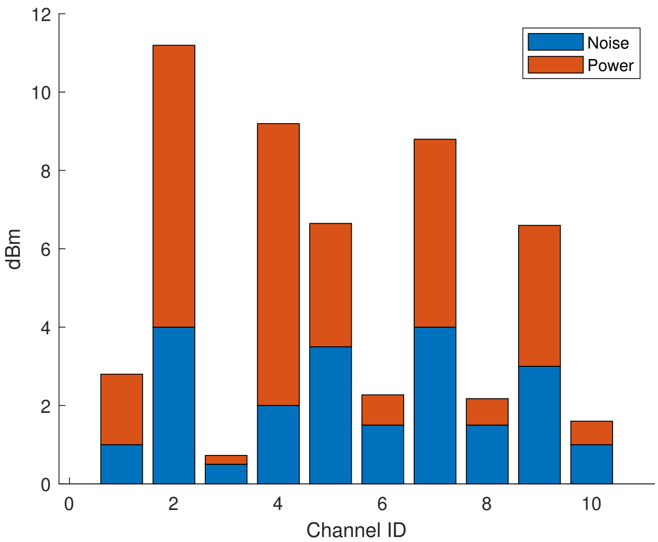


Figure 6.5: Power allocation respect to noise in fair approach

6.2.2 Allocation with a fair approach

To cope with the *unfairness* of previous Water Filling algorithm, we also implement a different technique proposed in [131].

This approach, which guarantees fairness among the sub-carriers, can be considered as a min max optimization problem [132]. The goal is to maintain a constant received Signal-to-Noise Ratio (SNR) for all the users. The allocated power P_k on the kth sub-carrier depends on the channel gain h_k in such a way that $P_k h_k$ is a constant value. The power vector P is obtained by solving the following system of linear equations

$$\begin{cases} P_0 h_0 = P_1 h_1 \\ P_0 h_0 = P_2 h_2 \\ \quad\vdots \\ P_0 h_0 = P_{K-1} h_{K-1} \end{cases} \quad \text{subject to } \sum_k P_k = P \tag{6.6}$$

where K is the number of users and P is the total available power of the transmitter.

Concretely, the greater the noise, the greater the power transmitted on that channel, as shown in Fig. 6.5.

From another point of view, we can say that the more the channel has a high gain, the less power will be allocated to it, and vice versa (Fig. 6.6).

In this way, all users will receive the same power and, therefore, they will achieve the same data rate.

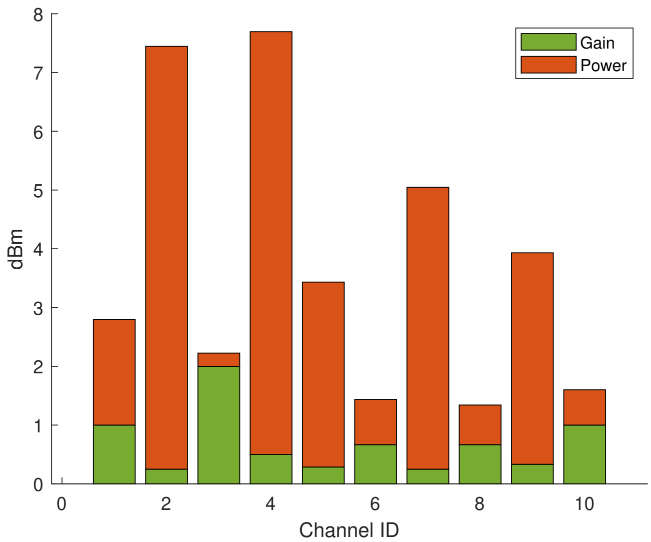


Figure 6.6: Power allocation respect to channel gain in fair approach

6.3 Semi Orthogonal user selection

In this section, we explain how a subset of the K users is selected. Only after this step, the power allocation will be applied to maximize the system capacity in (6.4).

We denote the set of unselected users with T_i at iteration i and the set S as the dynamic group of selected users who can connect to the gNB. At the beginning, T_1 is initialized to contain all K users while S is empty. At each iteration i, and for each user $k \in T_i$, the algorithm compute $\mathbf{g}_k$, the orthogonal component of $\mathbf{h}_k$ to the subspace spanned by already selected users $\{\mathbf{g}_{(1)}, ..., \mathbf{g}_{(i-1)}\}$:

$$\mathbf{g}_k = \mathbf{h}_k \left(\mathbf{I} - \sum_{j=1}^{i-1} \frac{\mathbf{g}^*_{(j)} \mathbf{g}_{(j)}}{||\mathbf{g}_{(j)}||^2} \right), \tag{6.7}$$

when for the first iteration, $\mathbf{g}_k = \mathbf{h}_k$. Afterward, the algorithm chooses the user with the best orthogonal channel component as

$$\pi(i) = \arg\max_{k \in T_i} \|\mathbf{g}_k\| \,. \tag{6.8}$$

At this step, the algorithm checks if by adding this new user to the list the sum capacity of the system (6.4) will increase or not. In case the capacity is increased, then the selected user is added to S, and $\mathbf{g}_{(i)} = \mathbf{g}_{\pi(i)}$. If $|S| < I$ then a new list for the next iteration is evaluated by considering the following orthogonality constraint

$$T_{i+1} = \left\{ k \in T_i, k \neq \pi(i) | \frac{|\mathbf{h}_k \mathbf{g}^*_{(i)}|}{||\mathbf{h}_k|| \cdot ||\mathbf{g}_{(i)}||} \leq \beta \right\}, \tag{6.9}$$

where β is the threshold for semi-orthogonality, which assumes a value between 0, i.e. perfect orthogonality, and 1. If the constraint is satisfied for a user, then it is added to T_{i+1} for the next iteration; otherwise, it is discarded. The pseudo-code of the users selection scheme is reported in Algorithm 1.

Algorithm 1 The algorithm for user group construction

Initialize $T_1 = \{1, ..., K\}$, $S = \varnothing$, $i = 1$.
while $|S| \leq I$ and $T_i \neq \varnothing$ **do**
    if $i = 1$ **then**
        $\mathbf{g}_k = \mathbf{h}_k$, $\forall k \in T_1$
    else
        Compute $\mathbf{g}_k$ according to (6.7), $\forall k \in T_i$
    end if
    Select ith user according to

$$\pi(i) = \arg\max_{k \in T_i} ||\mathbf{g}_k|| \tag{6.10}$$

    Calculate $\Delta R = R(S \cup \pi(i)) - R(S)$.
    if $\Delta R > 0$ **then**
        $S \leftarrow S \cup \{\pi(i)\}$
        $\mathbf{g}_{(i)} = \mathbf{g}_{\pi(i)}$
        Update T_{i+1} according to (6.9)
        $i \leftarrow i + 1$
    else
        Break.
    end if
end while

6.4 Framework

In the development of the work, there were two main stages.

Initially we followed a purely theoretical approach, in which all parameters were set arbitrarily or randomly, respecting only theoretical mathematical formulas and models. So in this first case we work in an abstract, ideal environment, without considering real factors and issues.

Subsequently, we submitted to the algorithm more realistic data, obtained exploiting some existing simulators, in order to verify the behavior. In this way, we are able to consider a lot of actual vehicular scenario parameters such as attenuation, signal reflection and refraction, obstacles and so on.

