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VÍCTOR MANUEL GARCÍA MARTÍNEZ

# WIFI MOBILE ACCESS WITH SOFTWARE DEFINED MULTI-CONNECTIVITY

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**VÍCTOR MANUEL GARCÍA MARTÍNEZ**

# WIFI MOBILE ACCESS WITH SOFTWARE DEFINED MULTI-CONECTIVITY

**Master's Dissertation presented to the Postgraduate Program in Electrical Engineering of the Technological Center of the Federal University of Espírito Santo, as a partial requirement to obtain the Master's Degree in Electrical Engineering.**
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VÍCTOR MANUEL GARCÍA MARTÍNEZ

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*to my parents*
*for their endless loves, support and encouragement*

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*"The human spirit must prevail over technology."*
*Albert Einstein*

# Abstract

The emergence of new applications have made wireless networks evolve towards their fifth generation, a novel network paradigm that aims at fulfilling a vast range of requirements set by upcoming services and applications. The use of software-defined networks and virtualization allow creating a service-oriented network, integrated with several radio technologies in its access network. WiFi is one of such technologies and, due to its current ubiquity use, it presents itself as an interesting option due to its popularity, ability to offload mobile data and good performance in indoor environments. However, WiFi suffers from crucial issues like spectrum interference, connectivity loss, long delay for client association and high latency handover, all of those with direct negative impact on communication reliability. This dissertation propose a SDN architecture to ensure enhanced communication reliability over WiFi wireless networks based on a user access multi-connectivity scheme. This work focuses on splitting the WiFi architecture functionalities in a more efficient way, designed to provide seamless mobility through multi-connectivity, introducing the concept of mobile Access Point in contrast to the traditional operation mode where the client station is the only mobile entity. The proposed architecture is validated through its implementation in real use cases for future 5G verticals, using the concepts of cloud robotics as a critical application to be supported. Results are shown and discussed, demonstrating the feasibility of employing such novel architecture to achieve high reliability service requirements. The results also demonstrate how new softwarization and virtualization technologies can be used in existing wireless architectures to overcome some deficiencies to achieve a successful integration of these wireless technologies in the new 5G network paradigm.

**Keywords**: Wireless Networks, 5G, WiFi, SDN, Handover, Reliability

# Resumo

O surgimento de novas aplicações fez com que as redes sem fio evoluíssem para sua quinta geração (5G), um novo paradigma de rede que tenta suportar uma ampla variedade de serviços com os mais variados requisitos. O uso das tecnologias de Redes Definidas por Software e Virtualização permite criar uma rede orientada a serviços, que também tenta integrar várias tecnologias de rádio em sua rede de acesso. Entre eles, estão as redes WiFi, uma opção interessante devido ao seu uso quase onipresente nos dias de hoje, graças a fatos como sua popularidade, capacidade de descarregar dados móveis e bom desempenho em ambientes internos. No entanto, o WiFi sofre de questões cruciais, como interferência espectral, perda de conectividade, longo atraso para associação de clientes e handover de alta latência que diminuem a confiabilidade das comunicações. Esta dissertação propõe uma arquitetura de SDN para garantir maior confiabilidade de comunicação através de redes sem fio WiFi implementadas através da multi-conectividade no acesso dos usuários. O trabalho se concentra em dividir as funcionalidades da arquitetura Wi-Fi de maneira mais eficiente, projetada para fornecer mobilidade contínua por meio da conectividade múltipla, introduzindo o conceito de ponto de acesso móvel em contraste com o modo de operação tradicional em que a estação cliente é a única entidade móvel. A arquitetura é validada através de sua implementação em casos de uso reais para 5G verticals, usando o conceito de robótica em nuvem como aplicativo crítico a ser suportado. Em ambos casos, os resultados são mostrados e discutidos, demonstrando a viabilidade de empregar o sistema para garantir os requisitos de serviços de alta confiabilidade e baixa latência. Os resultados também demonstram como o uso de novas tecnologias de softwarização e virtualização podem ser usadas em arquiteturas sem fio existentes para melhorar algumas de suas deficiências, a fim de alcançar uma integração bem-sucedida no novo paradigma de redes 5G.

**Palavras-chave**: Redes Sem Fio, 5G, WiFi, SDN, Handover, Confiabilidade

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# List of Acronyms

**3GPP** 3rd Generation Partnership Project.

**5G** Fifth Generation Networks.

**AP** Access Point.

**ARP** Address Request Protocol.

**BER** Bit Error Rate.

**BSS** Basic Service Set.

**C-RAN** Cloud Radio Acess Network.

**CA** Carrier Aggregation.

**CoMP** Coordinated Multi-Point Systems.

**COTS** Commercial off-the-shelf.

**CP** Cyclic Prefix.

**CSI** Channel State Information.

**DC** Dual Connectivity.

**eMBB** Extreme Mobile Broadband.

**fSTA** Fixed Stations.

**HetNet** Heterogeneous Networks.

**ICI** Inter Cell Interference.

**IMT** International Mobile Telecommunications.

**IoT** Internet of Things.

**ISI** Inter Symbol Interference.

**JT** Joint Transmissions.

**KPI** Key Performance Indicators.

**LoS** Line-Of-Sight.

**LTE** Long Term Evolution.

**LTE-A** Long Term Evolution Advanced.

**MAC** Medium Access Control Layer.

**mAP** Mobile Access Point.

**MBB** Make Before Brake.

**MBD** Make Before Degrade.

**MCS** Modulation and Coding Schemes.

**MDO** Mobile Data Offloading.

**MIMO** Multiple Input Multiple Output.

**MIT** Mobility Interruption Time.

**mMTC** Massive Machine-Type Communication.

**mmWave** Millimeter Wave Spectrum.

**mSTA** Mobile Client Stations.

**MU-MIMO** Mutiple User MIMO.

**Multi-RAT** Multiples Radio Access Technologies.

**NFV** Network Function Virtualization.

**NR** New Radio.

**OFDM** Orthogonal Frequency Division Multiplexing.

**PHY** Physical Layer.

**PRP** Parallel Redundancy Protocol.

**QoS** Quality of Services.

**R2I** Robot-to-Infrastructure Communication.

**R2R** Robot-to-Robot Communication.

**RAT** Radio Access Technologies.

**SDN** Software Defined Networks.

**SDWN** Software Defined Wireless Networks.

**SFC** Service Function Chains.

**SM** Spatial Multiplexing.

**SNR** Signal-to-Noise Ratio.

**SON** Self Organized Networks.

**STA** Station.

**STBC** Space-Time Block Code.

**TSN** Time Sensitive Networks.

**UDN** Ultra Dense Networks.

**URLLC** Ultra-Reliable Low-Latency Communication.

**V2X** Vehicle-to-Anything Communications.

**VANET** vehicular Ad-hoc Networks.

**VMAC** Virtual MAC Address.

**WiFi** Wireless Fidelity.

**WLAN** Wireless Local Area Networks.

# 1 Introduction

Wireless technologies have grown considerably in recent decades, so that the new generation of wireless networks being introduced today can be considered a new revolution in data communications. The development of wireless networks technologies has been going through different stages or generations that have sought to meet the users and applications requirements. The spread of applications that require large amounts of data and low latency transmissions, as well as the huge amount of wireless devices planned for the coming years, linked to the Internet of Things (IoT) paradigm, poses new challenges for wireless networks. In this sense, the Fifth-Generation (5G) mobile networks is likely to become a real technological revolution [1], allowing access to information and data sharing under the paradigm of anytime, anywhere, anyone and anything. The 5G technology can be used in a wide variety of applications, often referred to as 5G verticals, distributed in different economic and social sectors such as in the mobile broadband applications, autonomous control of vehicles, cloud robotic applications, real time control of energy networks and telemedicine applications.

## 1.1 Motivation

In order for the new 5G systems to provide high performance solutions, three general service cases have been established with specific requirements that this type of network has to meet, each of which presents several more specific use cases. The three main services are: i) Extreme Mobile Broadband (eMBB) to ensure data rates in several *Gbps* order on wireless interfaces to meet on-demand applications requirements; ii) Massive Machine-Type Communication (mMTC) that will provide wireless connectivity and scalability to accommodate a large number of devices; iii) Ultra-Reliable Low-Latency Communication (URLLC) to provide communication in mission critical applications scenarios [2]. Therefore, it is necessary to develop new technologies for wireless network in such a way that these new services are achieved through the incorporation of new bands in the radio-electric spectrum. It also requires the incorporation of different radio access technologies, new radio interfaces specifically developed for 5G systems and other technologies already established for wireless networks. Within these technologies, the IEEE 802.11 standards, popularly known as Wireless Fidelity (WiFi) technologies, pose themselves as interesting solutions, motivated with two main reasons, (i) the large deployment of this type of devices around the world and (ii) the rigorous work developing more efficient standards carried out by their community in recent years.

Within the three general services mentioned above, the URLLC service may be presented as the most challenging. This is fundamentally due to the fact that latency and reliability are opposite parameters, a fact that demands the implementation of efficient trade-off strategies. Within URLLC, 5G systems are expected to achieve end-to-end (E2E) communication delays of less than one millisecond, especially for real-time services [3]. To reduce latency in point-to-point transmission, a flexible physical layer offers advantages for applications with different requirements through solutions such as Software-Defined Radio (SDR) [4]. New signal processing mechanisms in the frame forming processes in the MAC layer and physical layer for wireless technologies will be required to reduce communication delays through knowledge of the communication channel status. The implementation of solutions based on Software Defined Networks (SDN) and Network Function Virtualization (NFV) will allow flexible network management and control to reduce delays during topology changes and network failure.

In addition to the low latency transmissions, URLLC aims to provide device-to-device communication services at any time without interruption during the mobility of client stations in wireless networks. For this, the use of SDN and virtualization can also actively contribute in handover processes that mobile users suffer in wireless networks [5], where the architecture should minimize the mobility interruption time, as well as guarantee the applications requirements all the time. High reliability communications solutions are expected to provide nearly 100 % of reliability with satisfactory service levels to meet the limitations of currently available commercial solutions. Currently, several diversity techniques are used as one of the main mechanisms to guarantee reliable communications, among which the following stand out: i) frequency diversity, ii) spatial diversity and (iii) interface diversity.

As a fundamental part of the new paradigm of wireless networks, the need for better synergy and flawless integration with the legacy systems (3G, LTE, WiFi) is one of the most important, supporting multiple Radio Access Technologies (RAT). Due to its ubiquitous use, WiFi is the first choice among wireless technologies available for indoor scenarios, and with a high deployment for Mobile Data Offloading (MDO) in the last years [6]. However, spectrum interference and service degradation can not be ignored when WiFi solutions are implemented, specially if such solutions are going to be applied in URLLC scenarios. There are also other phenomena intrinsic to the operation of the WiFi standard that impair the communications performance during the users mobility. The connectivity loss due to perceived signal degradation by users or the time it takes to exchange management frames with the Access Points (AP) for client re-association during handover process [7], must be carefully addressed to efficiently integrate WiFi technology to the 5G network paradigm.

## 1.2 Background

Re-transmission schemes are commonly used techniques to increase the communication systems reliability. Nevertheless, such schemes come at the cost of introducing latency into communication systems. For this reason, diversity-based systems have gained space as a way to achieve high reliability communication with low latency to meet the 5G networks requirements. In [8] a method with transmission diversity through the selectivity of the radio channel is presented. Solutions based on spatial diversity [9], frequency diversity [10] and polarization diversity [11] combined with collaborative communication schemes [10, 12] are used to achieve reliability in sensor and industrial control networks.

One of the ways to reach reliable communications without needs to modify the physical layer operation in the communication devices is using interface diversity, reaching different radio access points with multiple communication interfaces integrated in hardware. The interface diversity provides path diversity to reach a destination, making possible the use of multi-connectivity schemes to achieve system reliability and availability [13]. Multi-connectivity is implemented by connecting multiple interfaces of the mobile devices to a same technology network (homogeneous network) or to networks with different technologies simultaneously (heterogeneous networks). In addition, to provide system reliability, multi-connectivity enables better processing performance and efficiency through the use of new multi-path solutions at the network level [14], while introducing fault tolerance to wireless networks systems. The multi-connectivity solutions can be used then from low levels of the communication architecture like a data redundancy coding [13], to user plane levels solutions in 5G networks [15].

In this context, the SDN is presented as a consolidated network paradigm that proposes the separation of the networks data plane and the networks control plane, providing network programmability. With the use of programmable switches and the OpenFlow protocol [16], one of the most popular protocols, can be implemented and tested new networks solutions. In wireless networks, SDN has been widely used in solutions for cellular networks, wireless sensor networks and WiFi networks, but many of these solutions face challenges imposed by this type of networks that limit the use of SDN. Arises then the Software-Defined Wireless Networks (SDWN) [17], which coupled with NFV, are essential tools for dealing with problems that threaten low latency and high reliability solutions in wireless networks.

More specifically focused on the communication availability and reliability during wireless client mobility, these new technologies enable the creation of innovative handover mechanisms. Most of them leverage network-centric handover schemes, where the SDN controllers are the entities in charge of making the decisions on when and how this process should be done using context information collected at different levels. SDN orchestrators maintain a global network overview that allows more effective synchronization between user mobility in the access networks and route updates in the backhaul network, after a handover process or a network topology change. With the use of SDN, several innovative properties can be applied in the mobility of fronthaul and backhaul to ensure improvements in the user migration times.

Focused on WiFi networks as RAT of future 5G networks, solutions are proposed with the use of SDN focused on managing the user mobility in the network. In this context, users' handover process has been addressed, which is the main obstacle to ensuring seamless mobility communications, considering the diversity as a key element for achieving high communication reliability. Through the use of SDWN for WiFi networks can be implemented the client mobility control and the association/authentication processes, as well as implement load-balancing functions in the architecture. Many of these solutions are achieved through the creation of virtual APs in physical devices. In another line of research, solutions are focused in backhaul networks for wireless solutions, attempting to eliminate transmission delays introduced during handover process after user migration. In WiFi systems through the use of SDN solutions in the backhaul network can be implemented efficient use of network resources for this systems, providing fault tolerance and high transmission rates.

This work discusses the challenges and potentialities of use new SDN orchestrator techniques and with standard WiFi solution to obtain better performance from these networks as element of future deployments of 5G systems. Figure 1 shows an overview of the 5G network paradigm, showing its service cases and the main enabling technologies for 5G systems, including WiFi network as access technology and SDN and virtualization solutions as main enabling elements of control and management. Based on the main idea shown in Fig. 1 the following scientific question has been formulated: Can the new network softwarization and virtualization technologies together with existing wireless networks technologies like WiFi, guarantee performance requirements similar to those proposed for the novel 5G systems?

## 1.3 Objectives

To address the formulated scientific questions, the main objective of this work is experimentally evaluate a novel SDN architecture to ensure greater communication reliability over WiFi wireless networks implemented through users multi-connectivity access. The way to evaluate the system reliability in the proposed SDN-WiFi architecture is focused on decrease the communication interruption times during the handover processes experienced by WiFi users.

In order to comply with the general objective outlined, the following specific objectives are defined:

- Systematize the main characteristics and enabling technologies in the new 5G systems;

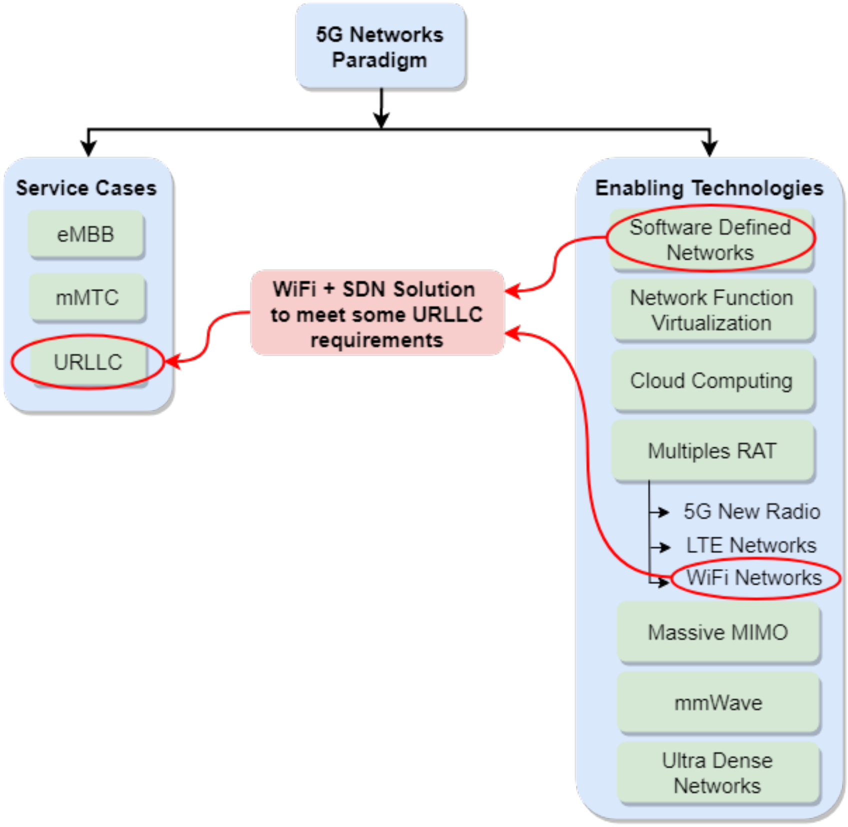



Figure 1 – Research main idea.

- Stress the importance of WiFi systems as an active Radio Access Technology for 5G networks, demonstrating the evolution of WiFi standards along with new services and applications demands;

- Study the main techniques for increasing wireless network reliability, focused on diversity techniques at different communication layers;

- Propose an innovative SDN WiFi communication architecture based on multi-connectivity;

- Validate the communication reliability using the proposed architecture in experimental WiFi scenarios with users mobility and in real use cases applications.

## 1.4 Methodology

In this project, an applied research will be carried out to obtain solutions and practical applications to the reliability and availability problems in WiFi networks during the users mobility. The research has a quantitative nature since the performance parameters of the communication networks will be collected and analyzed as a way for validating the system reliability. In relation to its objectives, the research can be classified as exploratory, given the bibliographic study that is performed about wireless networks and diversity solutions for increase reliability; while it can also be classified as explanatory, as it aims to identify the main factors influencing reliability in WiFi networks, and how through the creation of multi-connectivity mechanisms the system reliability can be improved. The place of accomplishment of the tasks is the research laboratory of the UFES' SDN Research Group, where the experimentation scenarios are implemented, using mostly commercial off-the-shelf (COTS) devices.

Among the procedures used are (i) the bibliographic research consulting books, scientific journals and scientific articles; (ii) and the experimental research using the scenarios created in the laboratory, where the data is collected and analyzed through direct observation and computing tools. The method of data analysis will be statistical, from the incorporation of graphs, tables and calculations of mean, variance and other quantities for the validation of the observed network parameters.

## 1.5 Dissertation Overview

In Chapter 2, after a brief presentation of the broadband wireless networks evolution, the new paradigm of 5G networks is addressed in greater detail, analyzing the main characteristics that their services propose as well as the main enabling technologies for these systems. A discussion about the role played by WiFi networks in the new 5G systems is presented, emphasizing the importance of integration to achieve better performances in the new generations of wireless networks. Finally, advances in the development of the new generation of WiFi standards are presented, which in parallel with the development of 5G systems also try to satisfy high requirements of applications and services.

Chapter 3 presents a study of the main diversity techniques used to increase the communication systems reliability. Without taking into account time diversity techniques that can introduce latency in the systems, a review of the micro diversity techniques is carried out, which focuses on mitigating the effects of multi-path fading. Macro diversity techniques are also studied, which mitigate phenomena such as path loss basing their operation on transmission schemes and topologies that implement different levels of multi-connectivity. The chapter ends with the presentation of the main techniques for the improvement of communication during handover processes, which try to reduce interruption times due to mobility.

An innovative WiFi communication architecture based on SDN is proposed in Chapter 4. The proposal implements multi-connectivity in access for WiFi clients, aiming to obtain seamless handover in scenarios that serve real-time control applications with high reliability. The system is validated through its use in real use cases for future Healthcare and Industry 4.0, both using the concepts of cloud robotics as a critical application to be supported. In all cases, results are shown and discussed, demonstrating the feasibility of employing the system to guarantee the URLLC services requirements.

The last chapter presents the conclusions and summarizes the main contributions of this work. Future work is discussed to point and suggest developments and increments of techniques that could be used in the proposed SDN architecture. Taking advantage of the SDN architecture multi-connectivity, technique like packets duplication can be used to increase the system reliability and meet other requirements such as latency and throughput.

# 2 New Era of Wireless Communications

The last three decades have been marked by an exponential growth in the use of information technologies, with a society more and more dependent on the new technologies. For this, wireless network technologies have played a fundamental role for accessing services and applications almost anywhere, with user mobility as their main benefit. This development has been led by two strong technological trends, (i) Broadband Wireless Networks focused on the coverage of large areas for and (ii) Wireless Local Area Networks (WLAN) that have dominated for many years indoor wireless communications. In this chapter, a study of the main characteristics and technologies of the new network paradigm for wireless communications popularly known as Fifth Generation Networks is carried out. The relationship between Broadband Wireless and WiFi technologies is also studied, analyzing the role of each of them in the future of wireless networks as well as the importance of coexistence and collaborative work that both will have to assume. Finally, are presented the new generation of IEEE 802.11 standards that are being developed to meet the demands and face challenges of modern wireless networks.

## 2.1 Broadband Wireless Networks

During the evolution of wireless networks, each generation focused on improving parameters performance such as transmission rates, mobility, coverage and spectral efficiency, in indoor and outdoor environments. Another important factor that has been present during the wireless technologies evolution is the spectrum allocation in which each technology operates, differentiating between licensed spectrum technologies and unlicensed spectrum technologies. Regarding broadband wireless technologies, its first two generations were characterized by using circuit switching, the main type of switching used in the 80s and 90s when these types of networks began to evolve, facing the disadvantages of this commutation type. During the second generation, the best-known and most popular technologies in the telecommunications market were the Global System for Mobile Communications (GSM) standard and General Packet Radio Service (GPRS) standard, which together achieved data transmission rates of up to 144 Kbps.

By the end of the first decade of the $21^{st}$ century, the first standard of the Third Generation Networks (3G) was introduced, jumping to transmission rates of 2 Mbps and incorporating packet switching together with the circuit switching. This stage was strongly promoted by the 3rd Generation Partnership Project (3GPP), which had been working on the development and maintenance of cellular networks since 2G, maintaining itself as the main driver in the proposal and standardization of Long Term Evolution (LTE) standard, LTE-Advanced (LTE-A) and more recently in what is expected to be 5G networks. Since the introduction of the LTE and Fixed Worldwide Interoperability for Microwave Access (WiMAX) technologies, considered as an evolution within the same 3G, the switching became exclusively for packets. This new feature contributed considerably in the network performance, increasing the network capacity and the user access to a varied amount of new services with high requirements.

With the development of multimedia messaging services and high definition video, the Fourth Generation (4G) of wireless mobile networks emerged to respond to this type of high demand services. With an operation based entirely on the IP protocol that offers network reliability, it allows theoretical transmission rates for some use cases of 1 Gbps, and was standardized by 3GPP through the LTE-A standard. The continuous development of new high-demand services such as ultra-high definition video, Virtual Reality (VR), critical applications of Industry 4.0 [18] and IoT solutions [19] continued boosting the development of wireless networks towards a new stage. This new stage that is considered to be a technological revolution, proposes a network paradigm with an integrating system of new technologies and existing technologies that can offer network services that accompany the new business models with high performance requirements. In this way, the concept of future wireless networks systems or 5G wireless networks arises.

## 2.2 The 5G Networks Paradigm

To address the socio-economic development of recent years, with the emergence of new business models and critical applications in different branches, the International Telecommunication Union (ITU) proposes the need for a new generation of mobile networks. The requirements that must be fulfilled by these networks began to be developed, preparing the open scenario for the investigation of new standards that would lead to the 5G networks emergence. Thus a new mobile communications standard begins to be developed, with the standards of radio interfaces for mobile communications governed by the International Mobile Telecommunications (IMT), which had led the development of 3G and 4G networks with IMT-2000 and IMT-Advanced respectively. In 2015 it is completed what for them would be their vision of society connected to 5G, published in recommendation ITU-Radio M.2083 [20]. This recommendation defines the objectives for the future development of International Mobile Telecommunications for the year 2020 and beyond (IMT-2020), where are also included improvements to existing IMT. From this moment, the project was promoted by the 3GPP, in charge of the development of the standards and the specifications to formalize an integral solution capable of satisfying the concept of this new network paradigm.

### 2.2.1 5G Service Requirements

The new 5G networks are characterized by a rapid response to allows multiple applications to provide several services simultaneously. It also seeks to enable the possibility of having completely reliable services anywhere and anytime with high quality performance independent of the access type to the system. These features are to be achieved even in high user density scenarios. The ITU-R IMT-2020 recommendation introduced the different service scenarios that the new mobile networks must address, resulting in an expansion of existing IMT. Three main service cases were defined, becoming the main objectives to be achieved by the 5G networks, as shown in Fig. 2.

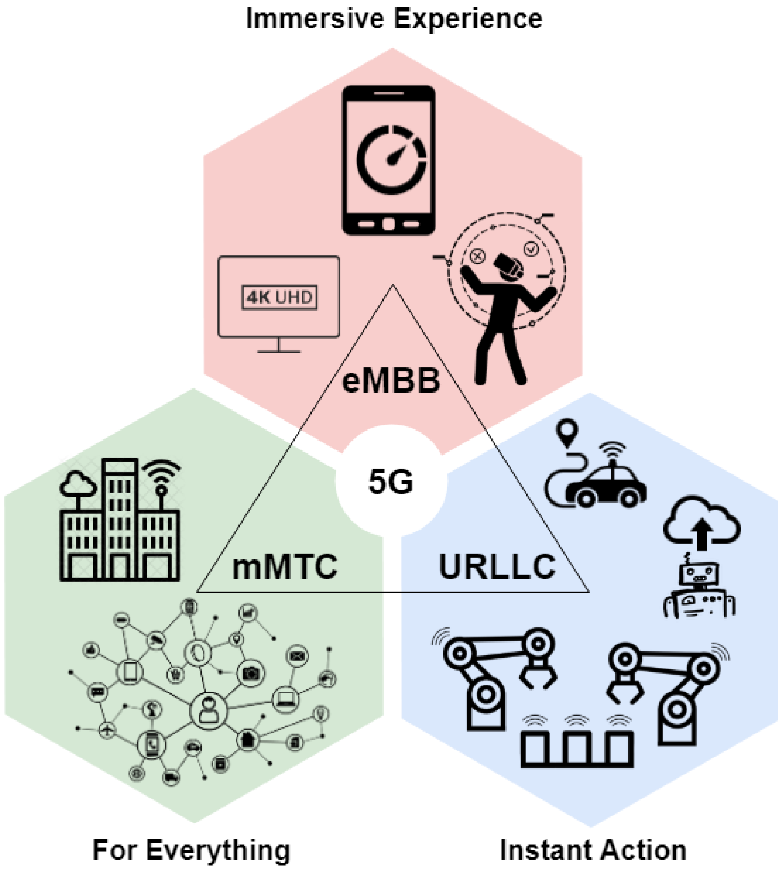



Figure 2 – 5G Service Case: eMBB, mMTC and URLLC.