6.4.1 Theoretical approach

The whole structure behind this part of the work, i.e. the construction of geometric scenario and the computation of the channel matrix, is carried out in Matlab. We provide in input the parameters as in Tab. 6.2.

Table 6.2: Theoretical simulation parameters

Parameter	**Value**
Number of antennas	16
Cell side	200 m
Antenna gain	10
Attenuation coefficient (α)	2
Number of users	$4 \div 36$
Orthogonality constraint (β)	$0 \div 2$

Scenario construction

Once the number of users and BS antennas have been set, we proceed with their positioning inside the cell. First of all, we have to establish the side of the cell. For simplicity, it is assumed square and the gNB is collocated exactly at the center. The positions of the users are then randomly generated within the boundaries of the cell. Fig. 6.7 shows an example of scenario with 80 users and a cell side of 200 m: the blue circles represent the users while the red square in the center is the BS.

The distance vector $\mathbf{d}$ is filled with the Euclidean distances between the gNB and each user positions:

$$d_k = \sqrt{(x_{BS} - x_k)^2 + (y_{BS} - y_k)^2} \tag{6.11}$$

where x_{BS} and y_{BS} represent the Cartesian coordinates of the BS, while x_k and y_k are the coordinates of user k.

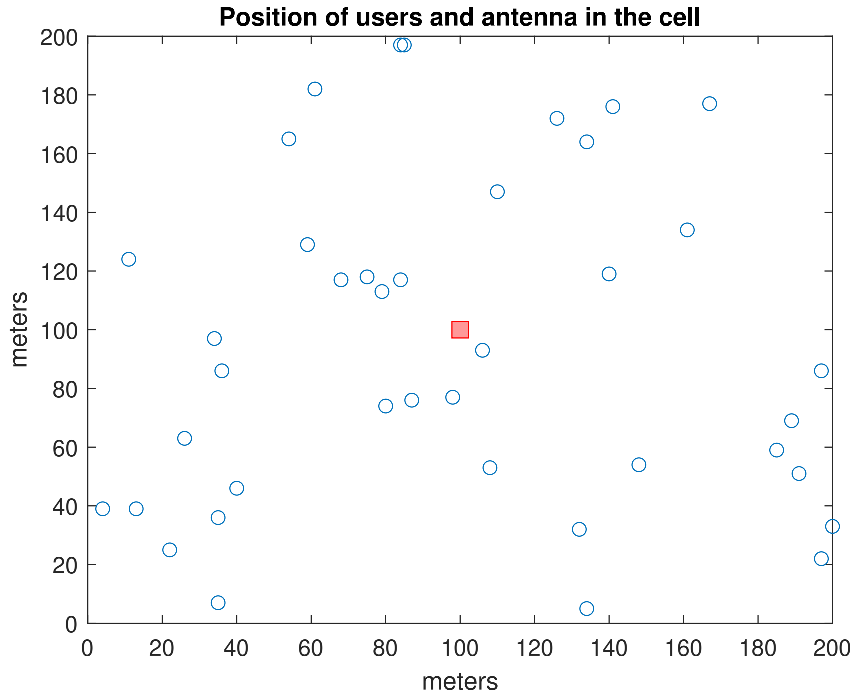


Figure 6.7: An example of generated random scenario

Channel computation

Based on the geometrical settings, we initially created a Rayleigh fading channel $\mathbf{h_0}(k)$, with i.i.d. (independent and identically distributed) zero mean complex Gaussian entities with unit variance.

Then we integrate the starting model of channel response with other important parameters [133], [134]

$$|\mathbf{h}(k)|^2 = G \cdot |\mathbf{d_k}|^{-\alpha} \cdot |\mathbf{h_0}(k)|^2 \tag{6.12}$$

where G represents the constant antenna gain factor of the gNB, $\mathbf{d_k}$ is the distance vector calculated above and α is the path-loss exponent.

Coexistence evaluation

For simplicity, we assume that each user can implement only one of these two technologies: WiFi or cellular.

To evaluate the coexistence aspect, we assign a weight λ to both technologies. This coefficient is multiplied by the channel gain before the user choice, so the formula (6.10) becomes:

$$\pi(i) = \arg\max_{k \in T_i} \lambda(k) ||\mathbf{g}(k)||^2 \tag{6.13}$$

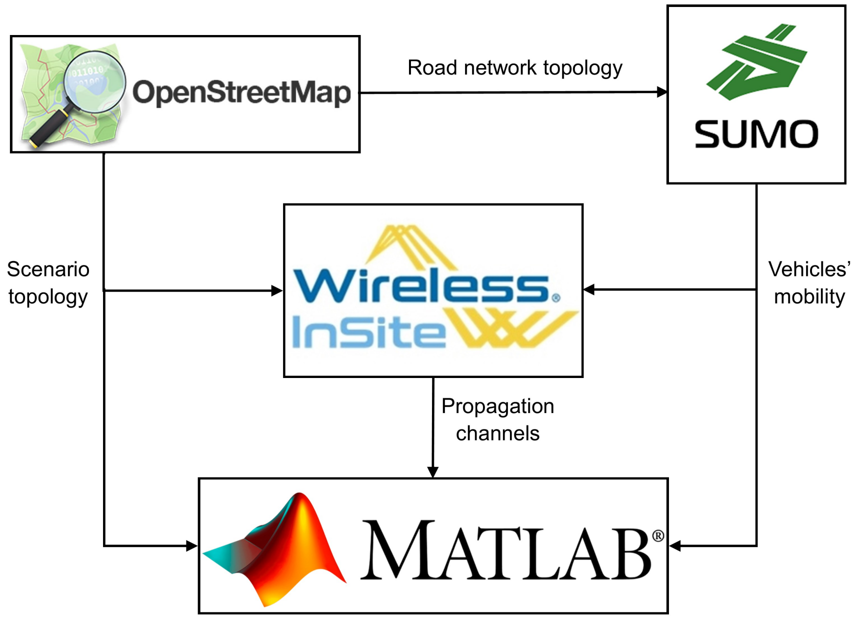


Figure 6.8: Realistic approach simulation methodologies

In particular, all cellular users have $\lambda_C = 1$, while WiFi devices have a variable λ_W. In general, this value can be assigned according to various criteria, such as larger λ to favor one technology over another or to ensure association to a group of users.

6.4.2 Realistic approach

Starting from the framework provided by [135], we developed a simulator for an mmWave I2V scenario that takes into account realistic mobility and maps, as shown in Figure 6.8. The modeling of the vehicle traffic over real road networks is here obtained by using a combination of OpenStreetMap [35] and SUMO software (Sec. 6.5.3), whose setting parameters are reported in Tab. 6.3. SUMO provides the vehicles states (position, velocity and heading) in each time instant. The output from SUMO is then processed by Wireless InSite (see Sec. 6.5.2), to characterize the channel impulse response between the vehicles and gNB.