Enhanced Mobile Broadband (eMBB). Mobile broadband addresses the human-centric use cases for access to multimedia content, services and data. A lot of attention have been devoted to this particular use case by the telecommunications industry since it directly represents the evolution of broadband mobile networks towards its fifth generation. For this, the main requirement that must be met in this type of scenario are the connections with very high peak data rates for all users. The objective of the eMBB service is to maximize data rates, so that values between 1 Gbps and 10 Gbps can be reached in real network scenarios.

Ultra Reliable and Low Latency Communication (URLLC). This requirement is designed to address critical applications that present strict reliability and latency requirements, closely linked to the applications of Industry 4.0, future Healthcare and Vehicle-to-Anything communications (V2X) [21]. In these cases, the URLLC data transmission rates are relatively low, being the main objective to guarantee high reliability of data delivery with a Packet Error Rate (PER) less than $10^{-5}$, which would represent networks with reliability of 99.99 %. In the transmissions of this type of applications, it is expected to achieve latencies for the control plane less than 10 ms and in the user plane less than 0.5 ms in the downlink or uplink communication in a separate way, representing a round trip time of only 1 ms, which means a reduction of 10 times the current latency in 4G networks.

Massive Machine Type Communication (mMTC). This last service case is directed to support solutions with a very large number of connected devices. It has been designed primarily for the deployment of millions of wireless devices that are expected to be operational in the coming years as part of the IoT paradigm [22]. In this type of networks, the devices transmit low volumes of data which are usually non-sensitive to delays and need to perform low power consumption to extend the life of the batteries. In these scenarios the anticipated application of network resources is impossible due to the large number of elements connected to the same Base Station (BS), so resources are shared through random accesses. As the number of devices that access at a certain time is also random, the objective of this use case is to maximize the arrival rate that can be allowed for a radio resource.

In order to comply with each of these use cases, the ITU-Radio also defined in recommendation M.2083 eight Key Performance Indicators (KPI) that must be guaranteed. Table 1 shows the KPIs with the values that are proposed for each of them [20]. These KPIs are the basis of other more detailed technical performance requirements, also defined by the ITU in recent years.

Table 1 – Parameters considered key capabilities of IMT-2020 [20]

| Key Performance Indicator (KPI) | Description | Value |
|---|---|---|
| Peak data rate | Maximum achievable data rate under ideal conditions per user/device | 20 $Gbps$ |
| User experienced data rate | Achievable data rate that is available ubiquitously across the coverage area to a mobile user/device | 100 $Mbps$ |
| Latency | The contribution by the radio network to the time from when the source sends a packet to when the destination receives it | 1 $ms$ |
| Mobility | Maximum speed at which a defined Quality of Services (QoS) and seamless transfer between radio nodes which may belong to different layers and/or radio access technologies can be achieved | 500 $km/h$ |
| Connection density | Total number of connected and/or accessible devices per unit area | $10^6$ $devices/km^2$ |
| Energy efficiency | Energy efficiency refers to the quantity of information bits transmitted to/received from users, per unit of energy consumption of the radio access network | 100$x$ $bit/Joule$ |
| Spectrum efficiency | Average data throughput per unit of spectrum resource and per cell | 3$x$ $bit/s/Hz$ |
| Area traffic capacity | Total traffic throughput served per geographic area | 10 $Mbps/m^2$ |

For its part, the 3GPP defined in its recommendation TR 22.891 [23] what are the service requirements that future wireless networks have to meet, according to studies conducted to determine the requirements for each service. Table 2 summarizes the four cases of uses recognized by 3GPP, in this case, 3GPP introduces a fourth type of service.

Table 2 – 5G Systems Use Case [23]

| Service | Use Cases | Feature |
|---|---|---|
| eMBB | High Data Rate | Scenarios for which the requirements of throughput peak, user experience, downlink and uplink can be obtained with User Equipment (UE) at pedestrian speed |
| eMBB | High Density | Scenarios with requirements for high volumes of data traffic by area or data transport of a large number of connections |
| eMBB | Deployment and Coverage | Scenarios where the requirements of the systems consider the deployment and coverage (indoor/outdoor, local area connectivity, wide area connectivity) |
| eMBB | High User Mobility | Scenarios for which the eMBB mobility elements can be defined |
| Critical Communication | Very Low Latency | Systems with critical latency requirements where messages between transmitter and receiver must be transported very fast (Tactile Internet, localized real time control, extreme real time communication) |
| Critical Communication | Mission Critical Service | Critical communications that need high priority over other communications in the network (Connectivity of drones, local Unmanned Aerial Vehicle (UAV) collaboration, telemedicine support) |
| Critical Communication | High Reliability and Low Latency | Systems with high requirements in latency and reliability with moderate data rates (Industrial control systems, Mobile HealthCare, vehicles real-time control, audio and video for Virtual and Augmented Reality) |
| Critical Communication | High Availability | Systems used when the cellular network is congested, or damaged, or coverage is not sufficient (Connectivity using Satellites) |
| Critical Communication | High Accuracy Positioning | Systems for fast, reliable and available acquisition of location information (Connectivity for drones, remote control, Local AUV Collaboration) |
| Massive IoT | Operational Aspects | IoT security, connectivity diversity, devices with variable data, devices initialization, devices configuration |
| Massive IoT | Connectivity Aspects | Service continuity, devices with direct or indirect 3GPP connection mode |
| Massive IoT | Resource Efficiency Aspects | Mobility management, variable data size, discovery mechanisms |

Due to the importance that vehicle communications have acquired in recent years, and more specific autonomous vehicle communications, 3GPP already recognizes V2X communications as a main service case for 5G networks. The service for V2X communications derived from the URLLC communications [24] addresses the issues of Mobile Broadband service with seamless wide area coverage, the improvement of network capabilities for vehicular communications and connections between elements of a vehicular network.

Simultaneously addressing all these use cases for a wide range of applications, it is stated that the 5G network paradigm provides access to services $4A$, which means Access Anytime, Anywhere, Anyone and Anything. We are in the presence of a flexible and intelligent network architecture, capable of executing dissimilar tasks through a virtualized platform and software defined orchestration. This architecture, based on network programmability, will be able to analyze all network data in real time to customize the services availability and the resources allocation. The new 5G network is differentiated from 4G networks by the evolution in performance at the radio level and by providing a great E2E flexibility, contributed by the introduction of a network softwarization approach. With these features operating in an integrated way, is projected the 5G network as a complex service-oriented network architecture [25].

### 2.2.2 The 5G Network Architecture

Given that the architectures for current broadband wireless networks are designed to serve voice services and data services, they are characterized by being not very flexible for new cases of use and services. Therefore, the flexibility of the network becomes a key feature of the 5G wireless networks architecture [4]. Flexibility allows (i) diversity of services to adapt to different traffic characteristics, (II) diversity to support different E2E QoS based on data rate, reliability and latency, (III) diversity in mobility levels including mobility of users at high speeds, mobility in large-scale networks and mobility through heterogeneous networks (HetNet). In this way, the network will be able to function adaptively to satisfy service requirements, even in cases where the requirements of one service are opposed to the requirements of another service. These functionalities will only be possible through an architecture designed with separation of the control plane functions and the user plane functions, which allows for the dynamic and on demand allocation of network resources for several services and applications.

A very important role will be played by the paradigms of SDN, NFV and Cloud Computing as enabling technologies for flexibility in 5G networks [26], from access networks to the network core. With these concepts supported by the underlying physical infrastructure, a network architecture based on services can be created, as shown in Fig. 3, improving the support to several 5G services.

The Cloud Radio Access Network (C-RAN) is responsible for implementing and orchestrating of RAN functions in real time and in non-real time to allow massive connections of different standards [27]. Real-time and on-demand functions, in which specific hardware with high processing performance is required located in distributed base stations, are responsible for power control, interference coordination, modulation and coding, among other physical layer functions. Non-real-time functions are performed in a

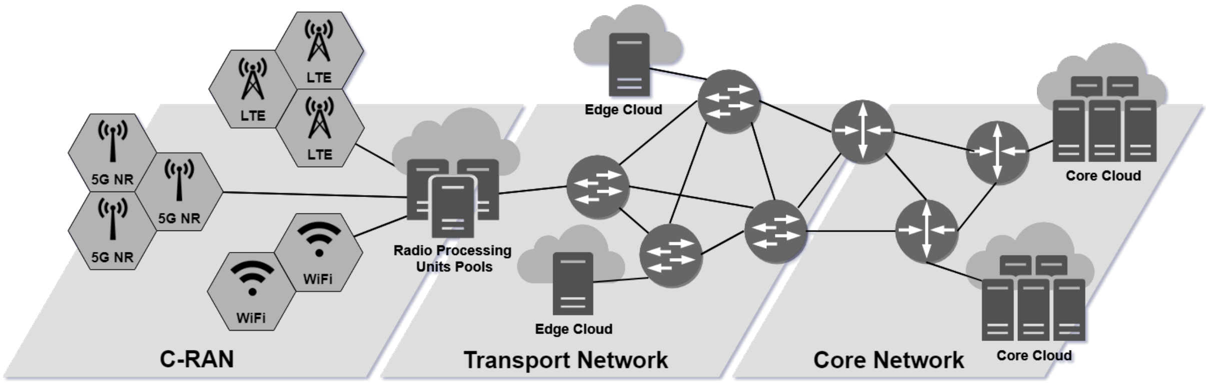



Figure 3 – 5G network architecture.

centralized cloud environment since they have minimum latency requirements such as the encryption of the user plane and the convergence of multiple connections. A management entity in the C-RAN coordinates the multiple processing of frequency and space capabilities, allowing C-RAN to support Multiples Radio Access Technologies (Multi-RAT) [28].

The radio processing rooms and the core network will be connected by a multi-domain SDN transport network managed by SDN controllers responsible for creating the specific trajectories based on the network topology and the requirements of the services [29]. Requirements such as high peak data rate and low latency directly impact the performance of this backhaul network, which must support high data volumes with minimum delay and cost. To satisfy requirements of this type, SDN controllers must also manage the network resources in order to create a flexible and high capacity network, and through wireless-optical convergence provide C-RAN/backhaul integration.

The service-oriented 5G mobile core network uses virtualization and cloud platforms to deploy user and network services as software entities [30]. A centralized orchestration in the network core allows a unique view of the network environment, reducing costs and facilitating the resources management throughout the architecture. The unified network core supports heterogeneous access networks performing functions of access and mobility management, authentication, session management, policy control, unified data management.

#### 2.2.2.1 Architecture Management and Orchestration

The 5G architecture is expected to be network-agnostic, where the network core will be common for all RATs that will be supported by the network, existing radio interfaces and the New Radio (NR) interface introduce for 5G. This feature makes it necessary to implement rigorous control mechanisms that allow uncoupling the network core from access technologies. At the same time other mechanisms should be implemented to orchestrate the interworking of these multi-RAT, 5G NR access network, mobile access networks such as LTE-A, WLAN and fixed networks. These mechanisms must be capable of mobility management and user session management for the services continuity during the transition from one technology to another. The multi-connectivity offered by the access through multi-RAT provides robustness to the network and better throughput performance.

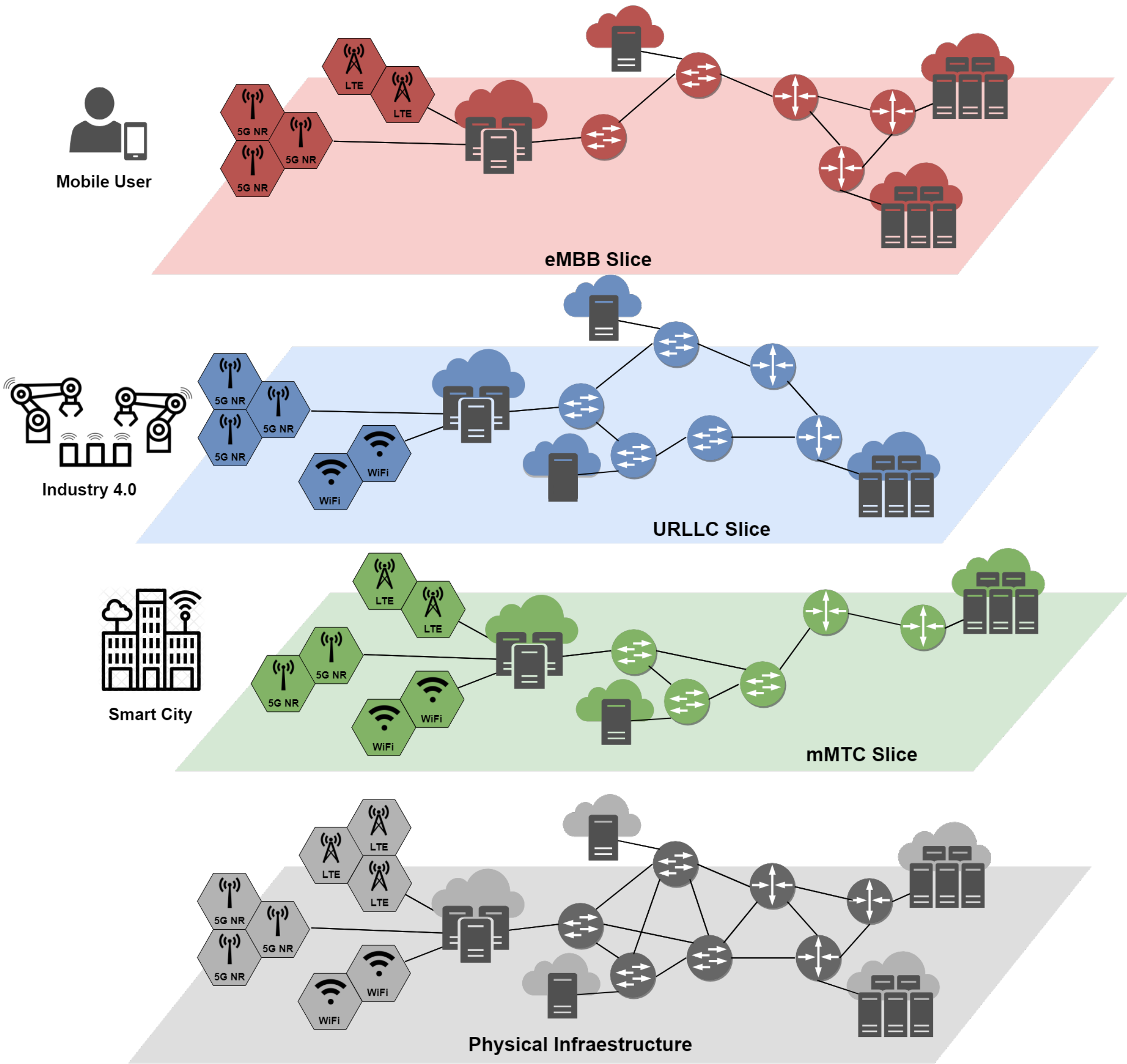



Figure 4 – 5G network slicing.

With the network resources virtualization, multiple networks slices with different characteristics can be implemented to address different service cases, as shown in Fig. 4, maximizing the network performance, QoS and Quality of Experience (QoE). The implementation of the networks slice is one of the main techniques in the deployment of 5G architectures [31]. They allow network operators to implement virtual logical networks and sets of network functions for different services over the same physical infrastructure. As each network slice is a logical entity independent of each other, it allows independent and customized functions of Orchestration and Management (OM) for the services. Virtualization also offers the possibility of having a network architecture with distributed functions that actively contributes to the reduction of core and backhaul traffic by placing many services on edge networks closer to users. This is undoubtedly beneficial in terms of latency for many critical applications in URLLC.

The orchestration and management of the network should therefore allow maximum performance during the implementation of distributed functions, network slicing and resource allocation. With different network domains working under the range of 5G access technologies [32], unified network management is one of the biggest challenges in these architectures to ensure compatibility and flexibility among all technologies. Within this scenarios, the management of network slices to implement solutions of various service cases becomes the heart of these architectures. The management must provide functionality such as optimization and capacity planning for a slice, granting the necessary resources according to the service type requested. It must be able to monitor the quality of the provisioned slice to take the necessary actions in case of re-optimization. Other vital functions that must be fulfilled are the management of the slice fault, inter-slice orchestration, management of slice security and monitoring, and analysis of slices resources.

### 2.2.3 Enabling Technologies for 5G Networks

To increase capacity in the new 5G networks, several fundamental approaches can be considered, each of which can be implemented through new technologies. The first of these is the high spectral efficiency requirement, where the use of large numbers of antennas in transmitting base stations is the goal. In this sense, the Multiple Input Multiple Output (MIMO) techniques and more recently the massive MIMO [33], are used to take maximum advantage of the spatial diversity of the communication channels increasing the spectral efficiency.

The second approach is to achieve high transmission rates through the increase of the communication bandwidth, for what transmissions in bands of millimeter wave spectrum (mmWave) are explored. [34]. These approaches are closely linked in their operation, and both are included in the design of new radio interface standards [35]. The transmission characteristics are integrated into topological solutions such as Ultra-Dense Networks (UDN) [36], achieving high densities of access points in the networks, thus increasing network capacity with better interference mitigation schemes. In addition, virtualization technologies are indispensable for the management and orchestration of the complete network architecture.

#### 2.2.3.1 5G New Radio

In order to meet the requirements of data rates, reliability, coverage, latency and capacity, the radio access technology for 5G systems must implement a new radio interface. The new standard for radio interface for 5G networks is being developed by 3GPP, aiming to achieve better energy performance in the system and the possibility of operation in very high frequency bands. The first NR specification was approved by 3GPP at the end of 2017 [37] with an NR operation in non-standalone mode, which means that the implementation would be carried out on an inherited LTE network infrastructure. In mid-2018 the standalone version of 5G NR [38] was officially completed, allowing new 5G system implementations in places that do not necessarily have an existing infrastructure, a solution completely independent of LTE.

The main features of the 5G NR standard are focused on the operation of the physical layer [39], responsible for the processing and transmission of radio signals. The radio waveform is one of the main requirements for wireless access technologies, being defined OFDM modulation with Cyclic Prefix (CP) for 5G NR to mitigate the inter-symbol interference (ISI) effects. This feature allows low complexity and low cost implementations for broadband operations supported by MIMO technologies. For this new radio interface, operations were mainly comprised in the most traditional spectrum bands known as sub-6 GHz between 450 MHz and 6 GHz, and a second frequency operation range between 24.25 GHz -52.6 GHz in the mmWave spectrum, which is supposed to be one of the great advances in wireless communications. In addition, the duration for the transmissions of the frames used is 10 ms, facilitating transmissions that meet the important requirements of low latency transmissions for critical applications, also contributing to the interference mitigation. The following sub-sections address some emerging technologies that make it possible the new wireless radio interfaces implementation.

#### 2.2.3.2 Massive MIMO

In order to reduce the effect of fading on wireless channels, the diversity concept is used, introducing the MIMO techniques that make use of spatial diversity in the communication channel. These techniques take advantage of the spatial diversity of the multi-path channels to transmit replicas of the same signal on uncorrelated paths. In this way the possibility of recovery of the entire signal is increased once all the received replicas have been combined, increasing the reliability of the communication. A more complete study of MIMO techniques is carried out in the next chapter as part of the diversity techniques analysis used to increase the wireless communications reliability.

The new 5G systems implement a new concept called Massive MIMO to maximize the spectral efficiency and energy efficiency of wireless networks. The concept refers to the use of large numbers of antennas in base stations transmitters, attending simultaneously many user devices. With the use of several antennas working in a coherent and adaptive way, the signal energy can be focused on smaller areas of the space through beamforming techniques [40], mitigating inter-cell interference (ICI) and inter-user interference. Massive MIMO is used in current wireless networks as radio access technology below 6 GHz, but its efficient use in 5G systems depends on its correct integration in the mmWave band [41]. These antenna techniques can also be used for wireless backhaul networks in small cell solutions [42] for their benefits in terms of interference mitigation.

#### 2.2.3.3 Millimeter Wave Communications

To maximize the performance of MIMO systems, the separation between the multiple antennas in the radio stations transmitter should be designed to be a half wavelength. In radioelectric spectrum bands operating between 2 GHz and 5 GHz this antenna spacing condition limits the number of antennas that can be used in the array due to the small size of mobile devices. To address this limitation, higher frequency bands are used, so that the distances between antennas can be reduced and therefore increase the number of antennas. In this way the use of the mmWave spectrum between 30 GHz and 300 GHz, becomes one of the key technologies in the implementation of 5G networks, providing direct benefits for massive MIMO system designs. Such high frequency bands also offers benefits to achieve high speeds wireless communications, since it provides channels with greater amounts of bandwidth, which exponentially increases the wireless systems capacity [43].

The mmWave communications can be used in indoor environments for wireless applications that demand high throughput or in outdoor environments combined with beamforming techniques and in wireless backhaul solutions. However, this band has not been explored in depth for mobile systems [44], so operators have begun to experiment for determine the frequencies with better conditions for mobile applications in mmWave band. The operators together with the standardization entities have carried out a study in two stages [45] for the implementation of systems using mmWave. The first stage focuses on exploring and researching frequencies below 40 GHz to address a subset of commercial needs of mobile operators, and the second stage focuses on the study of frequencies up to 100 GHz. The selection of the operation frequency in a wireless system depends on several factors such as the application type, the wireless channels types, and the propagation phenomena that can affect the signals, where the mmWave communications present interesting advantages to efficiently attend many of these system design requirements. The wide range of licensed and unlicensed spectrum in the mmWave band represents a considerable advantage in contrast to the bandwidth shortage below 6 GHz, where bands also suffer from high levels of congestion.

#### 2.2.3.4 Ultra Dense Networks

In wireless networks, spectrum re-utilization by reduced cell size is one of the methods employed to increase system capacity. The UDN can be formally defined as a network in which there are more base stations than mobile devices, considering that each cell is composed by one base station. The main objective is to guarantee high transfer rates per user in rural, urban, and industrial environments [46]. Density in networks tend to reduce the distance between access equipment and mobile users, increasing the probability of

Line-Of-Sight (LoS) transmission and mitigating the negative effects of multi-path wireless channels.

For that matter, the concept of UDN emerges through the implementation of novel small cell concepts, partially or fully seamless to mobile devices, to achieve high throughput requirements in 5G networks. With the network densification through the deployment of small cell solutions spectral efficiency can also increase, while addressing the growing demand for systems capacity. For network operators, the implementation of small cell also offers advantages, since it provides a seamless integration with the other existing network solutions without causing interference. Advances in Self-Organized Networks (SON) technologies are fundamental in high-density networks [47] since they reduce the operational and maintenance costs of wireless systems, providing self-organization, self-optimization and self-healing capabilities.

#### 2.2.3.5 Software Defined Networks

The Software Defined Networks have ceased to be a paradigm to become the present and future of the current data and telephony networks. [48]. The main concept proposed in the SDN is the separation of the network control plane from the underlying forwarding physical devices. This separation allows the design of the network with a centralized intelligence, offering the ability of network programmability for control and management from applications running in the control plane. This fundamental feature in SDN is expected to solve limitations in current networks for several domains. It also allows the creation and experimentation of new network concepts and protocols [49], making management tasks easier and increasing the flexibility, scalability and performance of communication systems.

A simplified architecture of the SDN concept is shown in Figure 5. In the bottom architecture the data plane is composed by the forwarding devices connected to each other to form a network infrastructure. The main function of this plane is to handle the data traffic forwarding according to instructions received from the control plane. The arrival of each new packet to the devices in the data plane is analyzed to determine what action execute on that data flow. With a proactive approach, the control plane based on some prior knowledge installs rules or policies to address certain traffic types in the SDN devices, so these packets are treated only by the data plane devices. In the case of the reactive approach, there are no rules in the devices to deal with the new traffic flows, so the packets are sent to the SDN controller. Some control plane application based on some programmed logic determines which treatment is given to the traffic with those characteristics, and installs the new flow rules in the data plane.

The control and management plane is composed of two layers, the control layer and the applications layer with network applications and management applications at the top of the architecture. The SDN controller centralizes the intelligence of the network, being

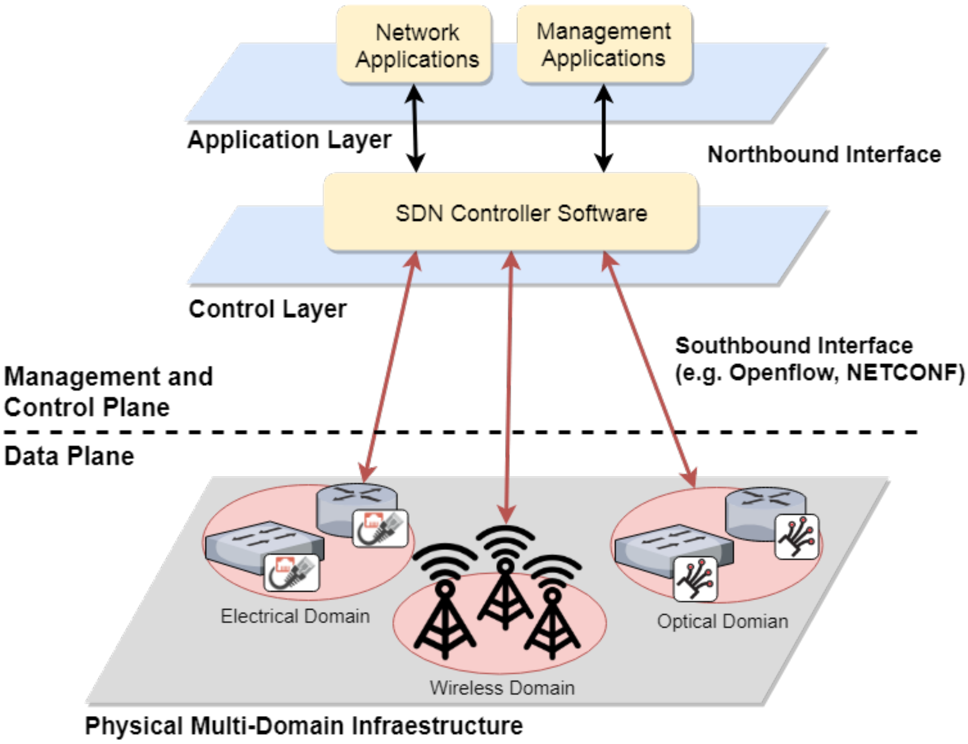



Figure 5 – Simplified SDN Architecture.

considered a network operating system [50] whose main function is to allow the interaction of the applications with the forwarding devices in the data plane. The southbound interface defines the communication protocol between the data plane and the control plane, formalizing the way in which both planes interact. With these protocols it is possible to program the forwarding operations of the data plane, perform statistics reports and event notifications. There are several protocols used for this task, OpenFlow [16] and NETCONF [51] are among the most popular and employed. Through the northbound interface the controller communicates with the application layer, allowing applications to access the underlying hardware, manage the system resources, and allow their interaction with other applications. The network and management applications programmed by the network operators, offer the functionalities for the implementation of control and logical operation in the network, defining policies that are sent to the data plane for treatment the data flows.

The abstraction that SDN performs on the data plane is the main feature for its implementation as a fundamental enabling technology for 5G networks. With SDN it will be possible to manage the complex topological and logical architectures that 5G networks propose. The intelligent orchestration offered by the control plane will allow the dynamic and on-demand provisioning of system resources, in scenarios of heterogeneous networks and even of different vendors. Perhaps the most important thing offered by SDN for service-oriented 5G networks is the ability to provide network virtualization, automation and the creation of new services over virtualized resources.