Figure 6.9 shows the simulation scenario, taken from OpenStreetMap map (Fig. 6.10). Each block corresponds to an obstacle (i.e. walls, trees, and buildings) whose density and electromagnetic properties are defined accordingly. The gNB (green cube) is placed at the center of the scenario, while the vehicles (red cubes) follow the predefined SUMO trajectories Wireless Insite provides the channels coefficients, corresponding AoAs, and AoDs in (6.1). Data are collected and processed by Matlab, where the resources allocation algorithm is implemented. The main simulation parameters of the communication are reported in Tab 6.4.

Figure 6.9: Wireless Insite scenario

Table 6.3: SUMO parameters.

Parameter	**Value**
Time step	100 ms
Time duration	20 s
Number of vehicles	50
Vehicles flow	1.5 veh/s
Maximum speed	50 km/h

Table 6.4: I2V communication parameters.

Parameter	**Value**
σ_n^2	0 dB
f_c	28 GHz
Bandwidth B	100 MHz
Antennas height (w.r.t. rooftop)	0.15 m
Antenna array dimension	8x2

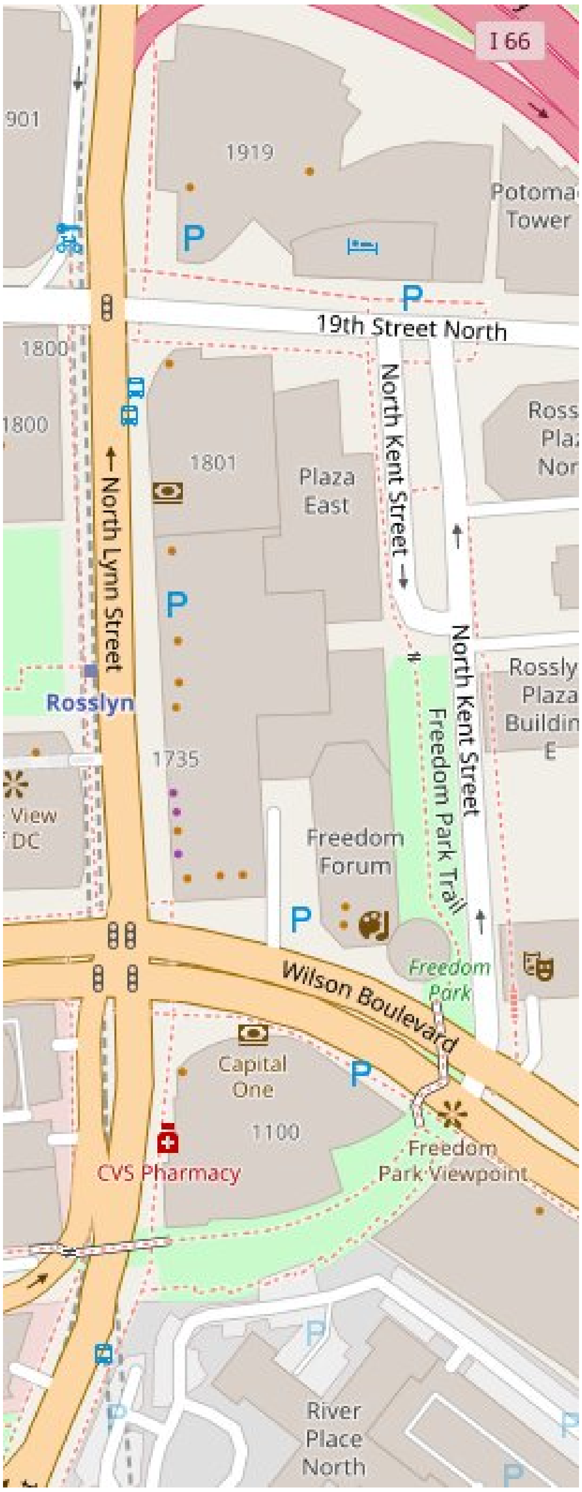


Figure 6.10: Exact real scenario area from OpenStreetMap

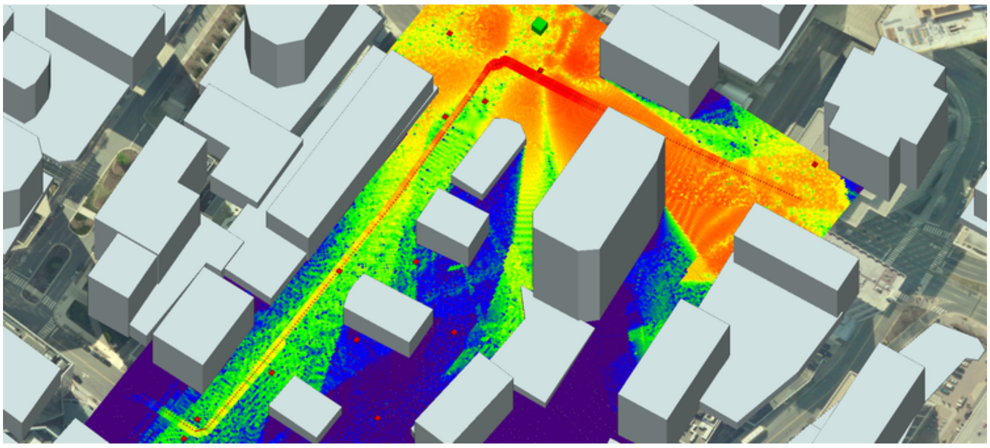


Figure 6.11: Example of WirelessInSite results

6.5 Tools and software

6.5.1 Matlab

MATLAB [136] (an abbreviation of “MATrix LABoratory”) is a numerical programming and computing platform developed by MathWorks. It allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages. As of 2020, it has more than 4 million users worldwide, from various backgrounds of engineering, science, and economics [137]. MATLAB is used in a lot of industries and universities due to its numerous tools to support the most diverse fields of study and runs on different operating systems.

All the plots and results presented in Sec. 7 are obtained from MATLAB simulations.

6.5.2 Wireless InSite

Wireless InSite is a suite of ray-tracing models and high-fidelity electro-magnetic (EM) solvers for the analysis of radio wave propagation and wireless communication systems. The RF propagation software provides efficient and accurate predictions of EM propagation and communication channel characteristics in complex urban, indoor, rural, and mixed path environments [37]. The software gives the possibility to create detailed scenarios, thanks to an equipped library for every feature present inside a communication link. The environment can be built step by step, by choosing objects, cities, and terrains to use. They can be imported from outside programs, to create a precise geometry, or defined inside the software. Wireless InSite is able to implement all the communication features such as: transmitters, receivers, antennas, communication systems, propagation models, and parameter uncertainty.

Several parameters can be analyzed during the simulations: EM components (i.e. received power, complex impulse response, doppler, direction of arrival etc.), information on the communication system (i.e. SNR, SINR, BER, capacity), static and

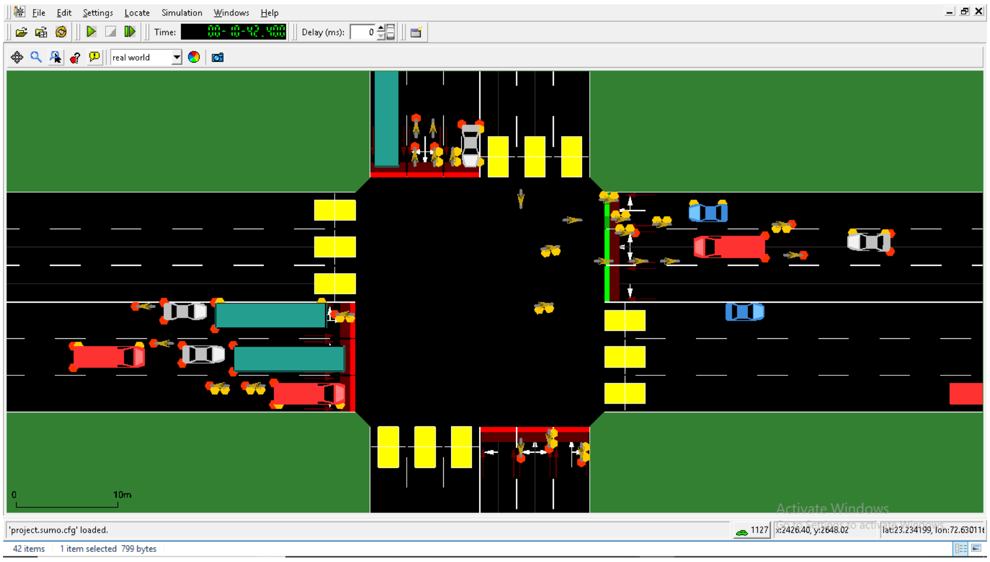


Figure 6.12: Example of SUMO interface

time-varying elements of the link. All the outputs can be exported from Wireless InSite and analyzed with other software such as MATLAB, as in our case. In particular, for our work, the output parameters mainly considered are: the received power, the complex impulse response of the channel (CIR), the Azimuth and Elevation angles of arrival and departure, the noise present in the channel, and the whole gain, which takes into account all the power degradation causes, as well as the antenna gain and all others possible reasons of signal degradation.

6.5.3 SUMO

Simulation of Urban MObility (SUMO) is an open source, highly portable, microscopic and continuous traffic simulation package designed to handle large networks. It allows for intermodal simulation and comes with a large set of tools for scenario creation. It was started to be implemented in 2001, with a first open source release in 2002.

SUMO performs purely microscopic traffic simulations: it means that each vehicle and its dynamics are modeled individually. Contrary, in a macroscopic case average dynamics like traffic density are simulated. The main benefit of macroscopic models is its fast execution speed, but the detailed simulation of microscopic ones is more accurate. For this reason, in SUMO each vehicle is defined at least by an identifier (name), the departure time, and the vehicle's route through the network. In addition, a more detailed description can be added and other properties can be specified, such as the lane to use, the velocity, or the position. Each vehicle can also be associated to a type which describes the its physical properties and the variables of the used movement model. Networks consist of nodes and unidirectional edges representing street, waterways, tracks, bike lanes and walkways. Each edge has a geometry described by a series of segments and consists of one or more parallel lanes. It is also possible to model other properties, such as width, speed limit and access permissions [36].

Figure 6.13: Example of OpenStreetMap interface

The simulation is time-discrete with a default step length of 1 second. SUMO allows to generate various outputs for each simulation run. Besides conventional traffic measures, it was extended by models which allow to evaluate noise and pollutant emission and fuel consumption model.

The most popular application for the SUMO suite is modeling traffic within research on V2X communication, as in our case. Other areas in which it is used are navigation systems, traffic lights algorithms and surveillance systems [138]. Further information and documentation can be obtained on the project's web site [139].

6.5.4 OpenStreetMap

OpenStreetMap (OSM) [35] is a collaborative project aimed at creating free content world maps. The project has the goal of a worldwide collection of geographic data, with the main purpose of creating maps and cartographies. OSM was founded in July 2004 by Steve Coast. The fundamental characteristic of the geographic data present in OSM is that they are distributed with a free license: that is, it is possible to use them freely for any purpose, including commercial, with the sole constraint of citing the source and using the same license for any works derived from OSM data. Everyone can contribute by enriching or correcting the data. In fact, it is implemented through the engagement of participants in a mode similar to software development in Open Source projects. The information is collected by many participants, collated on a central database, and distributed in multiple digital formats through the World Wide Web. This type of information was termed 'Volunteered Geographical Information'. Maps are created using data recorded by portable GPS devices, aerial photographs and other free sources.

An analysis of the quality of the OSM dataset is discussed in [140], evaluating its positional and attribute accuracy, completeness, and consistency.

Chapter 7

Numerical results

Multiple simulations were conducted during the thesis work to analyze the behavior and the contributions of the different described theory concepts and implemented techniques. To prove the consistency of the results, the experiments were done through variable and different scenarios, following a purely theoretical approach or by using a combinations of simulator as illustrated in Sec. 6.4.2. In both cases, we have chosen to place at most about 30 devices (vehicles, pedestrian, infrastructure) in the cell: it seemed to us a reasonable and realistic number considering that it is a simple road intersection.

This chapter will depict the main numerical results obtained from the simulations. We will illustrate the output achieved first in the simulated vehicular scenario, and then in the theoretical one. In both cases, we will evaluate the number of served users, the overall data rate and the per-user data rate. The most interesting result of this thesis work is described in the Sec. 7.2, where we will make a comparison and some considerations about the behavior of the proposed approach, underlining its limits in a real vehicular scenario. In the next section, several graphs obtained following a fair approach are given and commented. Finally, we will describe some results of simulations regarding the coexistence issue.

7.1 User selection and power allocation

In this section we analyze the sum rate capacity and multiple access potential of ZFBF over the practical I2V scenario at mmWave, and compare it to the abstract Rayleigh fading channel where a lot of multipath components exist between transmitters and receivers. In the former scenario, we process data from Wireless Insite and evaluate the channel vector for all the users according to (6.1), while in the Rayleigh fading, the channel matrix elements are derived from Complex Gaussian distribution with zero mean and unitary variance. Then, we apply the scheme explained in Sec. 6.3 to construct the user group at each time instance and associate power to them according to (5.6), assuming the power budget of 20 dB. In these simulations, water filling approach is exploited and we aim to maximize the sum data rate. Therefore, our selection algorithm add a new user to the eligible group if and only if the new overall rate is higher than the one without this new user.

In all of the following graphs, the parameter β is located on the x-axis, since we want to observe the behavior of the algorithm based on various orthogonality constraint. In particular, the values we are most interested in analyzing are the number of served users, overall and per user data rate. We repeated the simulations with multiple input values, in particular by varying the number of users in the cell and the number of antennas of the BS.