#### 2.2.3.6 Network Function Virtualization

A decisive impact for the deployment of the 5G communication systems will be the utilization of virtualization technologies [52] for the creation of software entities on the same physical device. Virtualization allows the allocation of available resources in the devices for the creation of logical functions, independent of each other. This isolation or logical segmentation allows different clients and services to create and explore several virtual network topologies as well as control over data flows. In this way, virtualization becomes the main technology for the creation and implementation of slicing in 5G network architectures, both in radio access networks and in the core network.

Virtualization, in addition to virtualizing resources of a physical device, allows to virtualize the network services that interact with the data flows. However, this virtualization of network services does not manage to face the challenges imposed by the wide deployments of services in heterogeneous and complex networks. With the use of SDN, the orchestration that it offers can be used in the services chain processes, convert these two technologies into the heart of the 5G systems, together representing an ideal complement to obtain also robust systems.

The NFV is then described as the way in which virtual network services are designed and deployed [53], bringing as many of these services to the network core on a cloud platform. It is through NFV that operators can perform virtualization and orchestration of network services to meet the requirements of a given application. Within the attributions of NFV are included the creation, placement, interconnection, modification, and destruction of the virtualized services. The services are built by the sequence of several service functions forming a Service Function Chains (SFC), where each service function is responsible for a specific treatment of the packages.

With the joint use of NFV and SDN, several of the main challenges of the 5G networks can be addressed [54]. With them, one can achieve the optimization in the allocation of resources on demand increasing the capacity of the systems. They also allow the mobility and scaling of VNF from the resources of one hardware to another ensuring the operation of the VNF, and also allow the coexistence of the VNF with other non-virtualized network functions of the architecture. Last but not least, the use of NFV is effective in reducing capital expenditures (CAPEX) and operational expenditure (OPEX) and in the efficient use of energy in 5G systems.

## 2.3 WiFi in the 5G networks

From the point of view of this dissertation, the concept of 5G networks is understood as a network paradigm rather than a specific isolated technology. For the success of this new technological commitment and for its main pillars (URLLC, mMTC, MBB) to be achieved, it is necessary not only to develop of a new radio interface that solves globally all the 5G challenges, but also integrate the various existing wireless technologies with consolidated acceptance in the market. Within these technologies, WiFi networks, governed by the IEEE 802.11 standards family, stand out as one of the main players in the integration of wireless technologies that the 5G networks will compulsorily implement if it wishes, in the long term, triumph in the complex scenario of a world increasingly demanding in terms of technology.

According to the worldwide industry leaders that participate in the development and implementation of 5G solutions for the year 2020, WiFi is recognized as one of the RAT that will be integrated with 5G, thus sharing the unlicensed spectrum. Among them, Intel recognizes and classifies WiFi as a critical wireless technology for the 5G paradigm [55], where bet on the joint evolution of WiFi and LTE, in order to create 5G networks in a heterogeneous network where several wireless technologies will have to work collaboratively as a whole. Samsung's vision [56] recognizes Multi-RAT as one of the key enabling technologies for 5G, which will allow the integration of licensed and unlicensed spectrum bands to achieve better performances. This integration will enable, according to them, better energy efficiency of the network, greater density of connections, mobility and data rates; with WiFi being one of these wireless technologies to be integrated due to its low deployment cost and the indisputable preference of mobile users. For Huawei [57] the 5G paradigm has among its critical missions, to guarantee the best delivery of any service to any user, so that the use of any spectrum band or any RAT is fundamental to achieve this goal. Again, WiFi is presented as one of the indisputable technologies for use in 5G networks due to being able to provide these features and the wide deployment around the world.

Even though these and other manufacturers include WiFi networks as a key RAT of the 5G network environment, there are many who see in 5G networks the end for IEEE 802.11 networks. On the other hand, the WiFi community defends the idea that 5G does not represent a risk for the survival of the technology, arguing that other attempts to replace WiFi failed completely as it did with WiMAX networks. In addition, WiFi development work groups have continued to work intensively in recent years to achieve an evolution of IEEE 802.11 networks. The result has been evidenced in the emergence of new standards to continue guaranteeing a competitive technology in tandem with the demands that users and new services impose for wireless networks.

It is important to understand in this debate that the evolution and development of WiFi is a phenomenon independent of the evolution of cellular networks. Although the development of both technologies can be said to have occurred in parallel, the fact that these technologies are governed by different organisms ratifies the independence in the development of each one. The new paradigm of 5G networks is a mobile networks standard that is being developed by the ITU-IMT-2020 and the 3GPP. For its part, the IEEE 802.11 standards marketed as WiFi technology were created and developed by the IEEE 802.11

Working Group and the devices of this technology are certified by the WiFi-Alliance, which also tries to integrate the industry and the manufacturers. That is why it should be noted that WiFi is not part of these 5G networks, but will surely be one of the main ally of 5G networks.

For specialists in the wireless technologies area, the development of WiFi has been evident, showing great acceptance for both its users and cellular operators. The global WiFi market will grow by 2020 at 33.6 billion dollars and that WiFi traffic in general it will represent more than 50% of the total IP traffic for that date [58]. The most interesting thing is that WiFi has not generated as much marketing as broadband mobile networks have done with their *networks generations* evolution strategy. Undoubtedly, this has been an interesting market strategy that operators and organizations have used to sell their services to users increasingly dependent on new technologies, but at the same time less knowledgeable about them. It refers to the operators that today promote their networks at 5G data rates, when such data rates are far from be considered 5G data rates by any mobile broadband standard, and even worse, the many users who then hire their services for being in the fashion of the last "*G*". Notwithstanding this, the evolution of WiFi technology can be identified and, in general, the wireless technologies of unlicensed spectrum, accompanied by the new business stages [59]. Starting with the stage of simple access where all kinds of internet use was supported with the best effort, we went through a stage of an intelligent access with integration with other mobile technologies making use of a better knowledge of the users' needs and another stage of operator level access to support various types of critical applications with high QoS requirements. Finally we reach a stage where access is massive to connect to all kinds of devices and "things", fitting into the IoT paradigm, to which 5G networks will also have to provide support in mMTC [60].

Despite those who push from one side to another to survive or impose one technology over the other, the fact is that most specialists believe in collaboration between the two technologies, seeing both technologies as complementary [61, 62]. For indoor environments, WiFi is and will remain the technology to be implemented, while cellular technologies will prevail more for outdoor environments. Both technologies will undeniably continue to collaborate, studies [63] have shown that WiFi is currently offloading 4G data for an amount of around 25 billion dollars, and it is estimated that this data will triple for 5G networks, which shows that 5G will need WiFi even more than 4G does today.

### 2.3.1 Mobile Data Offload

The Mobile Data Offload [64] has become one of the techniques that turn WiFi into a necessary technology in the face of different cellular wireless technologies. Due to the constant and rapid growth that mobile data traffic has experienced, it has caused cellular operators to look for solutions to the problems of saturation of radio links and the low penetration capacity in indoor environments presented by cellular signals. As a solution to these problems arise the well-known techniques of cellular traffic offloading, which are nothing more than architectures and protocols that have allowed mobile operators to establish and control alternative routes for the cellular networks traffic [6]. Offload solutions quickly became the main option for operators because the increase in base stations as a way to solve these cellular networks problems would mean prohibitive costs that would make these networks inefficient and unproductive. That is why it began to increase the capacity of the network to improve its performance and the QoS and QoE of the users through the use of alternatives RAN, which could offer the capacity increases that cellular operators needs.

Offloading techniques can be classified into several major types [65], the first of which is through the opportunistic mobile networks [66]. In the opportunistic networks, the mobile elements establish communication with their neighboring elements without using the cellular network infrastructure, achieving high data rates taking advantage of the proximity conditions and consequently also a considerable saving in the battery consumption of the mobile elements. In this way, this offload technique exploits device-to-device (D2D) communications [67] in cellular networks. The current LTE networks are capable of managing D2D communications by discovering the devices, establishing the connections and in some cases allocating the radio resources in the connection. These D2D communications can be cataloged in communications that make use of cellular frequencies, for which the direct radio link between the elements is made using LTE Direct technology; or in communications where radio links are established using the unlicensed spectrum, with WiFi Direct [68] being one of the most used technologies. The WiFi Direct standard allows communication between devices without using a traditional WiFi infrastructure and with it, the WiFi D2D offloading takes advantage of environments characterized by a high density of WiFi devices that can be organized as a cluster for communication between them and with the wireless infrastructure.

A second option to carry out the offload of cellular data is through small cell networks [69]. These networks are defined structures where the access points operate in the licensed spectrum at low power levels which allows the implementation of small coverage structures (small cells) to attend and provide service in homes or companies. Currently the academy and industry are more focused on the study of this type of networks implemented through solutions with femtocell [70], which are very attractive for users and operators due to good cellular coverage performance and high transmission rates in indoor environments, low power consumption for mobile devices and the ability for operators to place the coverage and capacity of the network where there is demand, in addition to its rapid deployment. Together with the development of the small cell networks, appear the interests and technical possibilities for the integration between WiFi and cellular networks. Fundamentally, these interests were driven by the similarity of the scenarios in which each of these networks were projected, with great emphasis on the areas of coverage that they are able to meet, resulting in the concept of Integrated Small Cell WiFi Networks (ISW) [71]. These networks present architectures whose main contribution is the integration of small cell with WiFi access points which are controlled and managed by a central operator of the network. These solutions are used to integrate licensed and unlicensed spectrum, providing efficient management of WiFi networks as part of a Small Cell solution.

Finally, WiFi networks themselves are the third option of offloading and perhaps the most used in cellular networks throughout the world. Several are the reasons that make WiFi technology an excellent candidate as a solution for offloading cellular traffic [72]. WiFi networks is the most widely deployed RAN technology at present with very low costs and most of the users' mobile devices have WiFi interfaces. On the other hand, similar to the small cell networks and femtocell, it is capable of providing an indoor service with high data rates, offering greater capacities and bandwidth in the network. These features make WiFi the option chosen by operators to address capacity limitations, spectrum limitations and poor indoor penetration that RAN technologies present in cellular networks. Even with all these advantages, WiFi has the great limitation of not being able to interact directly with cellular networks standardized by 3GPP. This limitation introduces problems related to the authentication of users, mobility management and control of the offload process, all directly influencing the QoS of the services provided in the broadband wireless networks [73]. For its own interest, 3GPP decided to address these problems and published in Release 6, a new architecture for the integration of 3GPP systems and WLAN which they called Interworking WLAN (I-WLAN) [74]. This solution was somewhat deficient in the treatment of user mobility between the different access networks (3GPP and WiFi), so an update was published in Release 8 which improved the issues of accessibility and continuity of users in the network, and already in Release 12 is defined LTE-WLAN radio level inter-working.

### 2.3.2 Spectrum Convergence

Precisely this possibility that WiFi networks provide for offload and onload of data from cellular networks is one of the keys that are leading to the convergence between licensed and unlicensed spectrum. Some years ago, unlicensed spectrum technologies began to be of primary interest for cellular networks and licensed spectrum networks in general. Thus, the great leaders of the broadband network industry understood that the coexistence and convergence of HetNet operating in both types of spectrum, are important points for the development of new wireless technologies such as 5G networks [75]. Those who carry out and promote the 5G project are not oblivious to this issue, and have placed this convergence of networks and spectrum in a privileged spot, without which they understand that the 5G networks will not achieve the expected economic and practical benefits. The WiFi community is also aware of this phenomenon, when the chairman of the Wireless Broadband Alliance on the occasion of the 2016 annual report stated that it was evident that the limits between licensed and unlicensed spectrum technologies were disappearing, leaving almost imperceptible [60].

As has already been explained, the use of unlicensed spectrum, and fundamentally WiFi technology, by cellular operators has grown considerably, even with the limitations of not being able to offer seamless coverage, high spectral efficiency and high reliability. For the spectrum integration proposed by 5G, solutions have already been developed for the coexistence of current cellular networks and WiFi. In its Release 13, the 3GPP defined and standardized the new technologies that allow the integration between cellular networks and WiFi. These technologies share the spectrum dynamically, allow operators to benefit from the additional capacity that networks of unlicensed bands such as WiFi offer. In Release 13, where it is considered that the LTE Advanced Pro features begin to be published as a prelude to the 5G networks, the Licensed-Assisted Access (LAA) feature was introduced, which adapts LTE to operate in the unlicensed spectrum [76]. To achieve this, access is made through a Carrier Component Secondary Cell assisted by a Primary Carrier Component that operates in the licensed spectrum and using the LTE carrier aggregation feature. The solution specifically allows the operation of LTE in the 5GHz unlicensed band providing an interesting WiFi protection feature, since LAA has been designed with a mechanism that selects a clean channel, so that it is able to dynamically avoid interference with WiFi operating in this band.

To provide cellular operators with greater control in the deployment and use of WLAN, the aggregation of radio-level traffic over LTE-WLAN, formally called LTE-WLAN Aggregation (LWA) [77], was also introduced in the 3GPP Release 13. With this feature, LTE systems can, through a function that lies in the base stations, divide the traffic to be directed towards WiFi infrastructures and at UE level the traffic of individual systems can be aggregated; the UE are also capable of sending traffic to both the base stations and the WLAN access networks. In these systems, the control of connections is maintained in the part of LTE systems, much of the justification for this is because WiFi systems lack efficient management and control solutions. Another technique closely related to LAA and also introduced in this same release for the coexistence of LTE and WiFi is the integration at the LTE-WLAN radio level with IPSec tunnel (LWIP) [77] where traffic between the LTE system and the UE is transported in a WLAN through a tunnel transparently. LWIP is expected to provide more efficient load balancing between LTE and WiFi in order to benefit from the increased capacity provided by WiFi. The main difference between LWA and LWIP is the level where the aggregation of LTE and WiFi traffic is carried out, LWA performs this function at the packet data convergence protocol level while LWIP does it at the IP layer. Unlike LAA, which uses a modified LTE waveform in the unlicensed spectrum, LWA and LWIP use a proprietary WiFi waveform, providing a deeper integration with unlicensed spectrum. These last three techniques represent, in addition to efforts for the integration of licensed and unlicensed spectral, strategies to also offer an efficient offload of traffic in cellular networks.

## 2.4 Software Defined Wireless Networks

The separation of the data plane and the control plane offered by SDN, makes these solutions very interesting to address several problems that still present in many established communication technologies. In wireless networks, SDN has been widely used in solutions for wireless cellular networks, wireless sensor networks and Wireless Mesh Networks [78], many of these solutions face the new challenges imposed by wireless networks on SDN. The SDWN can help in solving some issues like the clients mobility and QoS demand, creating handover mechanisms in which migration decision can be taken by the SDN controllers and no longer by the stations (STA). This also help to more effective update the clients location in the network and the routes in the backhaul to reach them.

The use of SDWN takes additional importance in the new scenes of wireless networks for the integration of multiple network domains and multiple communications layers. In these new scenarios, the end-to end management of network resources is very important, including radio access networks, backhaul network and core networks. For wireless systems one of the most important task is to achieve a global wireless-optical network integration. These features can be obtained with relative ease under a centralized orchestration of the network, thanks to SDN and its agnostic nature regarding underlying technologies.

Although SDWN are becoming one of the fundamental pillars for the 5G paradigm in wireless broadband solutions, those networks have also been widely used in wireless Ad-Hoc mobile networks, vehicular networks and wireless local networks. For wireless LAN networks, solutions have been explored critical issues of mobility, routing and load balancing in the access network for the IEEE 802.11 standards. The use of SDN together with these wireless technologies allows the creation of architectures capable of supporting new applications that demand very strict requirements of the network, even some with the same magnitudes as expected in future 5G networks.

### 2.4.1 Software Defined Wireless Networks for WiFi Handover

With the increase of mobile services, WiFi networks have experienced an accelerated growth in the last decades. For 5G applications, particularly for mobile robotics applications, being able to deliver continuous and seamless client mobility is a key requirement. In IEEE 802.11 networks working in infrastructure mode, the STAs are associated with an AP, which is able to serve several clients while acting as a bridge to access the services of the network. As a consequence of the mobility offered by these networks, the STAs need to associate with different APs to maintain connectivity when entering a different coverage area, as shown in Fig. 6. Since STAs with one wireless interface can only maintain connection with a single AP, a handover mechanism is triggered to move client communication from one AP to another. This mechanism is driven by the clients and not by the network infrastructure, and is based on different criteria used by manufacturers, such as the loss of beacon frames or the degradation of link quality [79]. During the handover, the exchange of management frames between the STAs and the APs is carried out, which implies a delay for the re-association of the client with the new AP. In addition, it is necessary to spend a certain amount of time for updating Address Request Protocol (ARP) tables and for generating new routes in order not to lose contact with the moving client [80]. All those factors generate interruptions on client communication.

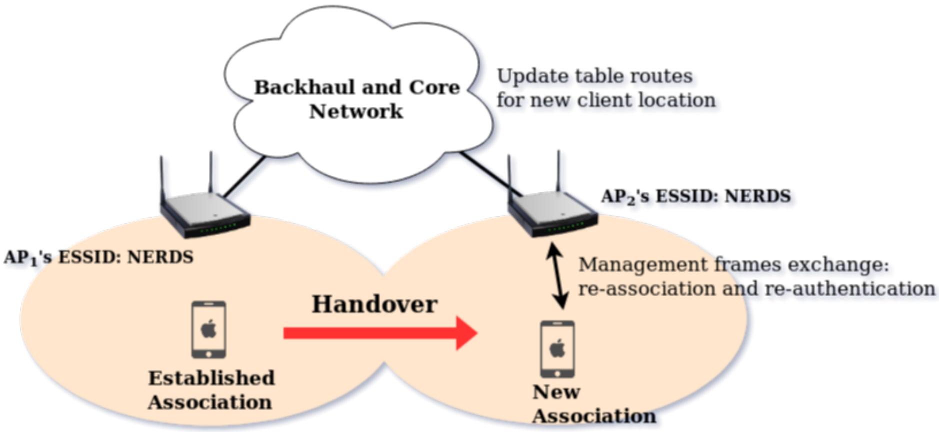



Figure 6 – Traditional WiFi handover process.

Several studies have been conducted to implement mobility management in SDWN. Ethanol, an SDN architecture for WiFi networks is proposed in [81]. This solution is able to control customer mobility characteristics and association/disassociation processes by denying association requests from the STA, forcing it to associate with another AP. A SDWN are proposed in [82, 83], where the creation of virtual AP for each client allows a seamless handover process through the migration of the virtual AP that serves the user who needs to move from physical AP. In these solutions, although handover processes are guaranteed without significant degradation in throughput, the aspects of updating backhaul after migrations are not addressed.

A mobility management mechanism is presented in [5], with a solution based on the concept of domains and on updates made in the backhaul depending on whether migrations are intra-domain or inter-domain. Though, it does not analyze the delays introduced by the exchange of management frame during the re-association process. In [80] a solution called BIGAP is proposed, in which all APs are configured with the same BSSID, creating a single global BSSID, but with different channel configuration for each AP. When the handover decision is made, the SDN controller copies the client's association information to the destination AP and generates a beacon informing the client of the new frequency (destination AP) of operation. After the destination AP is known, the SDN controller also updates the ARP tables or the routes in the backhaul as the case may be. Although

BIGAP efficiently addresses both the issue of the migration of APs and the delays that the re-association introduces, as well as the updates of the backhaul, its implementation becomes complex due to the number of states it has to manage and the synchronization that is needed for the migration and for updating routes.

Most of these proposals have one or more controllers in charge of triggering the handover process, and of performing the update of the client's association status in the destinations APs. However, none of them analyzes the occurrence of failures in the APs, a phenomenon that would cause a classic handover process, since the controllers could not migrate the client information for the available APs. In addition, these studies have maintained the operation in classic infrastructure mode of the WiFi networks. Inevitably, this type of operation forces clients during their mobility to re-associate with new APs, which imposes the need to find solutions that minimize the delays of the re-association. In [84], the mobility is placed in an AP through the use of a robot to obtain the best effective SNR between the AP and the client. Thus, if the normal 802.11 infrastructure mode is split into functional blocks, mobility could be placed in the AP and the access to network services could happen through non-mobile STAs. In this context, multi-connectivity can be guaranteed with the mobile terminal even if it has just one wireless interface, and allows to have more efficient handover processes and failover mechanism.

## 2.5 Conclusions

The development of wireless networks has gone through several generations which have been evolving to support different applications and services. At present, the world of wireless communication technologies is immersed in the implementation of the 5G of wireless mobile networks, a network paradigm that represents a true revolution for wireless communications. The 5G systems have the hard task of supporting a broad spectrum of new applications that demand high performance requirements from the networks that support them, considering applications that demand high transmission rate in broadband mobile scenarios, critical applications with high reliability and low latency requirements for communication and the management of thousands of communications for high density device scenarios. To achieve such objectives, the 5G architectures are based on a C-RAN that integrates a range of Multi-RAT within which includes a new standard developed specifically for 5G, connected to a virtualized service-oriented core network through software defined transport networks. The use of virtualization and cloud technologies allow the adoption of a network slice scheme for network resources allocation and management, so that different cases of uses and applications can be deployed over the same physical 5G architecture.

Among the different access technologies that 5G networks intend to integrate into their access networks, WiFi technology is presented as one of the most interesting. WiFi

Community specialists and wireless industry leaders agree in their 5G vision that WiFi is a fundamental technology to help 5G systems in their goals. Among the main arguments is the large deployment of WiFi equipment existing throughout the world thanks to the popularity achieved among users, along with the existence of WiFi interfaces in most of the users wireless devices. WiFi represents one of the basic technologies in the mobile traffic offloading, currently serving a considerable part of this traffic especially in indoor environments, a feature that will be increased in the coming years when the exploitation of 5G systems begins. In addition, 5G networks require the integration and convergence of licensed and unlicensed spectrum technologies, the latter predominantly dominated by WiFi networks.

The WiFi community has not been waiting to see how everything develops around them and have taken an active part in the development of the 802.11 standards to accompany the evolution of new business models. The new generation of WiFi standards address high throughput requirements, coverage distances, and device connections density or with capabilities to operate in new spectrum areas such as the mmWave band. These new standards seek to satisfy the same demands as the 5G systems for new applications and services, placing the WiFi networks in the competition with the new wireless technologies. However, the consensus of specialists in the branch is that 5G will not mean death for WiFi, on the contrary, both technologies will have to go hand in hand to converge in more robust and efficient wireless communication architectures. In this way, the use of already established standards supported by new technologies like virtualization and SDN can be explored to try to meet the new applications requirements in the existing network infrastructures.

# 3 Reliable Wireless Communications

In communications systems, latency is defined as the delay experienced by a information packet of a certain size, from the moment it enters a protocol layer in the transmitter until it leaves the same layer on the receiving side. Different applications define different maximum delay times that packets can experience in order for the solution to meet the performance requirements. From this, the communication reliability is understood as the probability that the packets will be delivered successfully within the defined latency limit, which may be affected by packets received with errors, lost packets or packets that have exceeded the deadline. Figure 7 shows the main requirements and technologies enablers for URLLC, in wich the characteristics that are addressed in this chapter have been highlighted. As discussed in Chapter 2, 3GPP has defined the Key Performance Indicators to URLLC, which highlights the reliability, latency, and density for throughput as the main ones, Table 3 shows the indicators for some industrial scenarios [85]. In this way, the main challenge of the 5G networks and in general of any type of network that requires URLLC is to achieve each one of these requirements, providing a balanced trade-off among them.

Table 3 – URLLC requirements for some industrial scenario [85]

| Scenario | E2E Latency | Reliability | Traffic Density | User Experienced Data Rate |
|---|---|---|---|---|
| Discrete automation motion control | 1 ms | 99.99 % | 1 $Tbps/km^2$ | 1 (up to 10) Mbps |
| Discrete automation | 10 ms | 99.99 % | 1 $Tbps/km^2$ | 10 Mbps |
| Process automation remote control | 50 ms | 99.999 % | 100 $Gbps/km^2$ | 1 (up to 10) Mbps |
| Process automation monitoring | 50 ms | 99.9 % | 10 $Gbps/km^2$ | 1 Mbps |
| Intelligent transport systems –infrastructure backhaul | 30 ms | 99.999 % | 10 $Gbps/km^2$ | 10 Mbps |

In this chapter, are addressed some techniques that allow increasing the wireless communications system reliability. The study is focused on techniques that exploit diversity in different ways to achieve reliable communications and the use of some multiplexing techniques that increase throughput and decrease latency. Diversity schemes are considered fundamental to achieve reliable communications in wireless channels [87]. To increase the reliability and availability of communication systems, diversity can be exploited in the time domain by repetitions or feedback-based re-transmission when the radio channel has changed its fading. This type of diversity that bases its operation in re-transmission schemes like Hybrid Automatic Repeat Request (HARQ) are widely used [3], but despite their good performance, they present the disadvantage of introducing latency in the system.

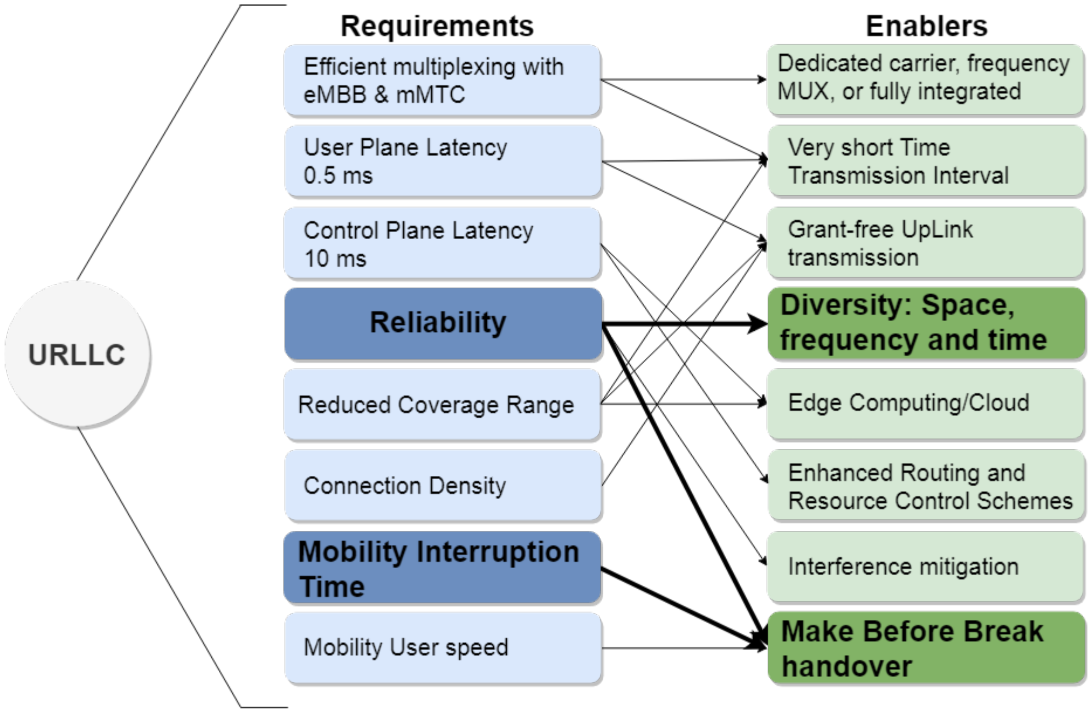



Figure 7 – URLLC: Requirements and enablers. [86]

The diversity schemes analyzed in this chapter do not need re-transmission techniques to achieve reliability, so time diversity schemes are not addressed.

## 3.1 Micro-Diversity

The wireless communication channels suffer, by their own nature, from dissimilar phenomena such as reflection, refraction and scattering, that cause the reception of the signals through multiple copies of the original signal transmitted [88]. This multiple paths propagation phenomena causes intense and rapid variations in the transmitted signal, generating alterations in the power of the received signal resulting of the summation of the copies arrived at the receiver. In this case, the signal can suffer from constructive interference when all copies arrive in phase or, in the worst case, destructive interference when the phase of the copies is different.

Another consequence of the multi-path is the temporary dispersion due to the delay, known as delay spread, which is the main cause of Inter Symbol Interference [89]. Due to multi-path, delay spread originates from a single impulse transmitted in time. If the time difference $\tau_{max}$ between the earliest arriving pulse and the latest arriving pulse is bigger compared to one symbol period, ISI can occur. The delay spread that occurs in the time domain is directly related to the Coherence Bandwidth ($B_c$) [90] in the frequency domain. The coherence bandwidth is the range of frequency over which the transfer function of the channel varies little, in other words, is the frequency range where the channel remains constant. Delay spread in the time domain translates directly into a frequency selective channel in the frequency domain. Narrowband systems are that with bands smaller than the $B_c$, characterized by being flat frequency. On the other hand, broadband systems are those for which the operating band is greater than the $B_c$, and in this case they are characterized by frequency selectivity and suffer from multi-path propagation.

### 3.1.1 Orthogonal Frequency Division Multiplexing

Frequency diversity techniques can be used to mitigate these phenomena of wireless communication channels. Frequency diversity [91] is achieved by forming a sub-channel through distributed sub-carriers, where the sub-carriers for the transmission are distributed pseudo-randomly through the available band. With this distribution, the probability that some sub-carriers do not experience channel fading is increased, and therefore the reliability of the communication in the transmissions using these sub-carriers is increased. The Orthogonal Division Frequency Multiplexing [92] also provides excellent benefits in fading mitigation, and although it is specifically a multiplexing technique, it bases its operation on the characteristics and advantages of frequency diversity for communication channels. OFDM is a digital multiplexing scheme that is considered one of the cornerstones of high-speed multi-carrier wireless transmissions. These techniques can be used both in radio frequency transmissions for local area networks and broadband networks, as well as for transmissions in wired media such as Digital Asymmetric Subscriber Lines (ADSL) [93] and optical fiber communications [94].

OFDM's greatest contribution is to implement a division of the radio channel into several narrowband channels to carry out the data transmission, creating sub-channels without selective frequency fading since for narrowband channels the channel can be considered constant. With this transmission scheme, multiple symbols can be processed in parallel and transmitted in serial through different sub-channels, increasing the transmission rates while guaranteeing a high spectral efficiency. This process, supported by the use of the Inverse Fast Fourier Transform (IFFT) for the multiplexing on the transmitter side and the Fast Transformation of Fourier (FFT) as a de-multiplexing on the receiver side, characterizes these systems as very efficient computationally [95]. OFDM systems also are characterized by providing high spectral efficiency, as a result of an equidistant separation between the sub-carriers frequencies, which allows in frequencies domain, that the sub-channels spectral overlap each other but maintaining orthogonality between sub-carriers. The orthogonality concept is the key in OFDM transmissions, allowing simultaneous transmission in a narrow range of frequencies.

The OFDM systems also mitigate the harmful effects of ISI [88]. This phenomenon, which is also result of multi-path wireless channels characteristics, occurs specifically when the transmitted symbol time is greater than the maximum channel delay $\tau_{max}$. To eliminate the noise produced at the beginning of the symbol by the delay in the arrival of the previous symbol, the symbol must be moved such a space so that it is not affected by the preceding signal, leaving a guard interval between symbols. This solution however is not enough, given that the absence of signal in these spaces of guard between symbols may lead to incorrect system operation, as those systems works in regime of continuous signals. As final solution to this drawback is introduced other main characteristics of the OFDM systems operation, the Cyclic Prefix [88]. This technique fills the guard space between symbols with a copy of the symbol tail, which keeps the start of the symbol outside the area affected by the ISI, whose length may vary depending on the specific characteristics of the radio channel.

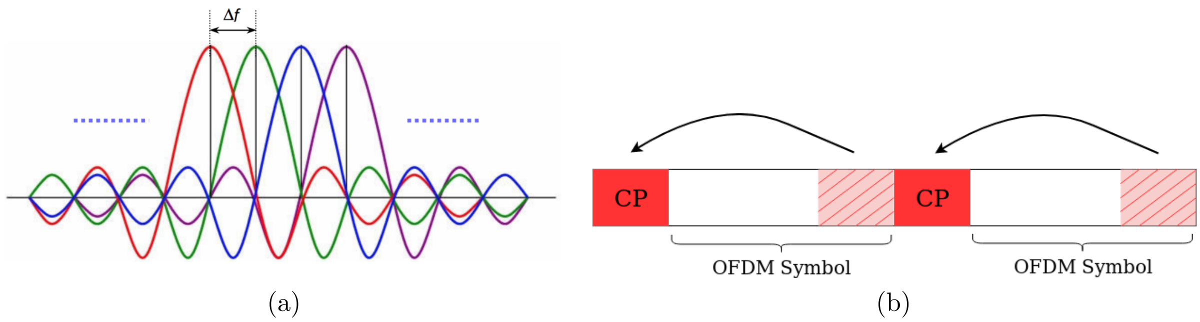



Figure 8 – OFDM for interference mitigation: a) OFDM frequency spectrum; b) OFDM cyclic prefix.

Multi-carrier transmission schemes, including OFDM, offer significant advantages over single-carrier transmission schemes. Single carrier schemes are not efficient in high-rate wireless transmissions, since to deal with the effects of ISI and the fading of multi-path channels, the complexity of their equalizers is very high. Differently, multi-carrier schemes can mitigate the negative effects of these phenomena efficiently, while maintaining simple reception schemes. Despite these advantages offered, OFDM systems may have problems with frequency synchronization, where the occurrence of frequency offset between the transmitter and the receiver causes the loss of orthogonality between subcarriers and consequently the appearance of ICI. In addition, the OFDM systems have disadvantages related to the Peak to Average Power Ratio (PAPR) [92], which measures the ratio between the maximum power that a signal can reach and the average power. The signal obtained at the output of an OFDM transmitter has a large dispersion in its amplitude, which means that its PAPR is high, and in some case can make the use of OFDM for mobile applications inefficient due to the use of very good amplifiers with a greater dynamic range to that of simple carrier systems.

### 3.1.2 Spatial Techniques

In order to reduce the impact of fading, spatial techniques are used in almost all current wireless systems. These techniques attempt to mitigate the effects of fading caused by multi-path channel transmissions taking advantage of the spatial diversity in communication channels. By transmitting replicas of the same signal through different propagation paths, each replicate suffers from independently fading. As with diversity frequency techniques, this increases the likelihood of a successful transmission, since the probability that all replicas will fade simultaneously decreases as the number of replicates increases.

The use of Multiple Input Multiple Output technology [96] has revolutionized wireless communications implementing space diversity through the use of multiple antennas in the transmitter and receiver. In MIMO, the multiple antennas can offer independent space paths operating at the same frequency between the transmitter and the receiver. These multi-antenna techniques, also known as micro-diversity techniques because they attempt to mitigate the effects of small-scale fading [97], can improve the performance of transmissions and increase the reliability of communication through the selection of the best signal or a combination of individual signals in the receiver.

A fundamental aspect in the micro-diversity techniques is the knowledge of the MIMO channel characteristics, as shown in Fig.9. The channel, represented by a transmission matrix, also known as Channel State Information (CSI) [98], determines which MIMO techniques is most suitable for use at a specific time, so that its knowledge greatly influences the channel capacity that can be reached. For Single Input Single Output (SISO) systems that use only a antenna, the status information of the SISO channel is constant and does not change, so CSI knowledge of this type of channel generally not is necessary since, it is characterized by a SNR in steady state. In multi-antenna systems, CSI varies rapidly, so diversity techniques allow the channel division in several sub-channels separated spatially for increase the system capacity [99]. The CSI Knowledge on both sides, transmitter and receiver, offers the possibility of incorporating this information into the design of intelligent systems. Each combination of transmitting and receiving antennas is represented by a complex number containing the amplitude and phase information of the the received signal after passing through the channel and undergoing the different effects of propagation in this type of channels.

There are three fundamental types of signal processing techniques in multiple antenna systems. These techniques are implemented through multiple chains of radio frequency processing, corresponding to the various antennas present in the system. Processing is implemented in hardware at the physical layer level, with control implemented at a high level by hardware controllers and drivers. These techniques are: spatial diversity, spatial multiplexing and beamforming.

#### 3.1.2.1 Spatial Diversity

Diversity refers to the transmission of replicas of the same signal through a fading channel such that each replica vanishes independently of the other. In addition, the combination of the different replicates allows that in case of deep fades their effects are significantly reduced because they do not occur at the same time. In this way, the reduction

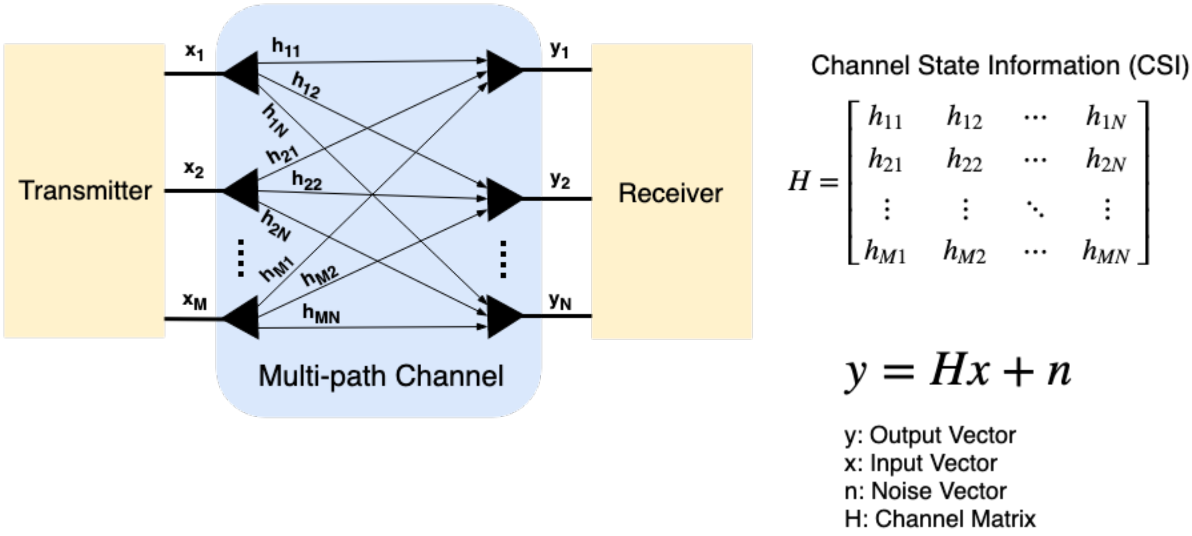



Figure 9 – MIMO System.

of the fading effects by spatial diversity can be characterized by two general processes: (i) the creation of independent replicas of the signal and (ii) the selection and/or combination of the signal replicas [100].

Through the use of reception diversity techniques, the signal replicas are combined at the receiver. The combination can be done in different ways, most of them with linear techniques whose output is only a weighted sum of the different paths, and depends on the complexity and efficiency of the system. This combination of signals from different branches requires a co-phasing process [101] so that all received signals are combined coherently with the same phase. The simple combination by overlapping signals omitting the co-phasing process in receivers with spatial diversity systems represents a signal combination that recreates the same channel fading effects without being eliminated. The combination techniques of multiple branches are performed post-detection in the receiver, which requires a specific radio reception chain that allows phase detection for each branch. This feature increases the hardware complexity and the power consumption for these devices when implementing several branches, so the commercial devices use at most 4 radio branch as a way to keep costs low.

The simplest type of combination in the receiver is known as a Selective Combination (SEL) [102]. This technique consists in comparing the received replicas at each sample time by the multiple RF chains and selecting the branch with the highest signal-to-noise ratio value for the output of the combiner. In this scheme only one branch is used at a time, which implies that the SEL requires only one receiver that is switched to the active antenna branch. In addition, since only one branch is used for the output, co-phasing of several branches is not required, so this technique can be used with coherent or differential modulation.

When a system transmits continuously, the SEL technique may require receivers for each branch in a way that allows it to monitor the SNR in each of these branches. To eliminate the need for a receiver for each branch, which increases complexity, another simple combination technique called Threshold Combination [103] can be employed. This technique performs a sequential scan of the different branches and places as the combiner output the first signal with SNR above a certain threshold. An element to keep in mind is that this method does not always use the branch of higher SNR, so its performance can be lower than that achieved in the SEL.

As a more advanced and efficient method to achieve reception diversity, the Maximum Ratio Combination (MRC) [102] can be used, which, unlike the previous techniques that only use the output of a branch, the output is the weighted sum of several receiving branches. The MRC optimizes the system operation by maximizing the capacity of the multiple input systems. This is performed by obtaining an SNR equivalent to the sum of the SNR received in each RF chain. In such systems that use this technique, the main objective is to determine the co-phasing factors that allow maximizing the SNR resulting from the combination. Since the resulting SNR at the output of the combination is the sum of the SNRs in each branch, the average of the combined SNR increases linearly with the number of diversity branches. To deal with the difficulty that represents the need of knowledge of the variation in time of the SNR in each branch for the combination of the signals, a simple technique of Equal Gain Combinations (EGC) [103] can be used. Basically this method co-phasing the signals in the different branches and then combining them with equal weighting. Figure 10 shows the comparison between receptions without diversity and with diversity using SEL and MRC [104].

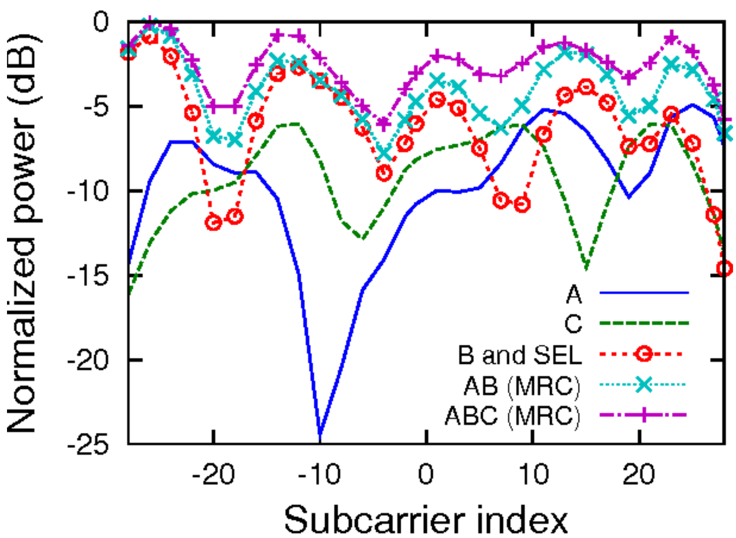


Figure 10 – Receive diversity. [104]

On the transmitting side it is also possible to implement diversity through multiple transmitting antennas, where the total power to be transmitted is divided among the multiple antennas. For systems in which transmitters generally have greater space and processing capacities, transmission diversity is an excellent option compared to diversity in reception. The implementation of diversity techniques in transmission can be somewhat more complex than those used in reception since they usually depend on whether or not the channel CSI is known to select between the antennas or pre-code the signals.

With channel information at the transmitter side (CSIT) [105], transmit diversity is very similar to the reception diversity, with systems that simply select the best antennas to transmit the information. When the channel is known, the transmitter precodes the signals, delaying them in phase so that the copies combination is constructively in the receiver antennas. In addition, the weighting of the total transmission power between the different transmitting antennas is carried out using the well-known Water Filling algorithms [106]. Water Filling employs optimization techniques that allow the allocation of different amounts of power to each space path based on its SNR. This type of systems are also known as closed-loop MIMO systems, since they require feedback from the receiver to obtain the most accurate information possible about the wireless channel status.

The main disadvantage is that the transmitter's knowledge of the channel depends on feedback from the receiver, after carrying out the channel measurements by means of pilot sub-carriers sent in the transmitted packets. It happens that in many occasions these feedback are not convenient because they can saturate the radio channel, especially in channels that vary more quickly with time and that need more frequent feedback. In these cases where the transmitters do not know the information of the channel, known as open-loop MIMO systems, spatial diversity and time diversity combining techniques are used for transmissions. To do this, the Alamouti schemes are used, which allow a Space-Time Block Codes (STBC) [107]. These encodes based on linear processing were developed for digital communication systems with two transmit antennas operating during two periods of symbols in which it is assumed that the channel gain is constant during this time. These space-time codes are easier to implement than precoding but their performance falls when the systems have more than 2 transmitting antennas. However, the Alamouti encoding was one of the first developed space-time codes, and is currently included in most modern wireless standards that employ MIMO techniques.

Another type of space-time coding used in systems to transmit diversity are the Space-Time Trellis Codes (STTC) [108], which can be considered an extension of the Trellis codes for MIMO systems. These codes can offer greater advantages than the STBC codes since in addition to offering complete order diversity such as STBCs, they also offer coding gain. The main disadvantage is that the complexity of decoding increases exponentially as the diversity orders increase, hence the STBCs represent a good alternative.

#### 3.1.2.2 Spatial Multiplexing

Spatial Multiplexing [109] refers to the transmission of multiple data streams through a multiple outputs system to exploit the multi-path feature of the channel. In this way, several different data channels transmit simultaneously over the same frequency range. As in other multiplexing schemes, the SM increases the number of bits per second transmitted, increasing the data transmission rates of the MIMO systems. In the SM schemes as the signals are placed in different space channels operating all on the same bandwidth, as shown in Fig. 11, they do not suffer from the bandwidth expansion as occurs in time and frequency multiplexing systems.

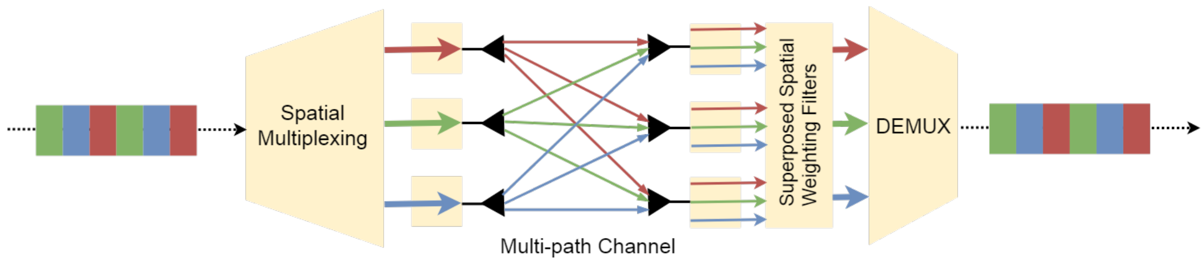



Figure 11 – Spatial multiplexing.

To achieve a good performance of the spatial multiplexing and achieve transmissions with high performance, the MIMO channel must present a significant amount of dispersion between the multiple paths. Although in conventional communication systems the multi-path channel degrade the communication performance, the SM takes advantage so that the transmitted signals suffer from independent fading. To reach the necessary degree of dispersion it is considered that the spacing between the multiple antennas in both the transmitter and the receiver must be at least half wavelength of the frequency at which the system operates. In this way, given that the SM practical gain can be limited by the channel spatial correlation, the dispersion indexes are increased to achieve communication channels that are as spatially uncorrelated as possible [110].

In order to achieve good performances in the spatial multiplexing operation by obtaining complete diversity orders, different coding mechanisms of the bit frames can be employed. The first and simplest mechanisms we there is the transmission of the bit frames through the multiple antennas using a serial encoder. In this case, the bits are temporally coded under the block length of the channel, so after being interleaved and mapped in the constellations to be transmitted, they are demultiplexed and sent to the different antennas of the transmitter. At the same time, this causes that the decoding complexity grow exponentially when the number of transmitting and receiving antennas increase, since a greater codec word is required to exploit the maximum diversity. In spite of being a relatively simple mechanism to implement on the transmitting side, serial coding in an impractical encoding because the difficulties faced by receivers in decoding.

Another simple method in the implementation spatial multiplexing implementation is the Bell Labs Layered Space Time (BLAST) architecture [96] for MIMO systems, in which the main feature is the use of parallel coding. With parallel encoding, the data stream is demultiplexed into independent flows and each resulting sub-flow is passed through a temporary encoder, interleaved and mapped to a signal constellation point and transmitted by its corresponding transmit antenna. It can also be found as a vertical encoder or V-BLAST [111], since it is considered a serial data encoding process in a vertical vector.

The maximum diversity order that allows vertical encoding to be reached is of the order of the maximum number of receiving antennas, lower when compared to serial coding, but the systems result in a simple coding complexity that is linear to the antennas number. In addition, complexity at the receiver can be reduced considerably in vertical coding systems by employing symbol interference cancellation techniques at the transmitter.

To take advantage of the diversity benefits offered by series code and the low complexity of vertical coding systems, the solution known as Diagonal BLAST (D-BLAST) was created [112]. In this scheme the data stream is first serially encoded and then the codeword symbols are rotated so that the codewords are distributed over all available transmit antennas. The complexity of the receiver is also linear in the number of transmit antennas, since the receiver decodes each diagonal code independently.

In MIMO systems, the existing trade-off between the reliability in the transmission achieved with the spatial diversity and the increase of the capacity of the system thanks to the spatial multiplexing must always be considered [113]. In addition to this trade-off, a key aspect is also added when designing and implementing a MIMO system, which is the hardware complexity that each specific technique imposes for transmitters and receivers. Thus, the systems must have mechanisms that allow the adaption and exploitation of the diversity and multiplexing gains relative to channel conditions at any time. To this end, radio access networks virtualization and software control of the proposed architectures in the new wireless networks paradigm will be of great help.

#### 3.1.2.3 Multi-User Diversity and Beamforming

As happens in systems that exploit spatial diversity, systems with multiple users can also take advantage of the fact that the channels used by each of these users suffer from independent fading. The systems that use this premise are said to implement users diversity [114], taking advantage of the fact that there are time instants where some users channel will have better conditions than other users. Therefore these schemes, allow transmissions of users with the best conditions, allocating system resources for these users who will be able to use them more efficiently. Multi-user diversity that was first created to increase throughput and reduce the chances of errors in the uplink channels, has been extended in the current wireless systems also to the downlink channels [115]. Its performance also depends on the number of independent channels available, so they are more effective in solutions with a large number of users that increase dispersion conditions.

To maximize throughput on a fading link, the entire band of the system is assigned to the user with the best channel in each fading state. In the case that users present different fading statistics, the channel is assigned to the user with the best weighted gain of the channel, depending on the gain of the user's channel, its fade statistics and its power restriction. This type of transmission to users based on the channel conditions is called opportunistic programming transmission [116], and helps increase the multi-user wireless links performance and Bit Error Rate (BER) values in wireless communications.

The transmissions programmed for the users with the best channel present problems with the impartiality when making the transmission decision and with the delay that some users face in order to carry out their transmissions. When the fading conditions in the users' channels vary slowly, then users who have earned their right to transmit would be occupying the system most of the time. This causes that the times that users with worse channels should wait are very long, directly affecting the critical applications performance, with system resources assigned unevenly for the users. To solve these problems, which fundamentally affect downlink links, can be used. An algorithm that analyzes if the performance between the different users is fair, in that case the resources are still allocated for the users of better channel condition [117]. In case that some user performance is deficient, that user will be favored in the allocation of system resources until their performance is reasonably balanced with that of the rest of the users.

Multi-user systems are also exploited in MIMO systems. In these systems, multi-user diversity offers abundant directions where users have good channel gains, so in addition to resources allocation for users with the best conditions, an adequate spatial separation is also provided that helps to limit interference between users as shown in Fig. 12. Multi-user diversity increases with dynamic range and channel fading speed. With techniques such as opportunistic beamforming [118] the amplitude and phase of the multiple transmitting antennas can be controlled to increase the fading speed and the dynamic range and thus obtain greater multi-user diversity gains.

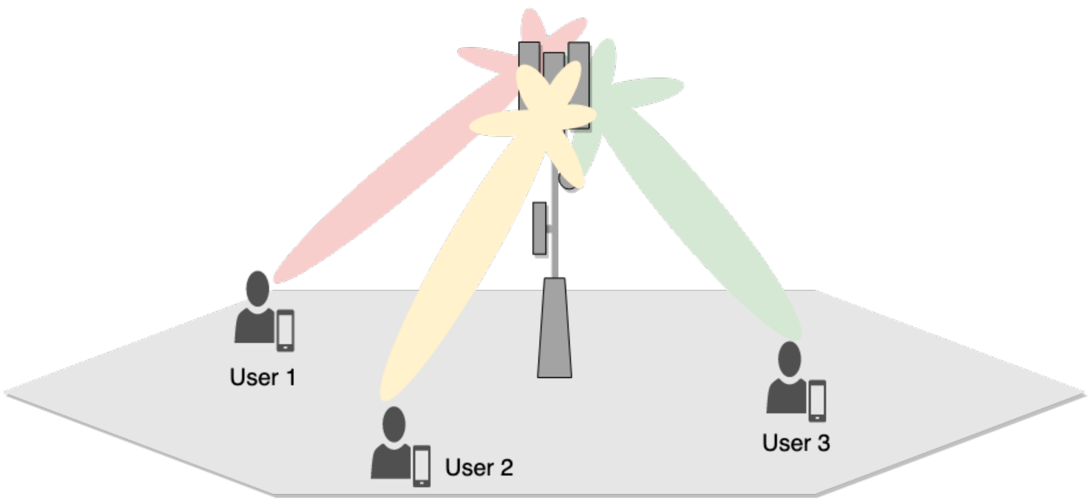



Figure 12 – Multi-user beamforming.

The beamforming techniques [119], realized through the use of adjustable electrical antennas, allow the direction of the beam towards the receivers without having to move the antenna mechanically, as shown in Fig. 12. With changes made in the transmission phase in each antenna, it is possible to concentrate the energy along lines of constructive interference between the elements of the array of antennas. For this, the beamforming transmission uses the channel estimates to determine the spatial matrices for the signal transmission. The objective is to improve the received signal strength at the receiver, emphasizing the dominant transmission modes of the channel. The receiver after receiving the CSI feedback sent by the receiver (closed-loop beamforming), builds the steering matrix and applies this mathematical transformation to the signal that is transmitted.

There is also another type known as implicit beamforming (open-loop beamforming) that does not use the exchange of frames to know the channel before transmitting [120]. In this last case, the transmitter infers the steering matrix through the information packets received from the receiver. Implicit beamforming to be based on less rigorous measurements of the channel does not provide high performance to the systems, but the systems complexity is lower because it only needs to be implemented in the transmitters.