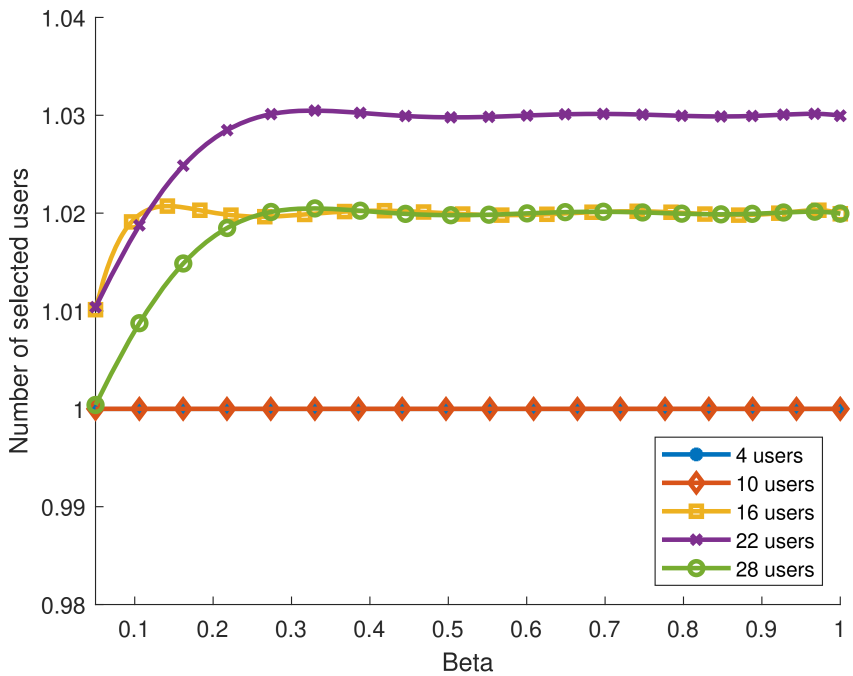


Figure 7.1: Number of selected users in a vehicular scenario with I=16 and a water filling approach

7.1.1 Realistic vehicular scenario

Figure 7.1 depicts average number of selected users with respect to β. We can observe that following the semi-orthogonal user selection, and applying ZFBF accompanied by water-filling, the algorithm barely selects two users for simultaneous transmission.

Moreover, Fig. 7.2 shows the total system rate according to (6.4) based on the I2V scenario at mmWave. In this figure, it can be observed that by increasing the number of users per cell, the algorithm has a higher opportunity to find users with better channel conditions that result in higher bit rate.

Obviously, since only one user is selected, all the available power is destined to it and therefore the overall rate corresponds to the per-user rate as can be seen in Fig. 7.3. These two figures also demonstrate the advantages of multiuser diversity (Section 5.8). In fact, existing more users in a cell, increases the possibility to have a user with the better channel condition. Therefore, gNB will allocate more power to that user and increase the corresponding bit rate.

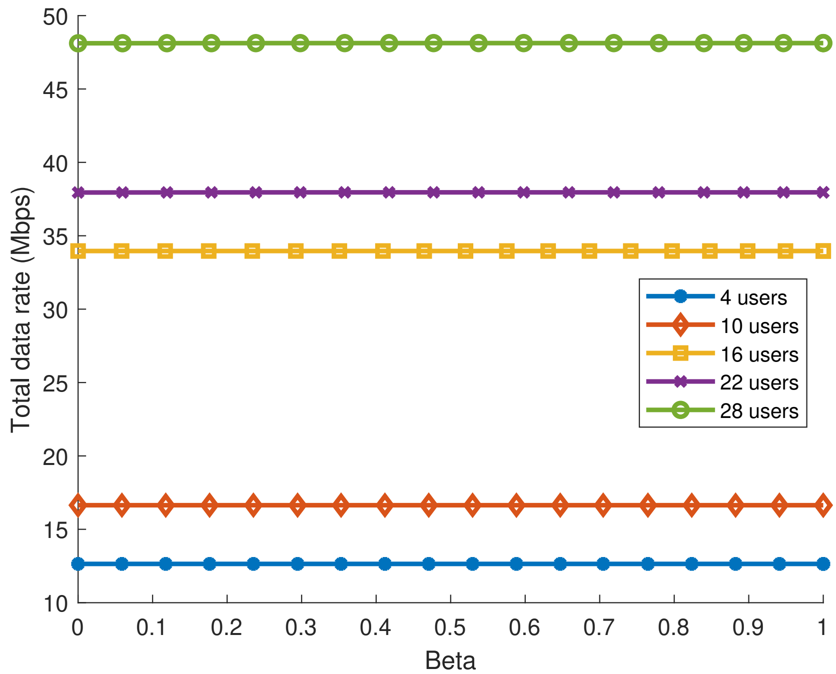


Figure 7.2: Overall data rate in a vehicular scenario with I=16 and a water filling approach

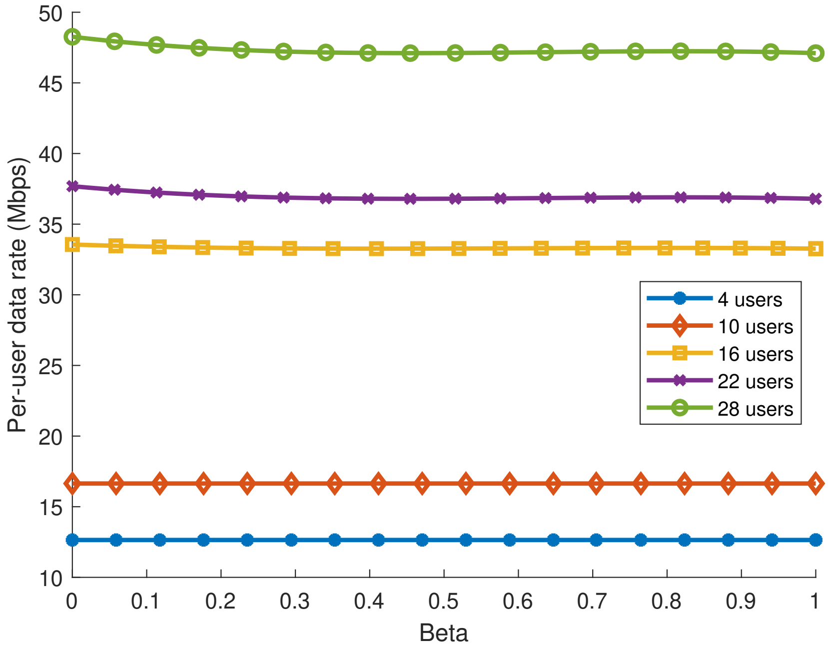


Figure 7.3: Average per-user data rate in a vehicular scenario with I=16 and a water filling approach

7.1.2 Theoretical scenario

Fig. 7.4 shows the amount of selected users in a scenario where Rayleigh fading channel is used. Unlike the previous case, the number of served users can reach the upper limit imposed by the number of elements of the antenna array.

Looking at Fig. 7.5, in particular the top three lines, we can appreciate the effect of the *multiuser diversity*: the higher the number of users, the better the algorithm chooses the best channels and therefore manages to allocate more overall power, which corresponds to a higher total rate. Multiple access also helps to increase the overall data rate. It can be seen that with higher β you can select more users and achieve higher data rates.

In Fig. 7.6, we can observe that the average user data rate decrease with higher values. This is because with higher β the algorithm select more users and therefore the power allocated to each user is reduced. We know that data rate for each user has a direct relation with power. Therefore, the data rate is reduced as well.