## 3.2 Macro-Diversity

Macro-diversity techniques are used to deal with slow fading phenomena in wireless channels such as path loss and shadow fading or when cell failures occur. Through the use of macro-diversity it is possible to establish more links to different radio access points, which may use the same access technology or combine together different technologies. Through the data duplication and multiple transmission techniques from the base stations, the macro diversity helps to increase the wireless communications reliability, and provides robustness to the systems during the handover process and recovery before possible failures of the infrastructure [21]. In some cases, the implementation complexity of some techniques is relatively simple compared to micro-diversity solutions since it does not require deep transformations at PHY layer of the wireless elements.

In 5G networks, the macro-diversity of accesses has been treated as dual-connectivity, which is the first stage to more complex and robust solutions that will use multi-connectivity to achieve ultra-reliability, low latency and interruption times almost equal to zero during handovers. Redundancy of links or multi-connectivity in broadband wireless networks can be achieved fundamentally in two ways [3],first through Carrier Aggregation (CA), that makes use of frequency diversity. The second, called Dual-Connectivity (DC) [3], uses the possibility to connect simultaneously with two different base stations. The main benefit of both methods is that more reliable transmissions are achieved by duplicating packets [121] that are handled by link layer protocols and sent over uncorrelated channels.

### 3.2.1 Carrier Aggregation

Carrier Aggregation is a multi-connectivity technique in the frequency domain [122] that was introduced by 3GPP for LTE networks in its Release 10. The main objective of this technique is to increase the transmission bandwidth by adding two or more carriers. In this scheme, the user station maintains its connection with the same base station through multiple carriers that can be continuous or not, intra-band or inter-band. Although the original idea is to increase the transmission rates thanks to higher bandwidths, the fact that the base station maintains more than one connection with the cellular infrastructure, allows to explore techniques that help to increase the communication reliability with redundant data through the carriers.

In carrier aggregation solutions, the base stations have two PHY layers that enable communication by multiple carriers with the user station [3]. Under this principle, the data aggregation and distribution process is performed in the MAC entity, with the component carriers being invisible to the Packet Data Convergence Protocol (PDCP) and the Radio Link Control (RLC) layer, as shown in Fig. 13. In this way, the solution have a minimal impact from user plane protocol perspective, and the MAC layer allows a centralized programming of the packages distribution and communication resources allocation. However, a great capacity for integration between this common MAC layer and the underlying physical layer protocols is needed.

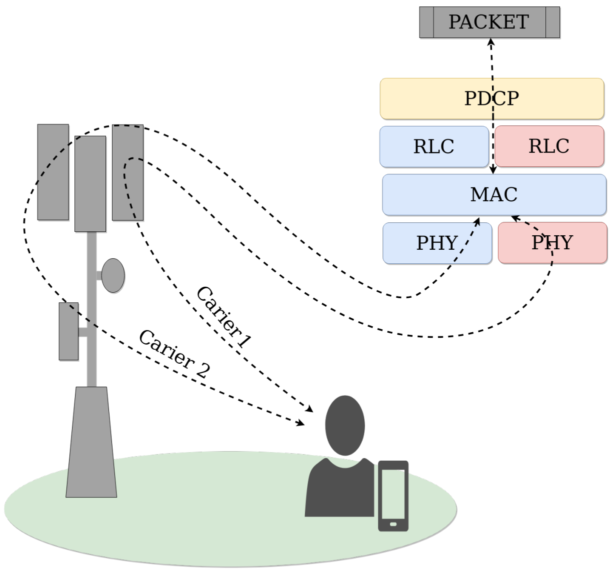



Figure 13 – Carrier Aggregation Solution. [3]

The introduction of carrier aggregation and its evolution has brought many advantages for wireless communications today. First of all, this technique offers a more efficient use of the spectrum than single carrier techniques, since operators can combine fragments of spectrum into larger blocks to obtain bandwidths greater than those achieved with a single carrier. With it, dynamic load balancing can be implemented for real-time network data, more reliable and robust network services, in addition to expanded coverage with carriers, providing scalability for the network. All these benefits directly influence a greater user experience through higher user data rates and lower latency.

### 3.2.2 Dual Connectivity

Dual Connectivity was introduced for the first time in release 12 of 3GPP for LTE networks and now extended for 5G systems [123]. Unlike in CA, user stations maintain simultaneous connections with two different base stations. In this case, one base station will operate as primary and the other as secondary, each operating at different carrier frequencies and both connected through a backhaul network. The DC techniques can also be used in heterogeneous network solutions, as a variant for the integration of different radio access technologies [124], where the primary station belongs to one RAT and the secondary station belongs to another. This last variant of DC will be widely used in 5G networks, for the integration of 5G NR, LTE and WiFi technologies.

The architectures where the base stations have differentiated functions in primary and secondary, offer more flexibility to the operators in the management processes of the communications and a better performance in the energy consumption management [125]. These advantages are obtained given that the primary base station is the only one that has the responsibility for the connection management with the user station, while the secondary base station is only activated in case there is data to be transmitted.Another important characteristic of DC is that the point of data aggregation and distribution is now carried out by the PDCP, as depicted in Fig. 14. Thus, each base station has its own individual MAC layer with better integration to the PHY layer protocols and with better adaptation to a particular connection with user stations [3].

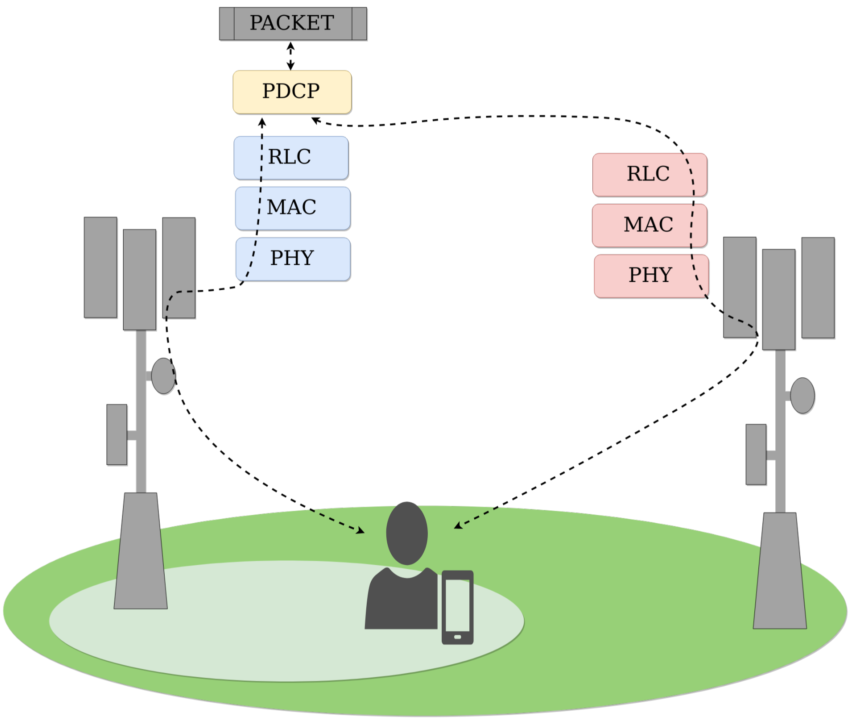



Figure 14 – Dual Connectivity Solution. [3]

The DC techniques developed for LTE networks, offer broadly the same advantages as CA in terms of increased transmission rates, decreased latency and increased reliability and availability of network infrastructure and communication. However, as previously mentioned, efforts in the sense of multiple connections with user stations must continue, both for the integration of different access technologies and for achieving more than two connections per user. In the new high-density mobile device scenarios, with the deployment of UDN networks and the implementation of picocell coverage areas, the use of two connections is insufficient to guarantee the best communication performance in these scenarios, so that new multi-connectivity schemes that exploit interfaces diversity mechanisms in user stations are necessary. At the moment 3GPP has published in its Release 15 [126] the use of CA and DC in LTE and NR as solutions to improve the reliability of transmission in higher layers, additional to the reliability that each PHY layer radio technology offers. With the support of these two multi-connectivity solutions, packet duplication is used as one of the main techniques to achieve reliability in wireless networks.

### 3.2.3 Packet Duplication

Macroscopic diversity techniques also allow the implementation of packet duplication through different or several base stations or access points, and the diversity is achieved duplicating the application's data packets and transmitting those through sockets attached to different communication interfaces. This data redundancy is one of the main characteristics to achieve high reliability communications systems, while mitigating the effects of interference between cells in wireless communications and also offers robust systems during handover processes in mobile scenarios. The packages duplication in addition to contribute with the reliability reaches its destination through different paths, also helps in the reduction of latency since the latency is determined by the first arriving packet, which will be the package that travel along the path where the network offered better performances. The theoretical foundation on which the packages duplication is considered as a technique to provide reliability for communication systems is based on the concept that system reliability can be increased through multiple subsystems operating independently in parallel [121]. In wireless system this parallel subsystems are represented by the different transmission link, so increasing the number of links carrying the same data increases the system reliability.

The duplication of packages as a technique to improve the performance of systems through the use of parallel redundancy was introduced with the Parallel Redundancy Protocol (PRP) [127], which was created to address the problems concerning fault tolerance in industrial Ethernet networks. This protocol to industrial networks exploits transmission redundancy mechanisms in the data networks and operates in MAC layer. The devices that participate in these systems remain connected by means of two interfaces to two different and independent Local Area Network (LAN) in a scheme that exploits the interfaces diversity [128], so the re-transmission of the information will only be necessary if both networks fail to deliver the data. The protocol works by adding a field called Redundancy Control Trailer (RCT) located after the Ethernet frames payload, which is used to tag all transmitted frames with a value of an incremental sequence. On the receiving side through the analysis of the tag value in the received frames, the protocol will only deliver to the upper layers the frames with labels received for the first time and will discard all the frames whose label has already been received.

Time Sensitive Networks (TSN) is a new Layer 2 technology [129] that aims to provide deterministic messages using standard Ethernet through switches capable of handling TSN flows. Through a centralized network management, this technology offers guarantee in the frames delivery and fluctuations minimization in the delivery using time programming, fundamentally for real time applications in industrial environments. Several protocols integrate the set of protocols used in the TSN, among them the protocol 802.1CB published in the year 2017 [130] that offers perfect redundancy, which is responsible for frames duplication and elimination for the communication reliability. The standard divides a flow into one or more member flows, which makes the original flow a composite flow, and to guarantee inter-operability with similar standards like PRP, are defined schemes to identify the packages belonging to each flow. Its main difference with PRP is that it can combine redundant routes with non-redundant routes by using TSN switch. These switches are the heart of the standard, since they duplicate, eliminate and work with the TSN flows that are handled by the final nodes with a single network interface.

Beyond its use in Ethernet networks, this protocols also has been presented as an interesting and powerful solution to implement reliable communications in wireless environments [131]. In wireless communication systems that implement packet duplication as a technique to increase the transmissions reliability through multi-connectivity architectures, the architecture must have the autonomy to decide when trigger or stop the packet duplication. If the link between a user and a base station presents excellent transmission conditions, to the point that reliable communication between them can be guaranteed, implementing techniques for packet duplication far from helping would cause unnecessary processing in the devices and spectrum use. To guarantee this important requirement, there are two main approaches for dynamic control of packet duplication. The approach where the decision to duplicate/deduplicate the packets is triggered by the network, in which the network uses the measurements of the state of the channel and the load information in the network itself to evaluate the base stations with the best conditions for support the duplicate transmission. In the second approach, the decision to trigger the packet duplication is made by the user's device only for uplink communications and generally when grant-free techniques are applied for short packet transmissions, the evaluation is based also on different measurements of the wireless environment [121].

For wireless communications in 5G networks, 3GPP implements the duplication of packets as a technique to achieve reliability in the user plane and control plane [132]. In the proposal, the packets duplication is implemented in the PDCP layer, the transmitter side is responsible for the duplication, and the same layer in the receiver is in charge of eliminate duplicate packets. The dual connectivity solutions allow to implement the duplication mechanisms without great efforts, using a same PDCP layer and different MAC/PHY layers. The packet duplication schemes can also be implemented in CA solutions where the user data is divided into multiple carriers in the MAC layer. Similar to the duplication detection in Ethernet solutions, in LTE networks that represent the prelude to the 5G solutions, the PDCP layer supports duplicate detection functionality based on the sequence number. In this way, the receiver only processes the first copy received from a specific sequence number, contributing directly to the reduction of transmission latency.

The main benefit of the packages duplication is its implementation simplicity to meet the strict requirements of URLLC in 5G networks, exploiting the frequency and path diversity, so it is considered a key mechanism in modern wireless communication architectures. Its characteristics to contribute in the reduction of the latency, potentially reduce the jitter of the wireless communications. The packets duplication in mobility scenarios is one of the fundamental techniques to guarantee seamless handover process. In these scenarios the duplication can help in the accomplishment of procedures of handover Make Before Break to diminish the interruption time during the handover, as well as offer robustness to the systems avoiding interruptions to possible failures.

### 3.2.4 Network Coding

Network coding are methods that can be used to improve the throughput, scalability, robustness and reliability of networks [128]. The network coding emerged with the objective that the routing and forwarding devices did not need to send the same packets they received, but could send any combination of the mixed packets. These techniques can be used for various applications such as multimedia streaming, cooperative communication, packet re-transmission, and protection of connections [133]. For the different future solutions of wireless networks, the network coding methods provide potential benefits, helping to achieve better levels of throughput in the networks since the coding allows the network nodes to realize a compression of the information to be transmitted. At the same time these schemes actively influence in the increase of wireless networks reliability allows to reach high throughput and in many cases eliminates the need for re-transmission in low SNR scenarios, contributing to the decrease transmission latency [134].

With these characteristics, network coding schemes can be used as techniques capable of supporting cases of use of URLLC for 5G systems. Reliability and latency parameters can be improved for solutions that implement interface diversity together with network coding [128] through different transmission strategies, as shown in Fig. 15. In the first strategy called Cloning, the source device performs the transmission of exactly the same message through all the available interfaces, giving maximum reliability to the system, in a similar way to the mechanisms of packet duplication. Another strategy is the Splitting of messages in which only a fixed-sized part of the encoded message is transmitted by each interface. In this way it contributes to decrease latency since the destination decodes the message with fewer messages received. In the last strategy the transmission of encoded messages of variable sizes is done by specific interfaces to minimize the transmission latency

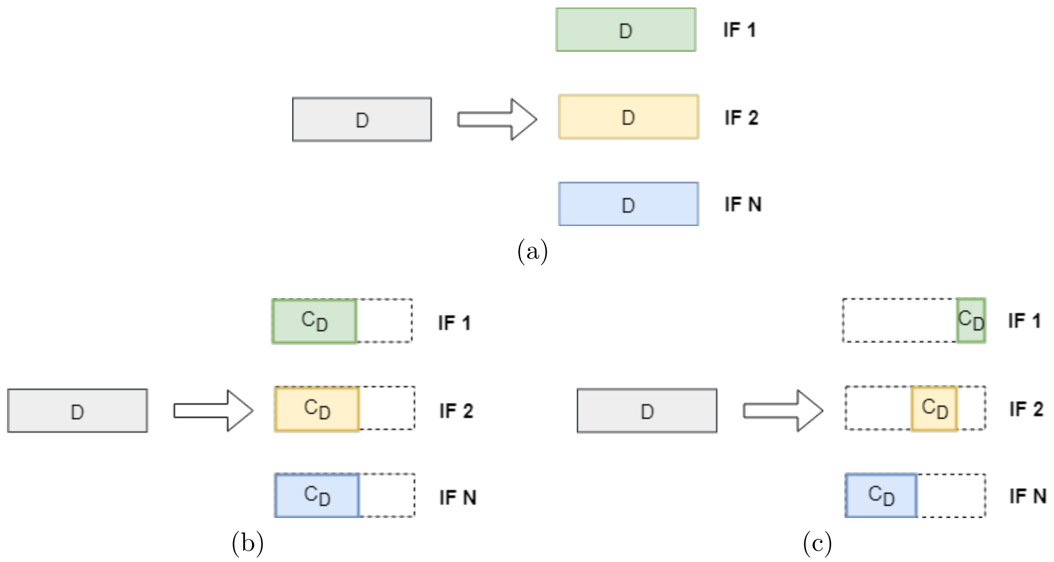



Figure 15 – Network coding transmissions strategies [128]: a) Clonning; b) Splitting $k$-out-of-$N$; c) Splitting Weighted.

or increase the transmission reliability, based on some previous knowledge of the of the channel state for each interface. Under the same principle of coding in smaller packages, solutions are applied to improve the performance of handover processes for local and broadband wireless networks [135, 136].

## 3.3 Network Topology

The way in which the network topology is projected is also another factor that directly influences URLLC. In order to achieve reliable connectivity through the association with base stations closest to users that have the best transmission conditions, the base station densification is one of the main solutions. The concept of UDN emerges through the implementation of novel small cell concepts to achieve high throughput requirements in 5G networks [46]. Distance reduction between users and base stations also contributes to reach URLLC through short association distance, per-user resource allocation increase, and multiple associations. However, this type of networks presents as a limitation the appearance of greater interference between cells, mainly in the downlink traffic, as a result of the high cell density, which can be mitigated by cooperation between neighboring base stations [137].

### 3.3.1 Network MIMO

When users of a wireless system are served by several access points, the network is known as a MIMO network [138]. In this type of solution there are assigned the same resources in the time and frequency domain to users, so to avoid interference between users, a spatial separation is made by transmissions through several radio access points. The MIMO techniques have been better known to be used as a kind of smart antenna technique in the last generation of wireless devices with which it seeks to exploit the spatial diversity as a way to mitigate the undesired effects in multipath channels. As is the case with MIMO antenna systems, MIMO networks, also known as Joint Transmissions (JT), use the CSI to make the best stations to transmit [139]. The information is shared through the backhaul network, common for all base stations.

As part of this macro diversity, the JT techniques in systems with cooperation between several base stations can be categorized or divided into the following types.

1. The coherent joint transmissions where base stations have detailed information about the state of the wireless channel of the link between all the base stations and a specific user, which is shared among all the base stations belonging to the same subset of cooperation. In this way, the BS transmit together the same message to the user in the same time-frequency resource, where the transmitted signal is jointly precoded with prior phase alignment and tight synchronization across base stations to achieve coherent combining at the user, exploiting the characteristics of phase and amplitude between channels associated with different base stations [140].

2. The non-coherent joint transmissions where the signal is transmitted by multiple cooperating base stations without prior phase alignment and tight synchronization across base stations, since CSI between base stations and client is not used. The main feature that aroused the interest in this type of transmissions is the low complexity of implementation compared with coherent transmissions and the ability that offer to implement load balancing [141].

These transmission cooperation techniques are widely used not only for increasing the performance and reliability of the links, but also for being a method to mitigate inter-channel interference at the edges of the cells or areas served by the access points [142]. The cooperation for broadband networks has already been consolidated through the Coordination Multi-Point (CoMP) solutions [143] with many researches to consolidate this type of solution for heterogeneous networks, however it has not been very popular for indoor networks using WiFi technology.

### 3.3.2 Coordinated Multi-Point Systems

The evolution of high density networks topologies, increased the tendency to implement smaller coverage cells to achieve better factors of frequencies reuse. These characteristics in addition to need migration techniques between cells more efficient and reliable, requires paying particular attention to the communications performance in each cell, performance that in these type of networks is significantly affected by inter-cell interference. To face this challenge, the 3GPP in Release 11 for LTE-A networks, proposes a cooperation technique for base stations in this type of networks that allows the optimization of transmissions and receptions from multiple distribution points [144]. Under a similar concept to the traditional MIMO techniques, CoMP unifies the multiple transmit and receive antennas of multiple sectors belonging or not to a physical cell, thus improving the signal quality by decreasing the received interference. The CoMP solutions are also expected to be one of the fundamental characteristics of the 5G systems [145] given their facilities to increase the capacity of these systems in homogeneous and heterogeneous networks.

The CoMP techniques are implemented based on the direction of the data traffic transmission, being categorized in downlink and uplink schemes. CoMP downlink transmission schemes can be classified in a general way into three fundamental types, which define the way in which data transmission is carried out. The first type is Joint Processing (JP), which may be a coherent or non-coherent transmission, and represent the same joint transmission techniques seen in the previous section. The second type is the Dynamic Point Selection (DPS) [146], considered a special case of JP whose main feature that differentiates it is that the user data is transmitted only from one base station at a time, and these base station is changed dynamically depending on the resources availability and the channel conditions. Finally for downlink transmissions can be implemented Coordinated Scheduling / Beamforming (CSB) [146], in this scheme the information of CSI is shared by the base stations to coordinate scheduling and beamforming design, and only from one station base is served the transmission. For CoMP uplink transmission schemes [147] can be implemented Coordinated Scheduling/Beamforming, precoding design is done by users with coordination between the base station in similar way to the JT downlink, and Joint Reception where the user data is received by multiple base stations jointly.

There are many challenges for these transmission schemes to achieve their objectives, and to create more robust systems against interference and with greater transmission capabilities. One of the main challenges is clustering and the way in which cooperating stations are grouped together. With the use of the self-organized network to support this task, can be implemented solution of static clustering, semi-dynamic clustering and dynamic clustering to achieve better network performances in terms of interference mitigation, energy consumption and resource allocation [147]. The estimation of the channel state is another CoMP challenges for cluster structures with large numbers of stations, especially in uplink transmissions that need larger amounts of orthogonal pilot sequences to make the estimates. Through the bakhaul network all the information is shared among the base stations to carry out the cooperation transmission tasks, so the backhaul reliability and availability with very small latency feature is another of the main challenges [148]. Other challenges that must be faced are aspects such as the stations synchronization in a cluster, and the design of control and management solution for CoMP orchestration.

## 3.4 Reliable and Seamless Handover

In mobile scenarios, the user devices move between different coverage areas, each one governed by a base station, and in order to keep a continue service delivery, handover mechanisms are employed. In function of the way in which the migration process of the traffic flow is carried out towards the new base station or channel, the handover mechanisms can be classified as hard handover or soft handover [149].

The hard handover, also known as Break-Before-Make (BBM) handover, represents one of the first techniques for the users migration between different base stations. In this technique, the mobile user is only connected to one base station at the same time, so to migrate and establish a link with the target base station, the link with the source base station is first broken. Even when telecommunications systems that use hard handover techniques try to maximize the performance of these mechanisms in terms of quality of service offered to users, the fact of breaking the link before connecting to the target base station degrades the communication performance given the time it takes to establish the new connection. This can be further aggravated if the user stations remain in a convergence zone between cells served by different base stations, which could cause the so-called ping-pong effect [150] which are nothing more than unnecessary handover processes.

The techniques of packets duplication are not limited only as enablers of reliable communications, can be applied in other cases of uses of which highlights the mobility scenarios. Soft handover mechanism are often used as a technique that connects the mobile terminal simultaneously to more than one base station. This approach based on the multi-connectivity concept offers a great advantage of reducing, or even eliminating altogether, the interruption time through Make-Before-Brake (MBB) procedures for handovers, which also helps eliminate the ping-pong effect occurrence. Under the hypothesis that mobile terminals could be provided with multi-connectivity, not only better performances would be achieved during the handover processes, but also it would be possible to guarantee failover recovery mechanisms.

To address the communication reliability in 5G systems, the Mobility Interruption Time (MIT) generated by handover processes must be analyzed in addition to the success transmission probability without delay. In this context, the most important requirement to fulfill URLLC constraints is to minimize the interruption time during the handovers [151] (most frequent in the UDN with small cells deployments), with the ideal objective to achieve zero MIT. To achieve this goal, 3GPP has introduced handover techniques for the NR interfaces of the 5G systems [152], some of which are already implemented in LTE-A solutions. To reduce the handover interruption time is used the handover MBB or an introduced mechanism for LTE networks called Random Access Channel (RACH) -less handover, which can reduce the interruption times to 15 ms and 41 ms respectively. To further increase the handover efficiency, both techniques can be combined to decrease the interruption time to only 6 ms. Exploiting the benefits of multi-connectivity systems, another mechanism known as handover MBB with two transmitters/receivers allows obtaining interruptions times well close to zero, with the user device able to exchange information with two base stations simultaneously.

The handover techniques addressed up to now are used mainly within homogenous networks with architectures that use the same radio access technology, so these techniques are called horizontal handover. However, as previously discussed, 5G systems must support heterogeneous technologies in their RANs, integrating 3GPP technologies and non-3GPP technologies. In this type of scenario, the user devices have multiple radio interfaces to interact with the multi-RAT systems, being able to make migrations from one technology to another, a process that is called vertical handover [153]. In heterogeneous wireless communication technologies, the handover management is crucial because RATs typically differ in terms of multiple parameters, making the decision algorithms more complex, so the use of SDN will play a significant role in these processes [154].

The decision algorithms used to trigger the handover can be very varied, ranging from the most simples and intuitive to the most complex and elaborate. Among the most used for its operation simplicity is the approach based on the Received Signal Strength (RSS) [155], which is used in horizontal and vertical handover mechanisms. This approach is often inefficient, especially in today's complex wireless scenarios, where channel conditions information, or bandwidth and quality of service capabilities that base stations can access, results in more valuable information. In this way, the handover decision algorithms have been evolving together with the networks themselves and with the own requirements that the applications demand, being able to find criteria based on Signal to Interference Noise Ratio (SINR) [156], based on cost where parameters such as the available bandwidth are analyzed [157] or the quality of service required [158]. Already with high complexity degrees, but capable of meeting the demands for the new generations of wireless networks, it is possible to find handover algorithms that use network context information to perform migrations of user stations, mainly in heterogeneous networks. These context-aware handovers algorithms [159] make active use of the network intelligence achieved through SDN solutions together with Machine Learning (ML) techniques [160], to obtain the best performance during these processes, increasing the wireless systems reliability, availability and scalability.

## 3.5 Conclusions

The 5G systems have among their main features provide support applications that demand strict latency and reliability requirements from the network. For these cases, the URLLC use scenario for 5G networks has been defined for support these applications, with special attention to the complex trade-off between latency and reliability. The communication reliability defined as the success delivery of data in the time limit required by the application, is one of the main challenges for the 5G networks, where their heterogeneous network characteristics make the task more complex. To increase the wireless communications reliability it is fundamental the use of different diversity techniques to be implemented at different layers of communication architectures.

The multi-path conditions in wireless communication channels cause unreliable transmissions that suffer from the fading effect, as also other phenomena such as path loss and shadowing. To mitigate the channels fading there are two very popular techniques in wireless systems that use different types of diversity and are implemented in physical layer. The OFDM techniques, makes use of frequency diversity to mitigate fading, transmitting by several narrowband channels to increase the reliability and capacity of the systems. The MIMO techniques take advantage of multi-path channel conditions to implement spatial diversity and spatial multiplexing techniques to also increase the reliability and capacity of the systems. Both techniques, considered as micro-diversity techniques, are used in most of the current wireless systems, including WiFi systems.

On the other hand macro-diversity techniques exploit in some way some type of multi-connectivity to increase the reliability of wireless transmissions. The carrier aggregation solution uses frequency diversity to connect mobile devices through two different carrier and dual connectivity that uses interface diversity diversity to also have more than one communication link, both contributing to increase systems reliability and capacity. With solutions that employ multi-connectivity by frequency diversity or interfaces diversity it is very common to use packet duplication schemes to transmit the same information by different path to increase the transmissions reliability. Also the interface diversity can be used to implement network coding to increase throughput and reliability in wireless systems. The users multi-connectivity with the base stations increases the transmissions reliability significantly when the CoMP systems are used through cooperation in transmissions. Multi-connectivity is also one of the keys to achieving seamless and reliable handover processes during user mobility, a process that is more frequent in topologies with high density of stations.