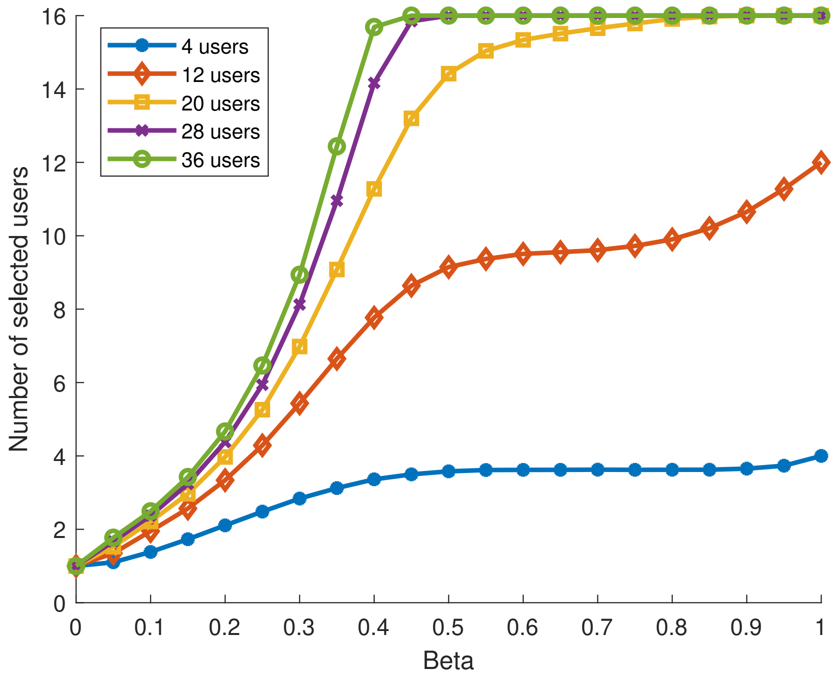


Figure 7.4: Number of selected users in a theoretical scenario with I=16 and a water filling approach

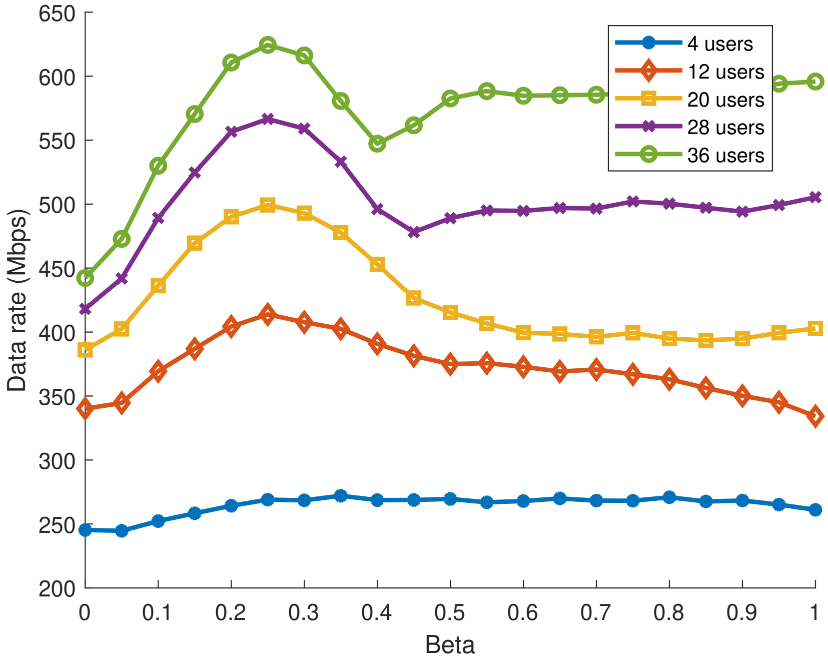


Figure 7.5: Average overall data rate in a theoretical scenario with I=16 and a water filling approach

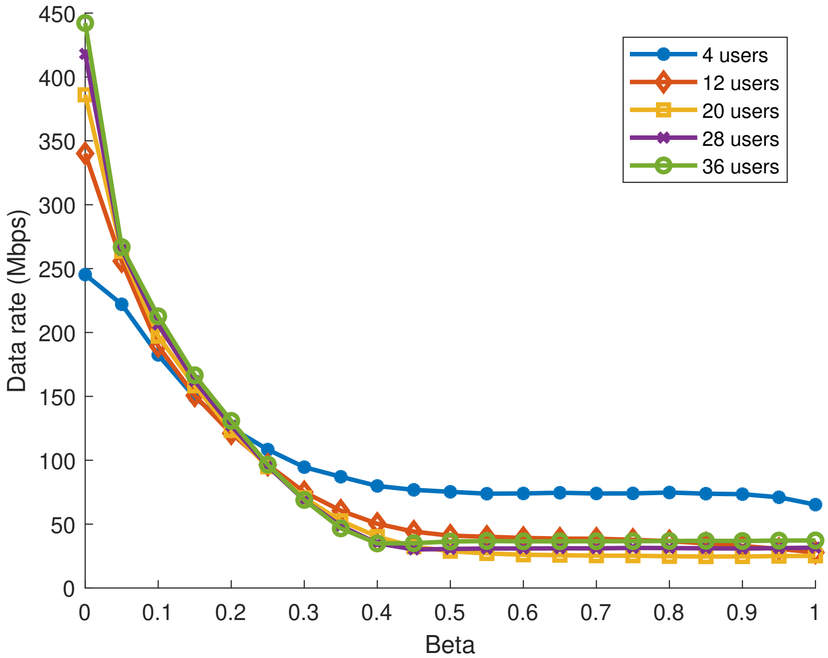


Figure 7.6: Average per-user data rate in a theoretical scenario with I=16 and a water filling approach

7.2 Comparison result

By comparing Figs. 7.1 with 7.4 we clearly observe that the algorithm succeeds to multiplex many users when the channel is Rayleigh fading, while in a real I2V scenario at mmWave, it selects at most two users. This is because the environment's geometry imposes significant constraints on the propagation pattern in real scenarios, as discussed in [141], where they use AOA/AODs pdf to define a probabilistic codebook.

Figure 7.7 illustrates the distribution of the AOD in our simulated scenario. We can observe that majority of the users are located in pointing angle of 80 and −80 degree with respect to the BS and correspond to the streets that provide LOS condition between users and BS. The other reason is the high path loss in mmWave. In I2V scenario, the channel attenuation is high that the algorithm needs to allocate the power only to one user rather than sharing among many of them.

Our results reveal that in a real case scenario, the system sum rate achieved by ZFBF does not benefit from multiplexing at mmWave, but only from multi-user diversity [142].