These macro diversity techniques have been focused and developed almost exclusively for broadband wireless networks, and represent the basis for future 5G systems. However, in the area of local wireless communications, mainly on WiFi systems, these features have not yet been exploited at the maximum. This means that there is a special interest in trying to develop WiFi communication solutions for indoor environments that can guarantee the transmission reliability as it happens in broadband wireless networks. Even when, based on what was discussed in the previous chapter, WiFi is also one of the key technologies for heterogeneous access networks in 5G systems.

# 4 SDN-WiFi Architecture with Multi-Connectivity

For many wireless applications, the use of WiFi is a natural choice due to its almost ubiquitous use nowadays. However, WiFi suffers from crucial issues like spectrum interference, connectivity losses, long delay for client association and high latency during handover. A proposal of a wireless communication architecture for seamless handovers in WiFi networks is presented in this chapter. The architecture arises from the split of the traditional functional elements of a WiFi network in infrastructure mode supported in the control and management offered by SDN. The solution aims through the integration of existing technologies to improve latency, reliability and availability as competent as those that future networks 5G proposes. At the beginning of the chapter, a brief review is presented with some of the main solutions based on Software Defined Wireless Networks to offer reliable mobility in WiFi scenarios.

The overall implementation is described in this chapter together with preliminary validation experiments. After the preliminary validation stage, the proposed SDWN architecture is implemented for its final validation studies with real applications. At the end, the proposed architecture is implemented to support reliable wireless communication in healthcare and Industry 4.0 use cases, two popular scenarios of cloud robotic verticals. During all the validation experiments it is shown how the multi-connectivity and access diversity features increase the reliability of the communication with a good performance of the architecture. The validation experiments are described and the results obtained are discussed.

## 4.1 Overall System Design

A novel SDN-WiFi architecture for high reliability handover is presented in this section. A detailed explanation of the architecture's functional blocks is carry out as well as its principle of operation.

### 4.1.1 The Proposed Architecture

The proposed architecture aims to increase reliability during the mobility of WiFi clients when, due to the characteristics of this type of networks, client migration is needed. The main contribution is the reduction of the interruption times that clients may experience when a handover processes is triggered. To values very close to zero, which undoubtedly contributes to increase the reliability of communication and decrease the data delivery latency during these periods. The architecture is based in split the functions of the elements in IEEE 802.11 networks operating in infrastructure mode and exchanges their roles creating a mobile AP ($mAP$) to which conventional STAs without mobility are associated and serve as access elements to the network services as shown in Fig. 16.

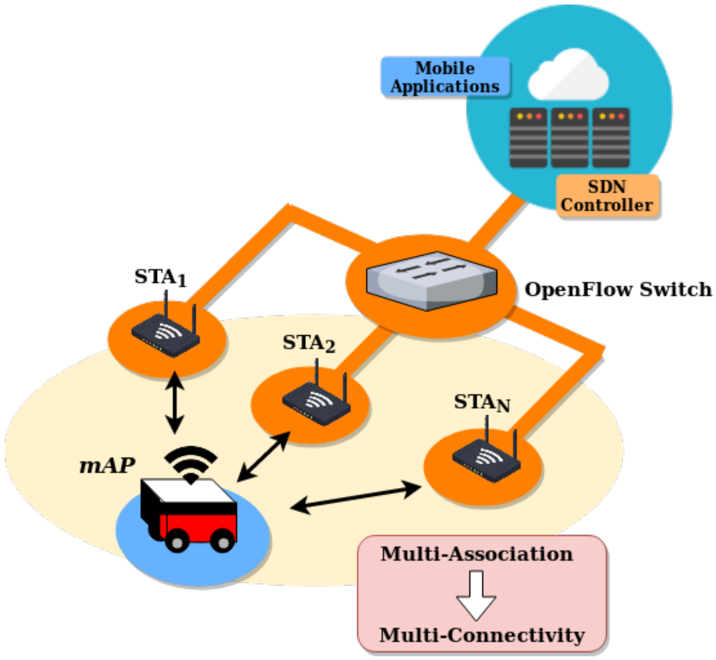



Figure 16 – Proposal Architecture.

The solution may provide multi-connectivity and, therefore, redundant association for the mobile client that enables seamless mobility and failover resilience. The possibility of multiple associations of the mobile element with different infrastructure access points recreates a scenario similar to that of mobile networks that use interface diversity techniques. In this solution, the placement of the AP functionality in the mobile element allows this element to manage multiple connections with the infrastructure access points, despite having a single physical interface, be considered a logical interface diversity technique. These features can be managed by a central SDN controller with actions executed from the backhaul of the WiFi network for increase communications reliability.

The architecture is composed by a $mAP$, located in the wireless communication module installed in a mobile entity, and an access network composed by non-mobile STAs with wired connection to the backhaul that communicates with a cloud. The architecture is focused on solutions that employ applications located in a local or remote data center in a virtualized environment, to which the mobile element accesses to perform various tasks, coexisting with the SDN Orchestrator that controls the architecture. This SDN Orchestrator through a OpenFlow SDN controller is in charge of the management of mobility and the handover process for the mobile element according to the information of the physical environment.

#### 4.1.1.1 The Mobile Access Point

The mobile access point is a concept introduced in this project, and its principle is based on placing the access point functions in the mobile element side. For this purpose, the software architecture is composed of several logical blocks. The mobile WiFi client is implemented with a $mAP$ as shown in Fig. 17.

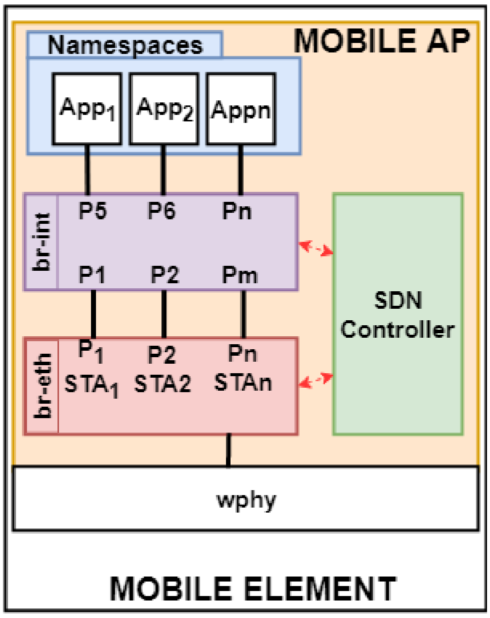



Figure 17 – Mobile Access Point Structure.

The routing mechanism inside the $mAP$ is implemented using two virtual bridges (native from OS), so the traffic routing process to reach any application is all virtualized. Directly connected to the physical wireless interface of the device where the $mAP$ is deployed, the $br-eth$ virtual switch is used to map all STAs associated with the AP at every moment with different ports in the data plane. Each $br-eth$ port representing a STA connected to $br-int$ ports, obtain virtual representation of the wireless links between the STAs and the applications in the $mAP$, and allows the traffic to be routed through the corresponding STA by placing specific rules in each virtual switch. With the $br-int$ each STA can communicate with the different applications using independent namespace mapped on $br-int$ ports.

The operation of the bridges is based on Openflow rules installed in each one. Rules in *br-eth* are generated using the MAC address information from the STAs and the AP, where each port linked with *br-int* is referenced by tuples composed of AP MAC and STA MAC values. The inbound traffic for *br-eth* is then sent to the corresponding port with the received MAC address, corresponding to one of the STAs associated with the AP. In the case of $br-int$, rules are generated by aggregating a specific Virtual MAC (VMAC) address for each application running in the cloud side. Thanks to the use of VMAC for each server application, the applications in the $mAP$ always see the other end of the communication with the same MAC address, even when a handover has been made and the communication is being carried out by another STA with a different MAC address. Here, $br-int$ performs a translation of the MAC address of the server application to the corresponding VMAC, previously defined during the design of the architecture. This feature reduces the latency generated in the ARP process in each handover and also reduces the overload of the radioelectric spectrum with ARP requests, which can be significant if it is considered small cells scenarios.

Inbound traffic to the $mAP$ is forward by an STA or by another, depending on decisions made in the backhaul network, so the $mAP$ already receives the traffic by a specific path depending on this selection. However, to route the outbound traffic, the $mAP$ needs to implement some logic that allows it to know by which STAs the traffic is arriving to be able to forward it to the correct *br-eth* port (representing the STA link that handles the traffic in that moment). For this, the $mAP$ entity has a local Openflow SDN controller responsible to apply the outbound rules in *br-int* by observing the inbound traffic. When the first traffic arrives at the $mAP$, it is routed through *br-eth* depending on the STA and upon reaching the *br-int* an Openflow PacketIn message is generated and sent to the local controller. In the controller, the message is analyzed to obtain the in port, with this data the controller creates the rule that is installed to guarantee the outbound through the same port, which is nothing more than sending the traffic towards the correct STA. Both rules are then installed, input and output for *br-int*, which are maintained until a new handover occurs, which causes the arrival of traffic through a new port and therefore the generation of a new PacketIn message to the controller.

#### 4.1.1.2 Access and Backhaul Network

The applications running in the $mAP$ accesses the cloud services through the STAs that are associated with it. An OpenFlow virtual switch is created in each STA, which is responsible for forwarding data traffic between the wireless environment and the wired network through the physical interface allocated in each STA, as shown in Fig. 18. Since traditional WiFi clients are intended as start point or end point for data traffic, the fact that the STAs routes traffic between network domains, makes it necessary to perform some actions over the traffic forwarded by these STAs. More specific, the choice of associating clients to an AP implies that all communication between them is only allowed for traffic that has the MAC address of the associated STA. As a consequence, Openflow rules installed in the virtual switches of the STAs not only route traffic between wired and wireless interfaces, but it is also necessary implement OpenFlow rules that modify the applications traffic generated in the cloud, enabling a translation of the source MAC address. Thus, the traffic is received in the $mAP$ as if generated from the STAs when really is being routed by the STAs, without the need to make more complex modifications in the operation of the IEEE 802.11 standard. The STAs also has an agent that maintains communication with a centralized OpenFlow controller. This agent sends to the controller the information about strength of signal reception and SNR in the STA, connection quality and the amount of traffic through the STA interfaces. The information is sent through a channel dedicated to the control that use a broker with Message Queuing Telemetry Transport (MQTT) protocol messages. Thus, the controller maintains a general vision and applying an algorithm with the information of physical layer conditions, decide which STA can best serve the *mAP* traffic. Then the decision to carry out the handover of the mobile element is carried out by a centralized intelligence in the architecture, and no more by the decision of the mobile client. Also with information sent by the agents, the SDN controller can monitor the status of the STAs to implement failover mechanisms that allow to recover the communication in the shortest possible time.

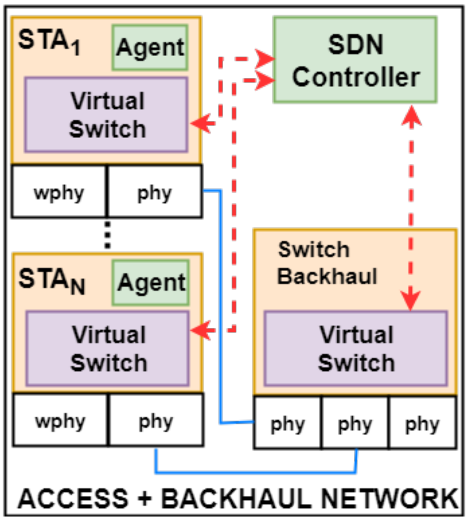



Figure 18 – Access Network and Backhaul Network Structure.

The STAs are connected to an OpenFlow enabled Switch that, together with the centralized OpenFlow controller, conform the backhaul network of the architecture. In this part of the architecture lies one of its greatest contributions, since the handover processes are controlled through the installation and modification of Openflow rules in the backhaul switch. By means of the SDN controller it is possible to implement a handover process where the migration of the mobile element is executed only updating the routes in the backhaul switch. This feature offers the advantage that it is not necessary to have a synchronization mechanism between handover processes and backhaul routes updates. When the controller decides to perform a handover due to the information obtained from the agents installed in each STA, then it performs a modification of the OpenFlow rule in the switch to forward the traffic for a new STA. Indeed, the *mAP* does not migrate from one STA to another, it only begins to exchange traffic through another STA, exchanging traffic then with another infrastructure access point like a handover process.

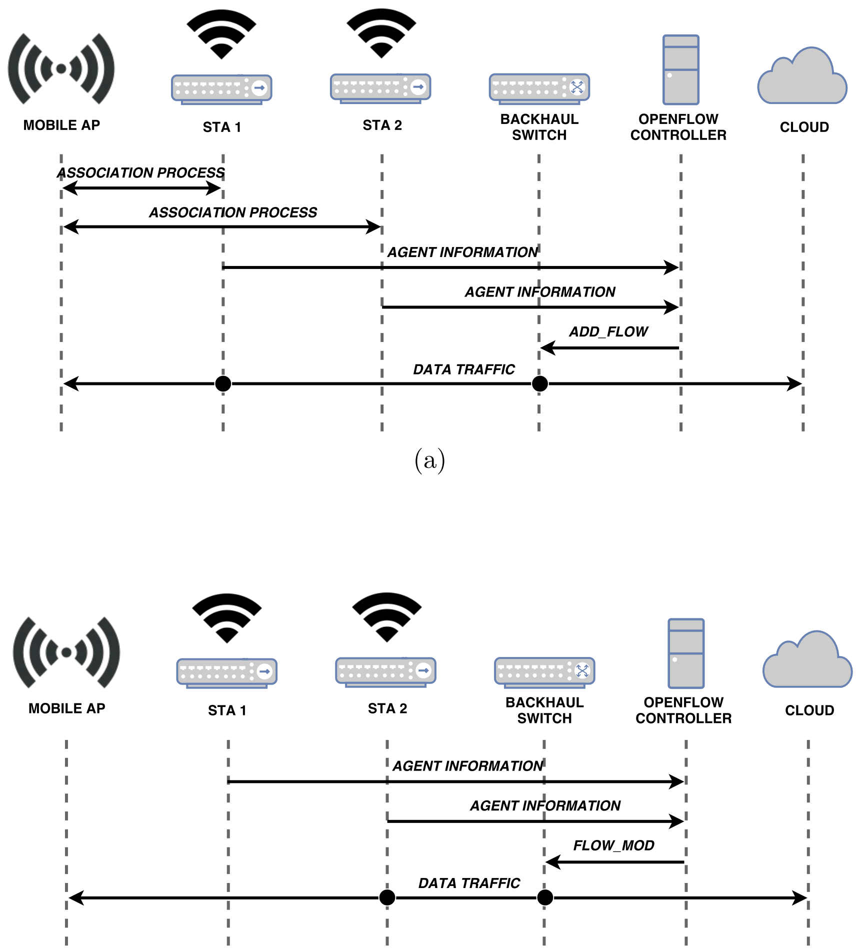
Given that several STAs are associated with the *mAP*, the architecture create a structure of multiple associations of the mobile element with the network infrastructure. This feature provides a multi-connectivity scheme in the architecture that helps to increase the communication reliability. As associations are made once the STAs have perceived the *mAP* signal, the exchange of management frames for re-authentication and re-association is performed before the traffic is sent by one of the STAs, so the times for these processes are reduced and consequently the traffic interruptions due to this cause are considerably reduced. The fact of having multiple associations translates into an architecture with multi-connectivity that helps not only for the semaless handover processes, but also helps in the implementation of failover mechanisms. These last in the same way by updating routes on the switch, once a failure is detected in the STA through which the traffic is forwarding. As it may seem intuitive, to ensure the performance of the proposal it is necessary that the *mAP* signal provides coverage to more than one STA, so that multi-connectivity can be guaranteed at all times to obtain seamless mobility and virtually zero migration times, thus moving towards a more reliable communication.

### 4.1.2 Operation

The non-mobile STAs are configured to make the connection with the wireless network using the *mAP*'s Service Set Identifier (SSID). When the association is made, the agent installed in each STA sends to the controller, the information explained in previously including the SNR link condition between the STA and the *mAP*. With this information, the controller employs a decision algorithm to select which STA can better attend the *mAP* and installs an OpenFlow rule in the switch to send the traffic through this STA. The algorithm is based in which STA have the better SNR within all associated STAs. The initial process is show in Fig. 19(a) with establishment of communication in a classical way through $STA_1$. At that moment the controller installs a rule on the switch to send the traffic through the $STA_1$ once it is the first and the only one associated with the *mAP*.

After the initial process, each new STA that enters the *mAP*'s coverage area is associated with it and, after that, its agent also begins to send the information to the controller. The controller that continues to receive the information sent by all the agents, perform the selection algorithm. Figure 19(b) shows the handover process, triggered as a consequence of the *mAP* movements. The controller determines if the SNR of any STA associated with the *mAP* is greater than 3 dB in relation with the actual STA. If the condition is satisfactory, the controller modifies the flow rule in the backhaul switch to redirect the traffic to this new STA. This implies an update of the routes in the backhaul which causes the *mAP* to start receiving data traffic from $STA_2$, this migration is assumed as a handover of the mobile element. Similarly, if the controller stops receiving the periodic information sent by the STAs agents as a keep alive mechanism, automatically considered that a failure occurred in that STA. As a failover mechanisms the controller selects the best available STA, in case the fault has occurred in the STA that handled the traffic.

The algorithm used for the handover decision is not very sophisticated or complex and employs very common metrics for decision making. However, it does not mean that




(a)

(b)

Figure 19 – Operation Process: a) Initial Association; b) Handover.

the solution is simplistic, as the real objective of the solution is to create an architecture capable of guarantee the mobility without interruptions of WiFi clients. The fact is that in the proposal, the handover decision is implemented from SDN Orchestrators that interact with the network infrastructure, leaves an open door, for users who use the architecture, implement their own decision algorithms since the underlying behavior in the solution is independent of these control applications. Later in this chapter we will analyze some use cases for this architecture, which use different handover decision algorithms will be analyzed.

### 4.1.3 Implementation

The architecture was implemented in a real environment using mostly COTS devices. In the mobile side, the $mAP$ was implemented in a Raspberry Pi 3 model B, slight and small device that allows to ship the $mAP$ communication module in mobile elements relatively easy. The Raspberry Pi runs the Raspbian Stretch Lite v4.9 Operating System (OS), a free GNU / Linux operating system based on Debian, with a processor Quad Core

1.2 GHz Broadcom BCM2837,and 1 GB of RAM. To provide AP functionalities, it was installed in the OS a hostapd 2.5 daemon that works by publishing the WiFi network without modifying its operation, remembering that the operation of the mAP module is based on layer 2 operations through virtualization of bridges to access the applications in the namespaces. For the wireless operation in physical layer is used a wireless interface TP-LINK TL-WDN3200 via USB to allow the operation dual band in 2.4 Ghz and 5GHz. The solution was developed using the IEEE 802.11n standard. The virtual switches are installed with Open vSwitch 2.5.2 and Ryu 4.18 as local Openflow controller responsible for the operation and AP management.

The non-mobile STAs are implemented in Dell desktop computer running Ubuntu Server 14.04 OS with processor Intel i5-7500 3.40 GHz, memory 8GB RAM. For wired communication is used the Ethernet interface embedded inboard and a PCI TP-LINK card TL-WDN4800, as a wireless interface capable of working in the 2.4 GHz and 5 GHz bands. Like in $mAP$ for routing functions was installed the Open vSwitch 2.5.2 for with support for OpenFlow 1.3. The agents used to get the link qualities information are python applications running in background inside the STAs. In the architecture, the STAs provide access to the cloud environment via Ethernet to an physical Supermicro OpenFlow switch which represents the backhaul network of the solution. This switch connects to a data center where the network services run in a virtualized environment in Openstack. The central Openflow controller in charge of the handovers is installed in a Virtual Machine running Ubuntu Server 14.04 and is implemented with Ryu 4.18. Ryu is an open source framework for SDN, which allows the easy development of network functions with python.

## 4.2 Architecture Validation

For the validation, the architecture was deployed in a real experimentation scenario. To support the process of experimentation the raspberry pi that executes the $mAP$ module was coupled to a smart walker, a cloud-enabled healthcare robot that provides a locomotion assistance service. In this case none of the smart walker functionalities tested, its use is based only on its inherent nature of mobility that allows locomotion through the space needing to reconnect with various WiFi access device. The experimentation environment access network was complete with three non-mobile STA allocated in the hall of the CT6 building in Federal University of Espírito Santo as show in Fig. 20, separated approximately 25 meters from each other. The STAs are connected with a backhaul switch located in the data center room where also an OpenStack cloud environment hosts the SDN controller and any other application that provides service to the mobile element.

### 4.2.1 Experiment Protocol

The experiments were conducted in the 5 GHz band, to mitigate the interference effects that are common in the 2.4 GHz band and operate in a cleaner radio-electric

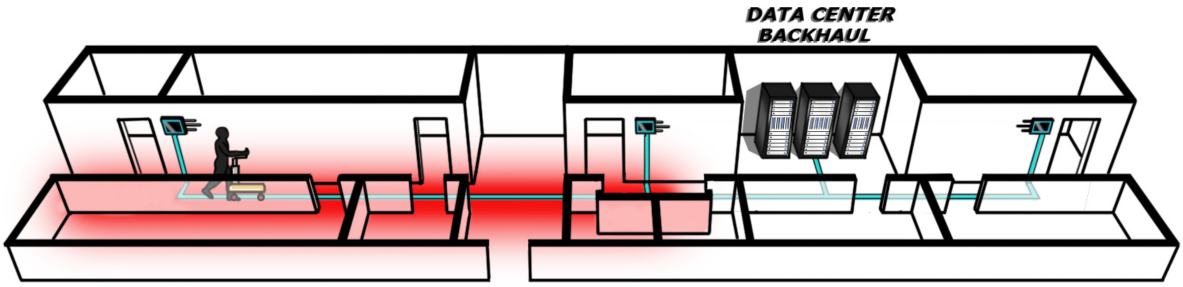



Figure 20 – Experiment Scenario.

spectrum. Although communication interruptions during WiFi clients re-association have been demonstrated and analyzed in several studies, it was performed a first experiment to analyzes the classical handover process in 802.11 networks operating in conventional infrastructure mode. A mobile WiFi client communicates with a service virtual machine through the AP to which it is associated. During the data traffic exchange, it performs a handover to another AP while maintaining communication with the same server. This first test use TCP traffic generated between the server application and the client application with the use of the iperf3 tool for throughput analysis.

The second experiment, using the described scenario, is performed to validate the performance of the architecture. The tests performed consists on the measurement of the communication throughput during two handover processes that the mobile element equipped with the $mAP$ will experience due to its mobility. In this way, intend to demonstrate experimentally the seamless mobility offered by the solution, observing the throughput values for a constant traffic of an application located in the $mAP$ accessing the cloud application. With iperf3 tool is generated a TCP traffic between a data center application and the mobile application during an interval of 100 seconds, time that allows the $mAP$ to move along the entire hall. The $mAP$ movement is commanded by the smart walker user, following a straight line path through the hall, and moves at approximately 0.5 meters per second. Under this locomotion regime, conditions are created so that the mobile element needs to be re-associated to a new access element given its distance from the access element to which it is associated. Under this assumption, the remoteness of the STA would cause a degradation of the link conditions evidenced in the reduction of the SNR perceived by the STA, which would trigger the handover algorithm of the SDN controller.

The third test also using proposal architecture scenario consists of the same measurements. In this case varying the $mAP$ displacement velocity at 1 meter per seconds and the duration of the TCP traffic generated at 60 seconds. The main objective of the third test is to observe the solution behavior for mobile elements that when traveling at a higher speed they need to perform handover more frequently, so the architecture must be able to react to these situations. Also under these conditions a failure is caused in the second STA while it handles the $mAP$ traffic. With this simulation of failure it is desired to analyze if the failover mechanism is efficient during the re-connection processes of the mobile element.

### 4.2.2 Preliminary Results

Figure 21 shows a multi-connectivity scheme obtained during the experiments in the scenario created for the architecture validation. At the start, $STA_1$ and $STA_2$ are associated with the $mAP$, while the traffic is routed by $STA_1$ because have the best SNR. As the robot moves along the hall, $STA_3$ receives signal from the $mAP$ and is associate with it. At this moment, it can be see that the scenario presents a state where the $mAP$ can be served by any of the STAs, due to the connection diversity condition established between the $mAP$ and the access stations, as shown the blue lines. Soon after, the first handover occurs and the controller routes the traffic through $STA_2$. After the second handover, when the traffic is handled by $STA_3$, the $STA_1$ client loses signal from the $mAP$ and disconnects from it, in this instant the $STA_2$ and $STA_3$ clients maintain connection with the $mAP$, maintaining yet the diversity condition in the architecture. It can be observed that the $mAP$ always has connection with more than one STA, and as already mentioned this feature must be guaranteed during the location of the STAs in the area to be attended for this solution. Thanks to the multi-connectivity feature, quick response times are possible during handovers and faults recovery, and a great flexibility is offered in the implementation of multi-path mechanisms in the chosen architecture.

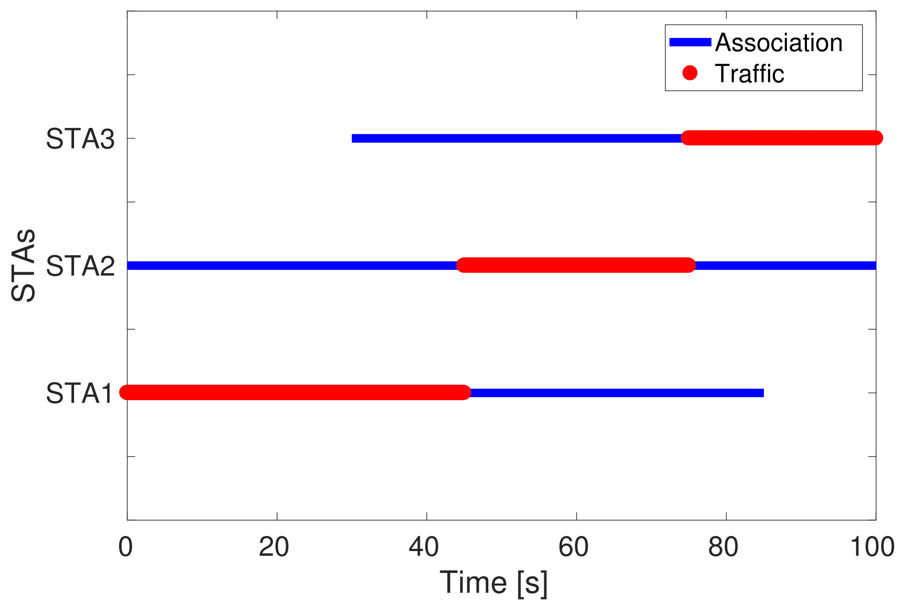



Figure 21 – System Multi-Connectivity.