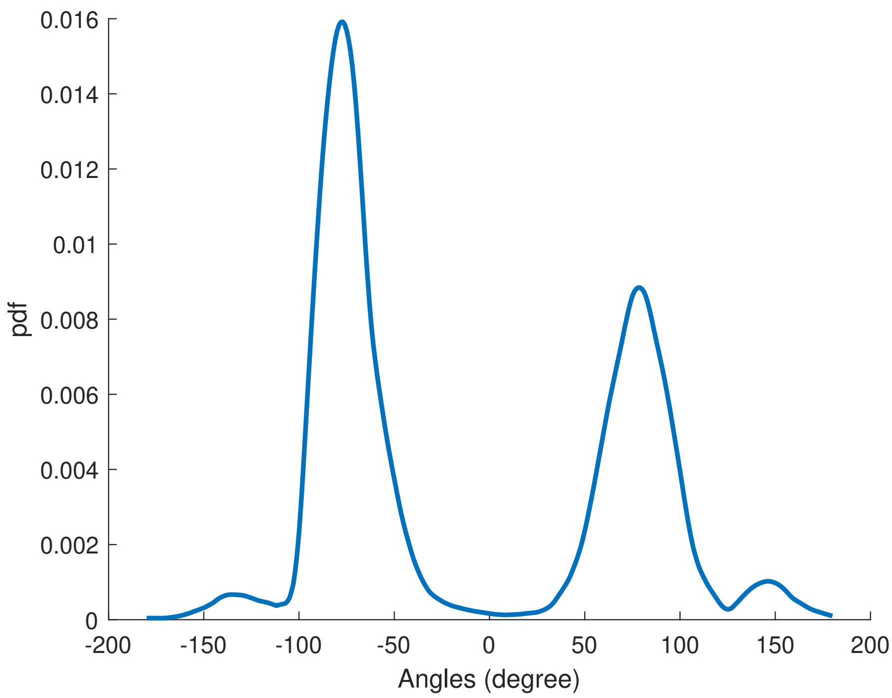


Figure 7.7: Azimuth of departure pdf with respect to angles in I2V scenarios

7.3 Fair approach algorithm

Contrary to the previous case, in which the water filling algorithm aims to achieve the maximum overall rate, the goal of this simulation is to maximize the number of served users.

Both in Fig. 7.8 and in Fig. 7.9, it can be observed that when the orthogonality bond fails the number of selected users reaches the number of antennas.

Figure 7.10 demonstrates that with higher Beta, more users are selected and therefore, average data rate is reduced, because the available power is split among the growing users.

The same observation can be made with an increasing number of antennas and a fixed amount of receivers in the cell, as shown in Fig. 7.11. If we have few antennas, the total transmitting power is concentrated to the few users served. On the other hand, in case of numerous transmitters the available power is shared among a higher number of channels.

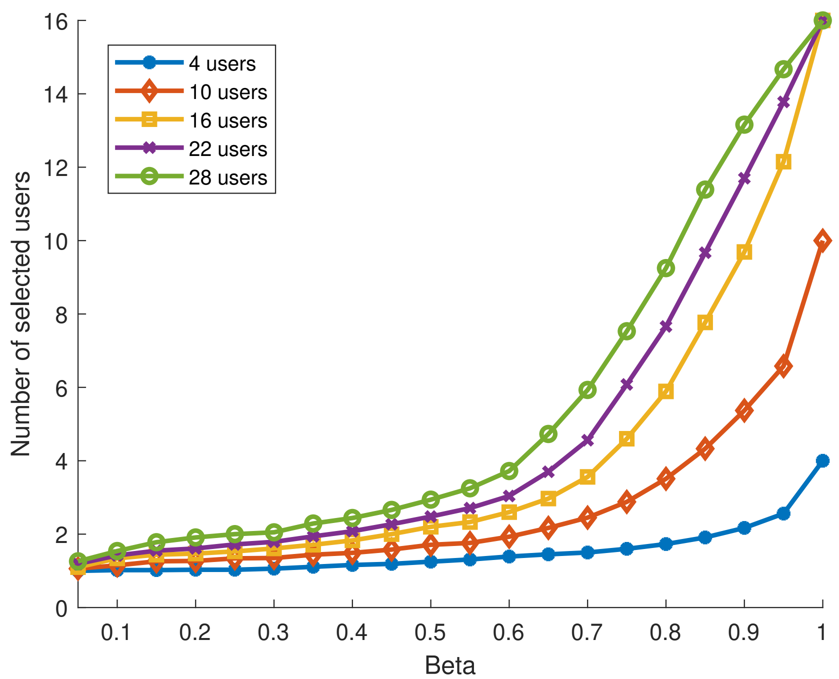


Figure 7.8: Number of selected users in a vehicular scenario with I=16 and a fair approach

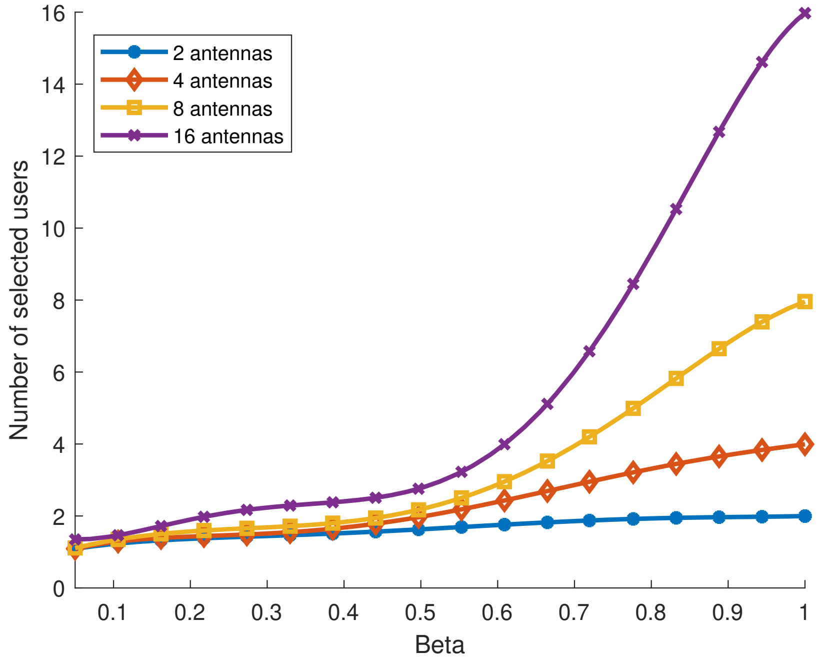


Figure 7.9: Number of selected users in a vehicular scenario with K=28 and a fair approach

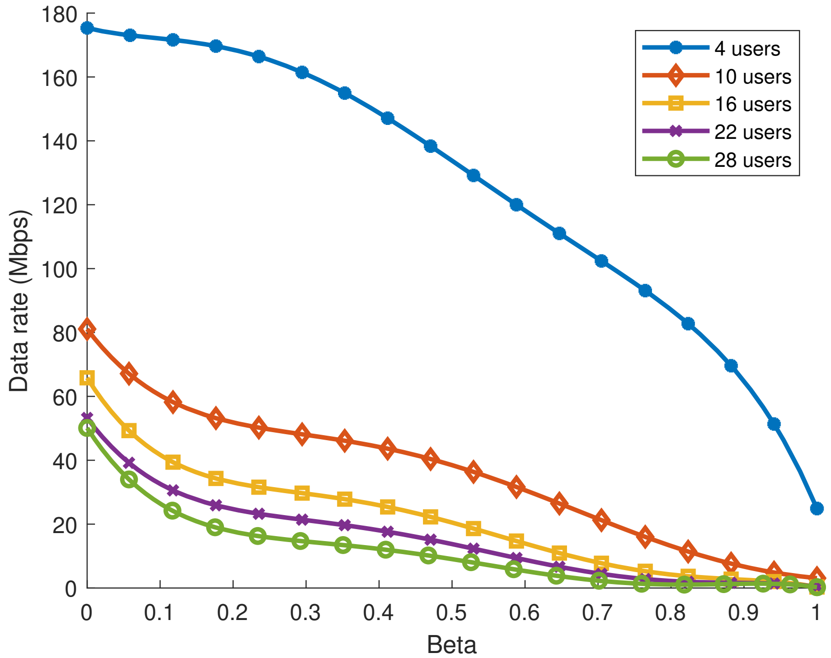


Figure 7.10: Average per-user data rate in a vehicular scenario with I=16 and a fair approach

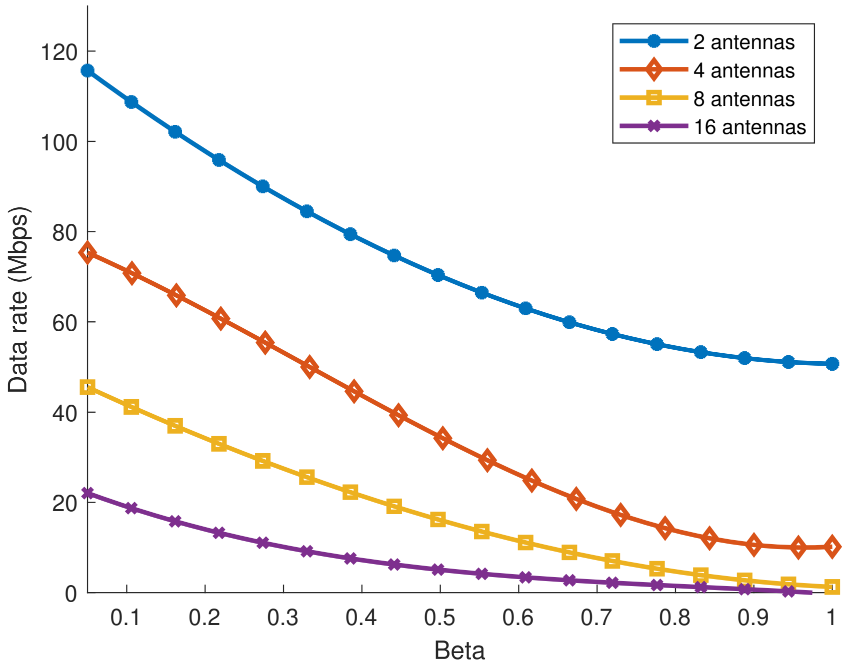


Figure 7.11: Average per-user data rate in a vehicular scenario with K=28 and a fair approach

7.4 Coexistence

In this section the results related to the coexistence issue are presented. This simulation has been performed only when the channel is modeled as Rayleigh fading since, as we have seen above, in I2V at mmWave the algorithm could not select more than one user. For this reason, the problem of the simultaneous presence of connected users of different technologies does not exist and so the coexistence issue is changed to scheduling users in time domain only.

In the previous section we have demonstrated that in Rayleigh fading channel model, many users can be spatially multiplexed. In Figure 7.12, we present the average number of selected Wi-Fi and cellular users for different values of Wi-Fi weight factors λ_W. In this figure we set the β equal to 0.3 to avoid interference among selected users.

As one might intuitively expect, the number of selected Wi-Fi and cellular users increases and decreases with λ_W, respectively. Similarly, larger number of antennas under the same value of λ_W leads to higher number of served users, since more antennas generate more access opportunities.

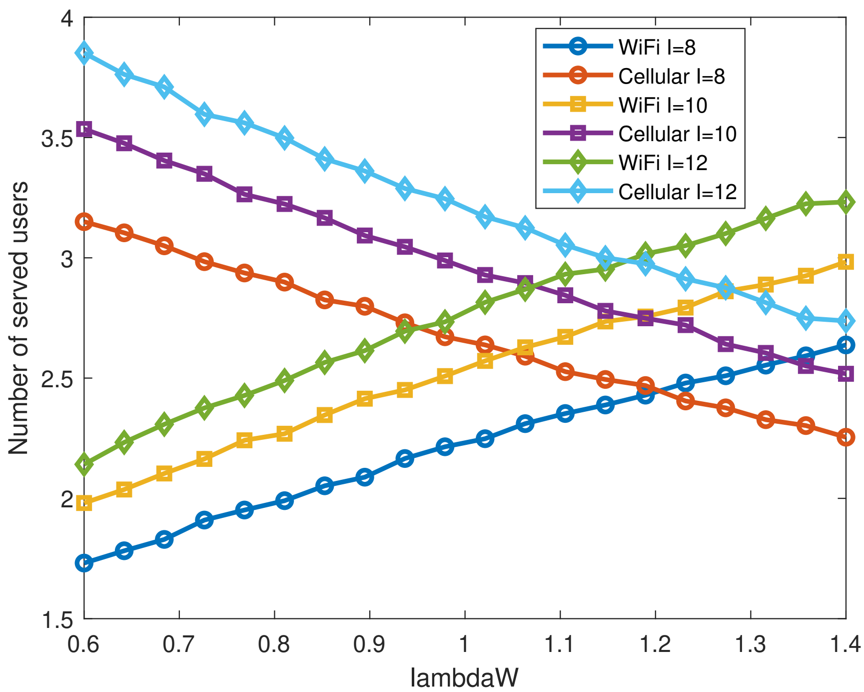


Figure 7.12: Average number of served WiFi and cellular users

Chapter 8

Conclusions and future works

In this thesis, we applied different existing techniques to a practical I2V scenario at mmWave, in order to evaluate their impact on a vehicular system performance. In particular, we exploited antenna arrays to implement ZFBF as a spatial multiplexing, a semi-orthogonal algorithm to construct a group of eligible users avoiding interference, and water-filling algorithm to allocate suitable power to the users.

We observed that due to geometry limitation and high attenuation at mmWave, ZFBF along with sub optimal semi-orthogonal user selection are not able to provide multiplexing gain. We showed how the algorithm perform differently with respect to the scenario when the channel is Rayleigh fading. So, while in [83] is highlighted the optimality of ZFBF in the case of the abstract Complex Gaussian channel, our results reveal that in a real case scenario, the system sum rate achieved by ZFBF does not benefit from multiplexing at mmWave, but only from multi-user diversity.

So the main conclusion of this work is that zero-forcing beamforming performance can be highly affected with respect to the geometry of the environment, and it can not multiplex many users, which is the main idea of ZFBF at the end.

In addition, we have experimented our selection algorithm with a different approach to try to guarantee a greater degree of fairness to users. On the one hand, this technique allows to serve a greater number of users simultaneously than the implementation seen above. On the other hand, however, both the per-user data rate and the overall data rate are penalized due to the high number of associated users.

Finally, we investigated the problem of coexistence between different technologies in the same cell, introducing a weight coefficient in order to control the selection process of the users served. About this topic, we can conclude that our scheduling algorithm fails with regard to a coexistence application based on spatial multiplexing on a vehicular mmWave scenario, since it is almost never able to serve more than one user at a time. On the other hand, however, this approach could be exploited to develop a coexistence scheme based on a time domain multiple access mechanism.

Thanks to the analysis carried out in this work and insightful results obtained by the simulations, new possible directions of future research have opened up:

- The first main result can be confirmed by the simulation in other urban scenarios, characterized by different geometries and physical attributes;
- The experiments can be made with different antenna patterns, to understand the effects of more complex directivity functions;
- The aspects of fairness and coexistence deserve to be more explored, in order to further improve the implementation, the performance and the quality of the service offered to users.

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