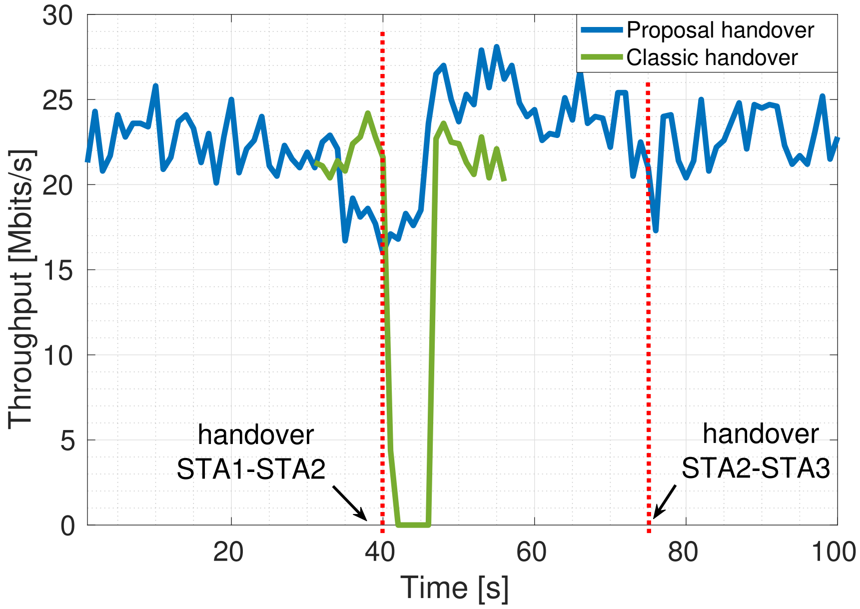
The results of the first experiment used to analyze the communication characteristics of a WiFi solution with classic handover processes are shown in Fig. 22(a) plotted in green. An interruption of the communication is observed starting at 40 seconds, time in which the client migrates to another AP. The duration of this interruption is about 5 seconds but its value can vary for different scenarios. The cause is mainly associated with the times that the client uses to exchange management frames with the new AP for the re-association and re-authentication in the access network side and the update of the ARP tables and layer 3 routing tables in the backhaul network side.

The results for the handover and failover processes in the architecture show that there are no interruptions in the communication. Figure 22(a) shows plotted in blue the result of the second experiments, the tests use the proposed solution, during the two handovers that the mobile elements with the $mAP$ experiences when passing through $STA_1$ →$\mathrm{STA}_2$ →$\mathrm{STA}_3$. The same graph is used both for the classic handover and for the proposed handover with all intention, to be able to compare both processes from the point of view of communication throughput. The handover occur at 45 and 75 seconds and the throughput only experience a minimal decrease, thus the communication is maintained over all the handover process. In both moments, after performing the handover the throughput is increased and stabilized because the SDN controller has made the transition towards an STA of better SNR.

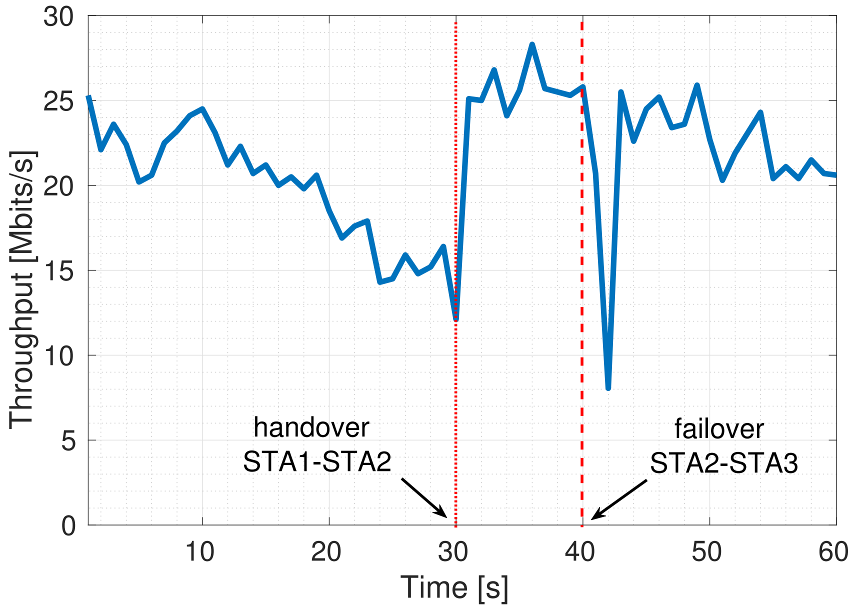
The third test shows similar results, observed in Fig. 22(b). During the handover, after 30 seconds of operation, the throughput after suffering a slight fall increases by a better SNR of the new STA, and there is practically no degradation of the communication. On the other hand, at 40 second when a failure is induced in the $STA_2$, the SDN controller detects it when it stops receiving the agent information from the STA and routes the traffic towards $STA_3$. In the case of the failure recovery the throughput suffers a greater drop than in the handover. This result was expected, since during a failure the controller has to wait for the generation of an unforeseen event by the agent and then make its decision to update the path in the backhaul. In this way handover processes in architecture are treated as proactive phenomena, since the system is the one who decide when to carry out the action, while the failover are reactive processes where the system only reacts when the failure occurs without being able to do no type of prediction, so it takes longer to recover from its effects. However, even with these features, the architecture controller is able to determine and implement a new route without interruption in the communication.

## 4.3 Use Cases

The proposed WiFi communication architecture is fundamentally aimed at the field of cloud robotics, although it can undoubtedly be used in any scenario where the communication reliability between a mobile client and the cloud is a primary condition. In the complex current scenarios of different sectors such as industry, education and health, make that fast decisions in these environments many times characterized by unknown condition, limiting the autonomous operation of robots operating with embedded




(a)




(b)

Figure 22 – Experimental Results: a) Handover of $mAP$; b) Handover and Failover of $mAP$.

programming. To face these conditions, increasingly complex control algorithms are necessary, and therefore, greater processing capacities, which in many cases are not viable in the robot itself due to computational, energetic and environmental conditions limitations. Thus, the transfer of the robot intelligence towards computational nodes that allowed to extend the tasks performed by robots with a minimum energy and computational consumption began to gain more and more interest.

The development of cloud technologies, such as cloud computing, virtualization, SDN and other technologies have allowed to face these challenges, emerging the cloud robotics as a new research field, placing most of the robot control in the cloud. The advent of cloud robotics can unleash a whole new generation of smart robotic devices, capable of better coping with the constraints described above. They will be able to communicate with each other and with remote computing platforms to share experiences, sensor data, and to offload heavy processing applications. The key point is that this new generation will make use of cloud-based compute power and other cloud-related services, rather than relying solely on its own embedded intelligence.

Along with this evolution, new technical challenges must be considered, many of them concerning the own use of the cloud, such as the resources allocation, scheduling and cloud security. At the same time, the way in which the data exchange between the robot and the cloud platform takes place is of vital importance in these systems. An enhanced, faster, more reliable and responsive wireless communication architecture will also allow robots to learn faster how to best adapt to new and dynamically changing environments. The adoption of cloud robotics in critical applications and new verticals with real time control requirements will certainly face communication challenges, related to uninterrupted connectivity and end-to-end reliability, latency and QoS. The proposed architecture serves to meet these communication requirements, mainly in interior environments where the use of mobile technologies proposed in the 5G paradigm may present limitations due to the inherit propagation characteristics.

### 4.3.1 eHealth

For health care environments the use of multiples intelligent devices contribute for a better quality in activities like surgeries, rehabilitation and logistic services in hospitals and clinics. In vertical eHealth, all technologies, included cloud robotic, require the strictest safety and reliability standards given how delicate and precise should be medical procedures in Humans. In rehabilitation field, robots for eHealth applications must perceive the surrounding environment and take prompt action to avoid collisions, between them and also for maintain patient and medical staff out of risk. The control techniques with a reliable communication system must be capable of dealing with safe and efficient displacement of devices with different degrees of autonomy and human interaction.

For human assistance and rehabilitation, a CloudWalker was develop in [161] making a integration of smart walkers and cloud technologies. The implementation in a cloud platform of the assistance tasks allows the use of the same physical device to diversify the services addressed to the patients, thanks to the advantages of cloud robotics already described. The CloudWalker system was validated in user experience and performance, however, given the wireless nature of the communication between the cloud services and the walker, the wireless network availability for the system operation remained as a point to pay attention. According to the author, it is necessary to guarantee communications with sufficient receive signal strength values and migrations between AP that allow to avoid downtimes.

#### 4.3.1.1 Robotic Network

For the validation of CloudWalker operation in mobility environments that require migration between different WiFi access points, the proposed architecture in section 4.1 was used. At the same time, a proposal is introduced to extend the communication architecture in an environment where a group of robots connect to the network to access control services in the cloud. For this type of scenario, referred to as robotic networks, robots not only access the cloud, but also share and exchange information between them.

To manage the communication of several robots, a layer of management and control is introduced to track the system state and manage the connections of mobile robots through an SDN Orchestrator. The same concepts of the proposed basic architecture are maintained, $mAP$ installed in some robots that establish communication links with non-mobile or fixed stations ($fSTA$) as shown in Fig. 23. This type of communication is referred to, in this extension, as Robot-to-Infrastructure communication (R2I). Other robots in the environment are configured in the role of mobile client stations ($mSTA$), which need to connect in some $mAP$ to access the cloud services, this case is called robot to robot communication (R2R). Thus, the robot configured as $mAP$ should be able to manage several robots (configured as $mSTA$) under its coverage area, fulfilling the function of head of the robots cluster and being the only one with communication with the infrastructure. A cluster is considered as the set of $mSTA$ that are associated with a $mAP$ to establish a communication link to the cloud. This particular type of multi-connectivity between $mSTA$ and $mAP$ provides communication between all robots for exchanging information of their sensors directly, without the need to access the cloud infrastructure.

In the initialization process of the architecture, each robot executes a bootstrap logic that determines its initial state within the communication architecture. If in this process, the robot does not receive beacons from any access point, it is auto-configured in the $mAP$ role, becoming a cluster head, then the nearby $fSTAs$ are associated with it. If, on the other hand, the robot discovers that there is already a $mAP$ close to it, since it receives the beacon from this $mAP$, the robot configures itself with the $mSTA$ role and is associated with the $mAP$. Because of the mobility that a cluster's robots can experience, the cluster may need to be reconfigured.

To guarantee the correct functioning of this complex robotic network architecture, SDN orchestration is used through a controller hosted in the cloud. Now, the controller in addition to being in charge of handover decisions in the same way that happened in the solution for a single robot, must keep a register of the state of each wireless node to command changes in the cluster structure. The SDN orchestrator gathers information

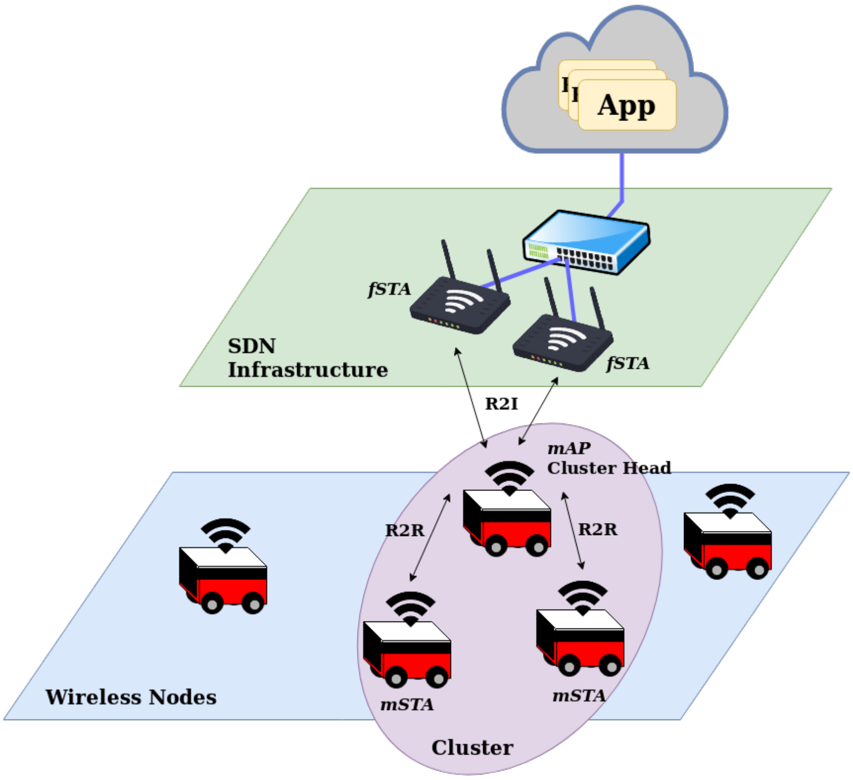



Figure 23 – Robotic network for health care.

about SNR regarding all wireless nodes and implements the best arrangement between them to ensure the fulfillment of the requested QoS requirements. A handover operation is required when a $mSTA$ robot leaves the coverage of its cluster head and enters in a cluster led by another $mAP$ robot or when a $mAP$ robot leaves the coverage of a $fSTA$ or when a $mSTA$ presents better link conditions (better SNR) with the $fSTA$, condition where the $mSTA$ could change its role to $mAP$ (cluster head) and therefore the $mAP$ changes to $mSTA$ to associate with the new cluster head. Thus, such topology modifications always affect directly the SDN orchestrator, which needs to provide new routes for the affected wireless nodes to communicate, mapping them to new associations to different $fSTA$ or $mAP$.

#### 4.3.1.2 Experiments and Results

For the experiments, the implementation of the architecture uses the same equipment described in section 4.1.3. In this occasion, the CloudWalker that will serve as a mobile element must communicate with the cloud to receive the remotely generated control signals. In the experiment to test the CloudWalker application during the handovers, two scenarios were implemented, (i) the first with the R2I communication were the robot is configured as a $mAP$ and must communicate with the cloud via the $fSTAs$ of the network infrastructure and (ii) the second scenario that explores the R2R+R2I communication where the robot is now configured as a $mSTA$, and thus associated with another robot that bears the $mAP$ role. In both scenarios, the $mAP$ switches communication between associated $fSTAs$. During the experiment, a background TCP traffic generated with the iperf3 tool is used as a strees test to perform the packet loss ratio measurement of the application data and the latency experienced by the application's data packages. The latency and throughput of the background traffic is also measured as an indicator of the architecture communication performance.

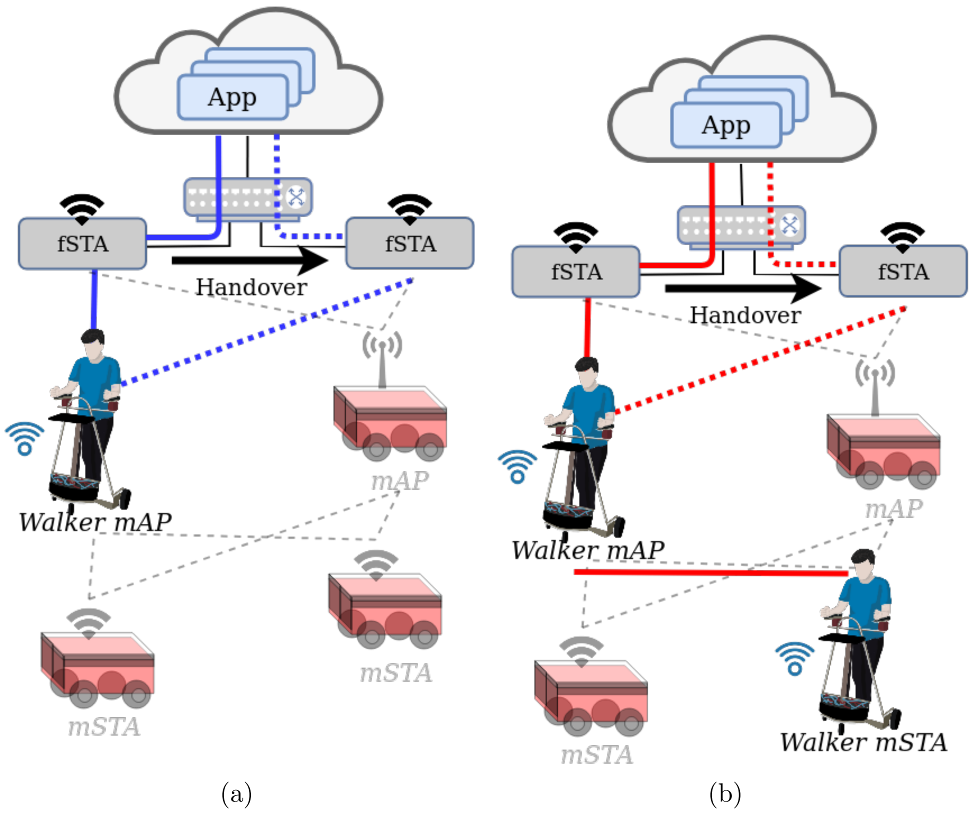
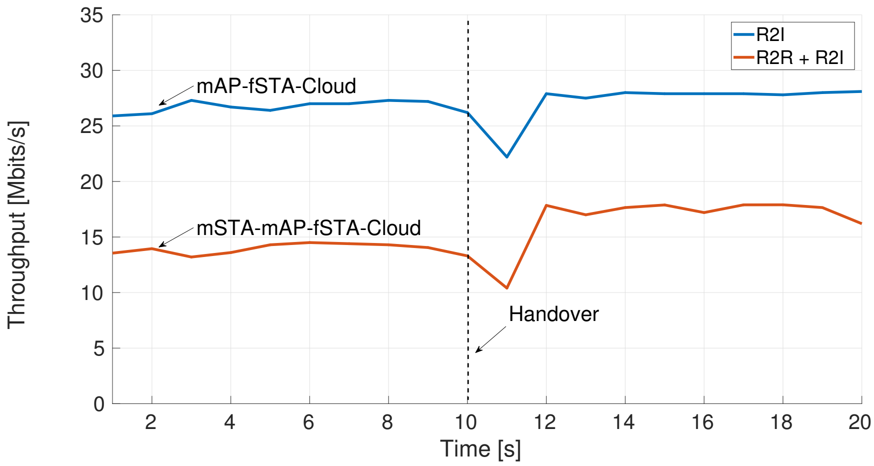
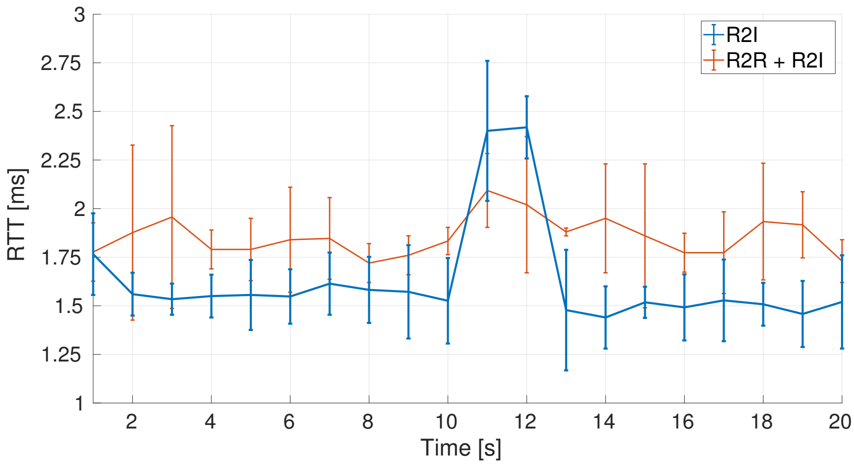



Figure 24 – Experiment scenarios: a) Single Hop (R2I) communication; b) Multi-Hop (R2R+R2I) communication.

As a result of the experiment for the data packages of the application, the average end-to-end latency is around 2.5 ms and 2.75 ms in scenarios R2I and R2R+R2I, respectively. In other hand, the observed packet loss rates are below 0.01% in both cases. These results show that there are no visible effects in use of the walker during the handover process, neither larger values are observed for packet loss nor latency on those moments. During the stress test, throughput values around 26 Mbps and 15 Mbps are obtained in scenarios R2I and R2R+R2I, respectively. The handover process occurs at 10 seconds as shown Fig. 25(a), when the $mAP$ migrates between the $fSTAs$. A minor degradation in throughput in both scenarios is observed but without connectivity interruptions, similar results to those obtained in the preliminary validation in 4.2.2. The Round Trip Time (RTT) as latency indicator behavior in both scenarios is shown in Fig. 25(b). Variation are kept under acceptable levels but is noteworthy that one-hop (i.e, R2I) connectivity is more sensitive to handover operations than the multi-hop one (i.e., R2R+R2I). This can be explained by the higher throughput loss ratio observed in R2R+R2I during handovers, which led to an increase in packet loss thus affecting the RTT measurements (i.e., queued packets associated with higher RTT times are more prone to be dropped, not affecting the RTT measurements). However, and as evidenced by the results obtained, the proposed communication architecture presents an acceptable performance on a real cloud robotics application. With these results it can be said that the solution is able to guarantee disconnection times well close to zero or zero MIT, which offers high reliability in communications for solutions that like the CloudWalker need guaranteed access at all times to the cloud platforms. The solution has also been validated for scenarios of multiple robots that can change their roles within a cluster managed by an SDN orchestrator.




(a)




(b)

Figure 25 – Experimental Results: a) Handover of $mAP$; b) Handover and Failover of $mAP$.

### 4.3.2 Industry 4.0

The phenomenon of digital transformation in industrial processes, considered as the fourth industrial revolution, begins to promote new and innovative business models. The industry of the future or more commercially Industry 4.0, bases its philosophy on the transfer of autonomy for systems and machines through the use of cybernetic and communication systems. This new industry concept identifies two new fundamental paradigms for its implementation: (i) systems based on the IoT in combination with (ii) the Internet of Services (IoS), which undoubtedly will revolutionize the interaction with the physical world through cyber-physical systems. Technologies such as machine learning, cloud robotic, Cloud platforms and Big Data, as well as the rapid development and evolution of mobile services and communications, are part of the main enabling technologies of this new paradigm of the industry.

To take the important step of migration towards more efficient and sustainable productive processes through Industry 4.0, exist an important flow the analysis, evaluation and approval of the task. In this flow, one of the keys is the use of experimentation environments (Testbed), as a way to prototype and test processes for the implementation of these technologies, as well as training and preparation of companies for their exploration. Universities, as the vanguard of research for the social development of any country, play an important role with the creation, together with industries, of Testbed for the study of new technologies. For this purpose, and taking advantage of the advantages offered by virtualization and cloud technologies, large-scale Testbed development has been governed by the coordination and federation of multiple small-scale Testbed. In this particular, the availability of the resources of the experimentation space with colleagues in remote places through the federation of the Testbed, is today one of the main tasks to be developed. In this way, Industry 4.0 will allow new businesses and services with a efficiency, sustainability and integration vision.

#### 4.3.2.1 Remote Real-Time Control Applications

In industrial environments, different mobile devices, such as industrial robots, will be in motion throughout the production space, therefore, they can not be served by the coverage area of the same base station or access point due to coverage restrictions. Industry 4.0 introduces requirements to perform handover processes between wireless stations to guarantee zero interruption times as part of the reliability demanded by real-time control applications hosted in the cloud. In addition, in this type of networks the reliability and latency requirements are stricter, as well as ensuring topologies to provide adequate values of traffic density where customers do not need to dispute the available band when there are other clients operating in the same space.

For this purpose, and as part of a Testbed solution for Industry 4.0, the wireless communication architecture proposed in this work has been evaluated for remote real-time control applications. The Testbed integrates cloud-enabled robots and network sensors in an intelligent environment, connected to an edge cloud through the WiFi wireless solution with split functions. Trying to reproduce a scenario analogous to the real industrial scenarios, the objective of this Testbed is the evaluation of the impact of cloud computing technologies and SDN in systems that execute applications in real time. In this case, through the navigation control of a robot without intelligence, complying with end-to-end low latency and high bandwidth requirements. To achieve these objectives, a robust wireless communication solution is needed that can offer adequate values for the requirements that this type of application requires.

Figure 26 shows a physical view of our Testbed, which is built around the concept of Intelligent Space (IS) [162]. The IS is based on computational vision, where the four cameras installed are used as the main means for locating robots in an indoor environment. The location by computer vision offer advantage in indoor scenarios where other solutions such as the Global Positioning System (GPS) are not able to provide precise locations, besides being easy to deploy for the number of cameras already available in these scenarios. After the processing of the images received in the cloud, the localization algorithms generate the trajectory control commands for the robot and are sent to it through the wireless network infrastructure. The entire process, from the moment that cameras capture the space's images and until the robot receive the control commands, must satisfy a strict control close-loop that depends on the delays of processing in the cloud and the delays of transmission in the network.

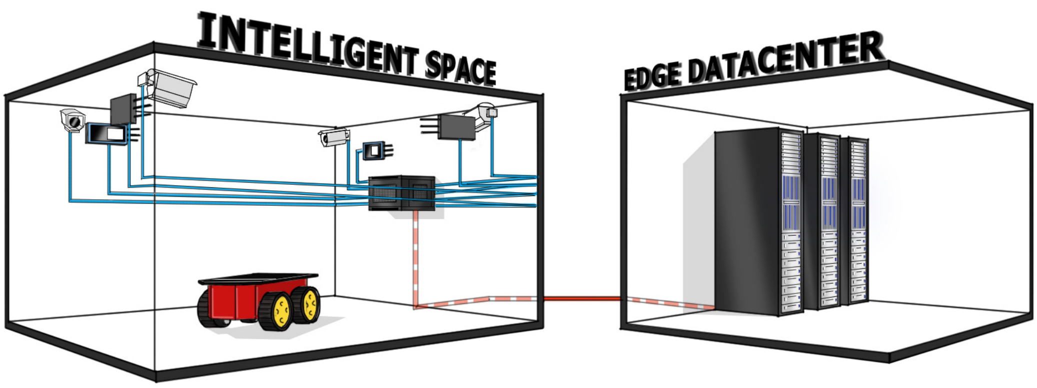



Figure 26 – Testbed Scenario [162]

#### 4.3.2.2 Federated Testbed Integration

In addition to the communication functions, the proposed WiFi architect needs to be integrated into the Testbed ecosystem where it is necessary offer the possibility of configuring their parameters to the Testbed's users. Thus, the options of band and channel configuration in the $mAP$ and traffic density configuration for the space, translated into the number of access points operating in the area, were available for the users. The configurations of the $mAP$ to start the Testbed becomes a difficult task for remote users, since the $mAP$ is embedded in the robot, whose only way of communication is through the wireless network with the associated $fSTA$.

The solution to this was the creation of a control channel that uses WiFi beacon management frames for the exchange of configuration and control information between the $fSTA$ and the $mAP$. This solution was implemented based on the fact that the beacons frames can be captured from the environment with the use of virtual interfaces in monitoring mode, with no need to have prior association of the $fSTA$ with the $mAP$. Figure 27 represents the flow of actions that is executed to configure the wireless network before starting the Testbed.

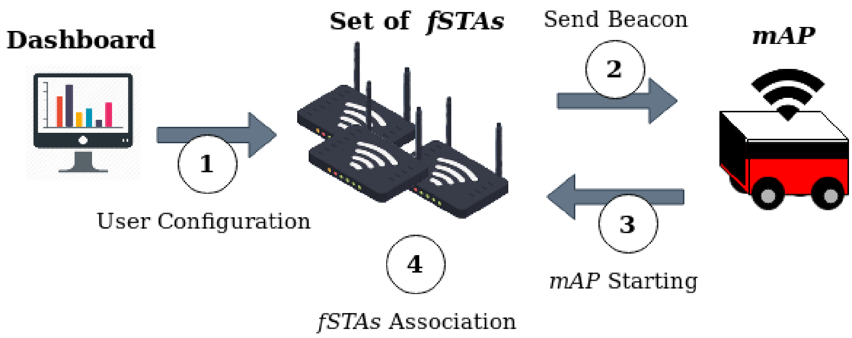



Figure 27 – Wireless Configurations Control.

The solution is based on a distributed configuration service and is composed of software agents running on the four $fSTA$ and the $mAP$. The process begins when the experimenter that interacts with the dashboard introduces the wireless frequency band configurations and the operating channel in the selected band, and this information is received through the message bus by the agent of each $fSTA$. The fSTA, which has a virtual wireless interface in monitor mode and a virtual interface for communication, build a unicast beacon frame in which place the configuration information received, send this beacon through its monitoring interface on the wireless channel and remain listening to the channel, waiting to receive beacons from the $mAP$ already configured. In the robot, an agent that also listens in the channel waiting for configuration beacons, takes the information of the first configuration beacon received, extracts the band and channel information to configure and starts the *hostapd* daemon with the specified configuration. At this moment, the $mAP$ begins to announce its presence with the sending of beacons as it happens in the normal operation of any access point. The agent in each $fSTA$ through the monitoring interface detects the presence of the $mAP$ and performs the association with the $mAP$ through the wireless interface. From this moment the agent in the $fSTA$ starts the publication of the WiFi metrics that will be used by the Testbed monitoring service and to implement decisions in the control plane.

#### 4.3.2.3 Experiments and Results

For the validation of the proposed WiFi wireless communication solution, the experimental scenario was built by placing four $fSTAs$ in the intelligent space. This deployment allows each $fSTA$ to route the client's data traffic for a specific area, each area defined by Cartesian coordinates, the same system used by the location service of the robot. In this way, small wireless communication cells are created which allow to increase the traffic density in the experimental space. The deployments of small cell topologies for wireless communication present the characteristic of needing more frequent handover processes, so the proposed communication architecture has to support the requirements for the control loop in another cloud robotic application.

As previously mentioned, the architecture uses simple handover decision algorithms based on the conditions of the links between the mobile element and the access stations, this being suitable for other decisions, since it is executed as an application in the control plane. For the particular case of the Testbed, the handover decision algorithm was modified, the handover being now triggered based on the location of the robot in the intelligent space. Since each $fSTA$ serves a specific area, it will be the $fSTA$ of the area where the robot is located which route the traffic to the $mAP$. In this way, the handover service becomes a client of the localization service implemented by computer vision, and fSTA that will serve the communication is the one that is closest to the robot. Assuming that LoS conditions exist between the $mAP$ and all $fSTAs$ associated with it, it is expected that the shortest distance is the connection that guarantees the optimal communication. Another reason for this is that when a high density of base stations is deployed in a small space, the link conditions between the $fSTA$ and the $mAP$ do not have significant changes to be considered a decision information, remembering that the objective in the Testbed is guarantee traffic density.

In the previous validations of the architecture have shown that the multi-connectivity of the architecture is able to offer handovers with imperceptible interruptions, similar to what happens in mobile networks that use the concept of MBB handovers. Due to the dynamics mobility in industrial environments, the degradation of communication links in these scenarios can be caused by people or equipment that transfer any type of materials. With the help of the own computer vision already present in the solution, the localization service can be used to predict situations of LoS interruption. The use of this context knowledge can be exploited to proactively trigger a handover to a non-occluded base station. This solution, denominated Make Before Degrade (MBD), makes use of the context aware network with the location information as knowledge of the context to network services take decisions such as the handovers.

The LoS obstruction leads to SNR degradation, which affects Bit Error Rate in the communication, and therefore the most basic system reliability metric. Figure 28 shows the BER curves for the main modulation schemes used in WiFi systems, simulated considering transmissions in a Rician fading wireless channel with a high LoS component. Examining the BER curves it can be verified that the decrease of the SNR in fact increases the amounts of transmission errors.

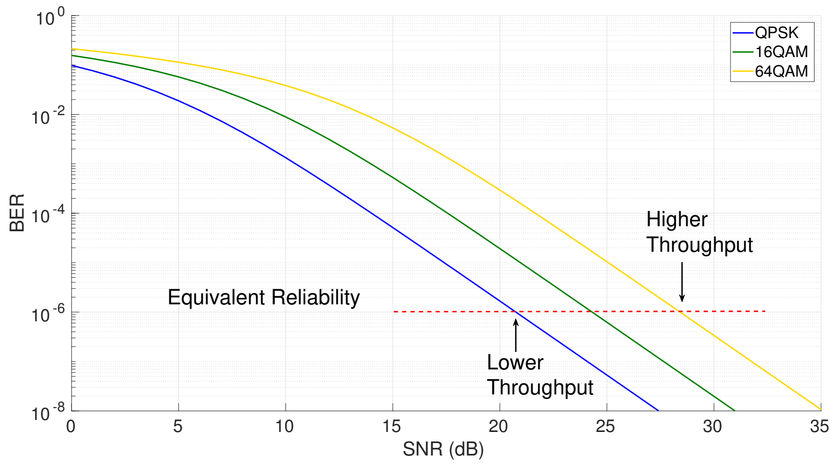



Figure 28 – BER curves for WiFi modulation schemes in Rician fading channels.

It is considered that the reduction of the SNR may cause the WiFi system to react by switching the MCS trying to maintain the best performance of the system for given conditions. Two cases can be analyzed: (i) the WiFi system maintains the same modulation scheme but decreases the coding index, since lower coding indexes have lower corrective capacity, the need for data re-transmissions increases and consequently the communication latency increases, affecting the requirements for critical applications; (ii) the WiFi system decreases the modulation scheme (with the same or lower coding index), in this case even when the communication reliability can be maintained as shown in Fig 28, the throughput suffers from a decrease, affecting the requirements of traffic density by area and user experience data rate of Table 3.

In summary, WiFi solutions, while maintaining reliability at adequate levels despite SNR degradation, are affected by latency increase and/or throughput decrease, that are also key requirements to meet for URLLC applications. To address these situations, a design choice can be to implement a solution capable of maintaining the WiFi users being served by access stations that maintain the same SNR levels, so that MCS changes are not necessary, and maintain reliability, latency and throughput requirements.

The first experiment is performed to analyze the system performance during the handover processes, by observing possible interruptions of a background traffic that

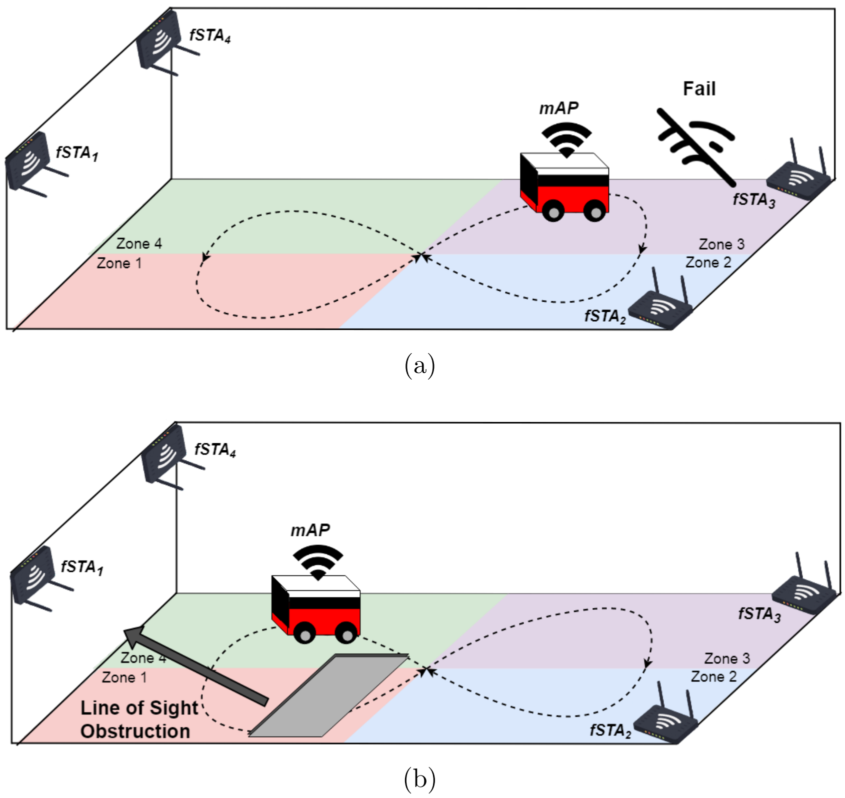



Figure 29 – Experimental setup: a) Scenario A - Make Before Brake and Failover; b) Scenario B - Make Before Degrade.

coexists in parallel with the robot's control data traffic. As in previous experiments, the failure recovery capacity of the communication system is also evaluated. The experiment is also performed in the 5 GHz band for the reasons justified and during its trajectory (eight trajectory), the robot travels through the different areas of the space forcing handover processes and therefore is attended by the corresponding $fSTA$ in each area. The SDN orchestrator of the architecture uses the location service as a trigger of the handover process every time the robot enters a new zone. In the second round of the lap, a fault is generated in the $fSTA_3$ for test the failover mechanism.

The second experiment tries to demonstrate how computer vision techniques can be used as LoS obstruction prediction method to avoid degradation of wireless communications. The robot executes the same trajectory under the same conditions of the first experiment, and during the execution of the task a metal object with attenuating characteristics moves through the space obstructing the LoS condition between the $mAP$ and the $fSTA_1$. The object is identified and located by the localization service of the Testbed by means of an algorithm infers the possible obstruction and proactively avoid signal degradation making a smart handover before signal degradation. The scenarios of both experiments are shown in Fig. 29.

The results for the first experiment are shown in Fig. 30. In the figure we can see small degradations that the throughput experienced during the handover when the $mAP$

moves through the intelligent space. At the beginning of the second lap, around 26 seconds the $fSTA_3$ suffers a failure and the handover SDN orchestrator needs to implement a failover recovery mechanism to keep connectivity with the $mAP$. The results obtained in this experiment continue to show that the solution can offer the reliability in the wireless communication that cloud robotic applications and specifically remote real-time control applications demand. The end-to-end throughput graph shows that even for reactive processes such as failures, the architecture guarantees zero MIT as an indicator of communication reliability. It can also be observed that 10 Mbps is obtained for each user that is served by the $fSTA$, which implies a traffic density of $1Mbps/m^2$ distributed throughout the area, which meets the requirements in Table 3.

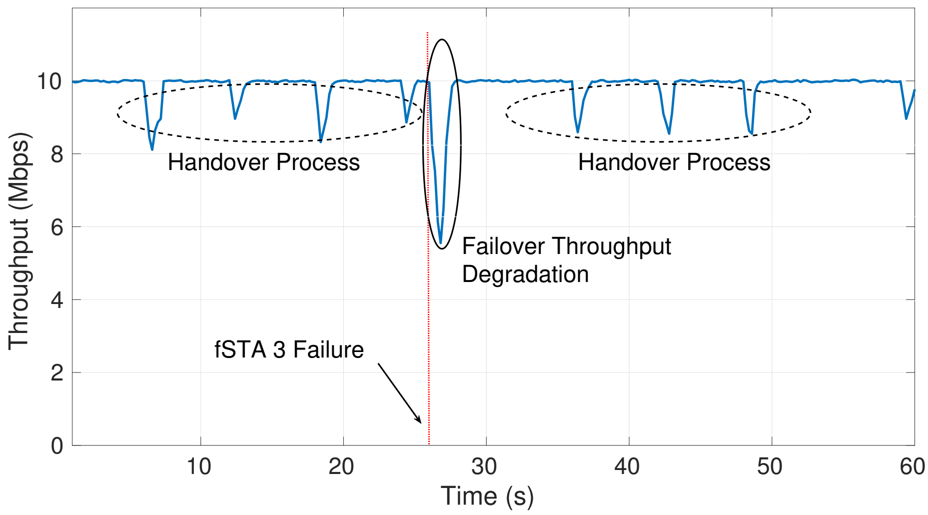



Figure 30 – Overall throughput: zero mobility interruption time.

Regarding the fulfillment of the robot's navigation task controlled by the application of in the cloud, Fig. 31 shows the results. According to the graph it can be concluded that the robot perform its movement properly if compare the real trajectory plot in red with the ideally drawn trajectory. This shows that the communication architecture supports handover and failover that meet the latency requirements of the control loop for real-time navigation application.

In the second experiment while the robot performs the navigation task, around 31 seconds is detected by the computer vision system an object that moves towards a possible obstruction of the LoS condition. A graph that shows how the handover service performs the traffic migration through the different $fSTAs$ is shown in Fig. 32. The figure also indicates the moment in which the system identifies the possible obstruction. The SDN orchestrator throws a trigger to avoid transmission thought $fSTA_1$ selecting the nearest $fSTA$. In this case the Fig. 32 shows how, contrary to performing the handover towards the $fSTA_1$, the SDN orchestrator keeps the traffic being served by the $fSTA_4$ and after performs the handover towards the $fSTA_3$.

In order to observe the operation of the MBD throughout the experiment, the SNR

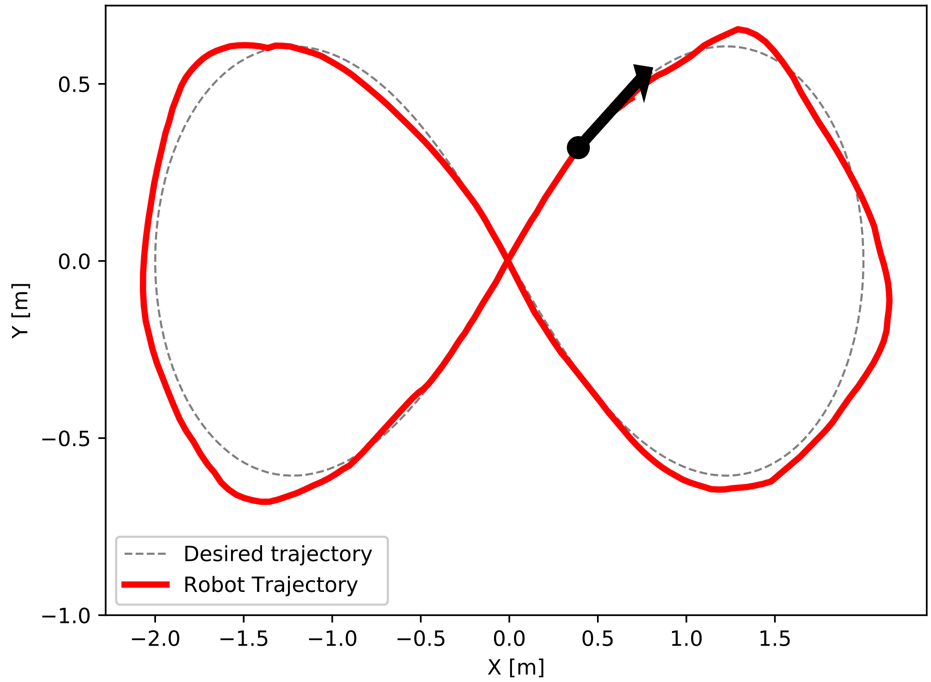



Figure 31 – Robot's Navigation Task.

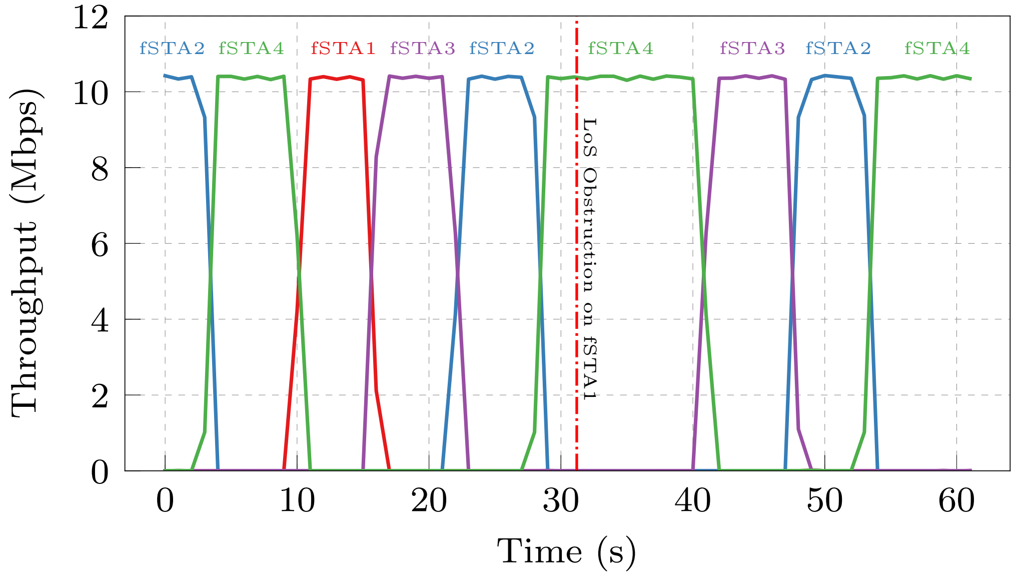



Figure 32 – Throughput Measurements: Make Before Degrade.

metrics were collected for each $fSTA$ as shown in Fig. 33. It can be clearly seen how soon after the possible obstruction was detected and the SDN orchestrator takes measure to keep the data flowing through a f$STA$ in which no obstruction was detected. After such event, the SNR level of the $fSTA_1$, which was the nearest one to the robot at the time, went down by more than 10 dB. This result indicates how a context aware handover can make it possible to avoid degradation in communication before the actual LoS obstruction occurs. With this result it is demonstrated how the MBD handover solution can maintain a throughput without degradation, attending the previous analysis made for the modulations BER curves.

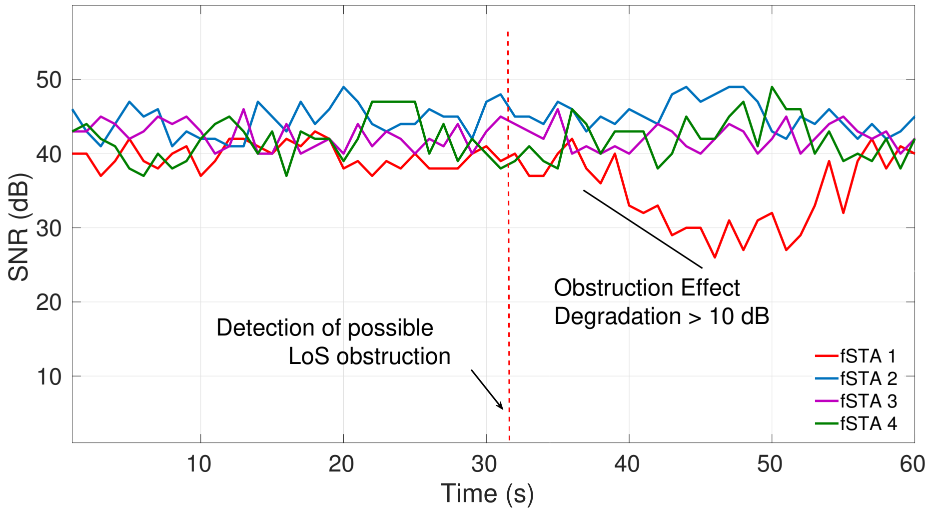



Figure 33 – Make Before Degrade: SNR perceived by each $fSTA$.

## 4.4 Conclusions

This chapter presented a new architecture to facilitate high reliable communications in WiFi scenarios where users mobility is taken into consideration, together with SDN orchestration and smart splitting of the functions of the elements in a WiFi network. The main novelty is in the use of a mobile access point that contributes with multi-connectivity and diversity to obtain fast handover and to better handle failovers, just using updates in the routing of the backhaul network. A first validation of the architecture is evaluated by running several experiments, with results that indicate that the proposed architecture satisfies reliability requirements for wireless links providing communications without interruptions. The use of SDN together with these wireless technologies allows the creation of architectures capable of supporting new applications that demand very strict requirements of the network, even with the same magnitudes as expected in future 5G networks.

The proposed architecture was implemented and a prototype built with commercial off-the-shelf components to foster robotic cloud-enabled applications. The architecture performance was validated in a Health Care scenario through a cloud-based haptic guiding service to assist mobility impaired individuals using a cloud smart walker. In this scenario, it was also evaluated an extension of the proposal for robotic networks in which the network's mobile nodes can work either as client or AP under SDN orchestration. Another validation was conducted using the architecture in a Testbed for Industry 4.0 environments. For this use case, the architecture guarantee high traffic density and high reliability in indoor environments with context-aware solutions based on computer vision, edge computing, SDN, and WiFi networks. A Make Before Degrade paradigm can be implement to boost reliability of traffic streams thanks to the multi-connectivity that the robot in the industrial space maintains through diversity of access to the base stations, that permit alternate path. The context-awareness of MBD was able to preventively steer traffic to a different cell, in which the LoS was not obstructed by the metallic object, avoiding altogether the signal degradation.

With the SDN WiFi communication architecture proposed in this work together with the results obtained during its validation, it can be affirmed that SDN technologies are an excellent option to improve the deficiencies of current network solutions. Moreover, the use of SDN solutions applied in wireless technologies such as WiFi allow to achieve network requirements similar to those required in the new 5G networks. In this way, a large number of proposals and solutions can be developed with the use of COTS device for satisfying new verticals in URLLC environments.

# 5 Conclusions and Future Work

This work presented and experimentally validated a WiFi architecture based on SDN that performs a split of its functional elements to increase reliability in wireless communications. The proposed architecture demonstrates how new softwarization and virtualization technologies can be employed in existing wireless architectures to improve many of the deficiencies that some technologies – like WiFi – still face. For the most part, these deficiencies can and should be solved to achieve a successful integration of WiFi technology in the wide range of technologies for the 5G networks paradigm, technologies in which high performance requirements are demanded to meet new applications and services.

## 5.1 Conclusions and Contributions

A study was performed to systematize the main characteristics and enabling technologies in the new 5G systems. The development and implementation of the 5G wireless networks is receiving most of the attention in the wireless technologies research, given the complexity to integrate all the elements in these systems. The 5G systems have the hard task of supporting a broad spectrum of new applications that demand stringent performance requirements from the networks. Three general services have been defined to cover a wide range of use cases, eMBB for high transmission data rate, URLLC for high reliability and low latency requirements scenarios and mMTC focused en management high density device scenarios. To achieve all the services, the 5G architectures are based on a C-RAN that integrates Multi-RAT, connected to a virtualized service-oriented core network through software defined transport networks.

Several enabling technologies have been identified that have and will have a decisive role in the implementation of 5G networks. Already established paradigms of SDN and VNF are the keys to achieve a completely service-oriented system, implementing the concept of network slicing and supported by cloud computing platforms. On the other hand, new radio technologies such as the use of Massive MIMO in new bands of the mmWave spectrum are used in RANs with high density base stations topology deployments. The C-RAN integrates and manages multi-RAT solutions, some standards developed specifically for 5G systems and other already with a wide use in current wireless systems, with WiFi technology present. WiFi Community specialists and wireless industry leaders agree in their 5G vision that WiFi is a fundamental technology to help 5G systems in their goals. Several reasons stand out: (i) popularity and large deployment of WiFi equipment existing throughout the world; (ii) WiFi currently serving a considerable part of the mobile traffic offloading; (iii) WiFi has better performance in indoor environments where broadband wireless networks often can not serve their users. Along with these facts, the WiFi community has worked hard in the development of a new generation of WiFi standards capable to provide high requirements similar to 5G systems to satisfy the demands of new applications and services.

To support applications that demand strict latency and reliability requirements from the network, the URLLC service has been defined, with special attention to the complex trade-off between latency and reliability. To increase the wireless communications reliability, the employ of diversity techniques implemented at different communication layers represents a key solution. Micro-diversity techniques are implemented at physical layer in most modern wireless systems to mitigate the negative effects of fading in multi-path channels. Macro-diversity techniques exploit in some way multi-connectivity schemes to increase the reliability of wireless transmissions. The multi-connectivity condition in wireless systems opens possibilities for the use of other techniques that help to increase the reliability even more. Techniques such as packet duplication and information coding through different interfaces are commonly used, supported by network topologies where stations collaborate to improve the transmissions performance. Multi-connectivity is also one of the keys to achieving seamless and reliable handover processes during user mobility, more frequent with high density of stations. The macro diversity techniques, and especially the multi-connectivity schemes, have been focused and developed almost exclusively for broadband wireless networks. However, the WiFi system are only standards for physical and MAC layer, and the multi-connectivity schemes have not yet been exploited, becoming one of the main challenges to improve the communication reliability in these systems.

The architecture presented in this work is focused in WiFi scenarios to increase reliability during the handovers when user migrates between APs. The solution implement multi-association and multi-connectivity scheme with the user, introducing the new concept of mobile AP. Within this new concept, traditional stations become access points to reach the services that would be hosted on a cloud platform. Thus, several fixed stations would be associated with mobile AP, so there are several path to reach it. As the architecture has a backhaul network composed of an Openflow switch, to carry out a user migration (i.e., handover), an SDN controller only modifies the forwarding rules of the switch to send the traffic through another fixed station. The proposed architecture was implemented and a prototype built with commercial off-the-shelf devices, and the first validation results indicates that satisfies reliability requirements, minimizing considerably the communication interruption times in WiFi handovers.

The architecture was implemented and integrated in two different real scenarios, to evaluate their performance in real-time control applications based on cloud robotics, as part of URLLC services. The first use case considers a future Healthcare application for patient assisted mobility, where through a rigorous SDN orchestration, the communication system maintains high reliability values for a robot networks in cluster with dynamic change of the WiFi element roles. In the second use case focused in scenarios for Industry 4.0, the proposal architecture for seamless handover is employ in a novel Make Before Degrade paradigm. This solution is a smart context-aware handover that in addition to guarantee reliability for users migrations, is also capable of guaranteeing traffic density by area and data rate experienced by users in indoor small cell environments avoiding possible degradation of the SNR perceived by users, supported by the context information. In both case, the proposed architecture offered the reliability and latency requirements that these remote real-time control applications demanded, then it can be affirmed that SDN technologies applied in currently wireless technologies such as WiFi allow to achieve network requirements similar to those required in the new 5G networks. Several proposals and solutions can be developed employing commercial off-the-shelf device to satisfies new verticals in URLLC networks.

## 5.2 Publications

During the realization of this work, the following paper was published and is directly linked to the work here presented:

- MARTINEZ, V. G. et al. Ultra Reliable Communication for Robot Mobility enabled by SDN Splitting of WiFi Functions. In: *2018 IEEE Symposium on Computers and Communications (ISCC)*, Natal, 2018, pp. 527-530.

Other works under rewiev are also directly linked to the research:

- GUIMARAES, R. S. et al. An SDN Context-Aware Handover for Enhanced Wireless Mobility: Modeling and Implementation. IEEE Transactions on Network and Service Management, 2019. *(Under Review)*

- MELLO, R. et al. Cloud Robotics for eHealth: An SDN-Based Infrastructure for Patient Mobility Aid. Journal of Intelligent Robotic Systems, 2019. *(Under Review)*

Lastly, the author participated on other research activities in the duration of this work and contributed in the papers listed bellow:

- MARQUES P. et al.Optical and wireless network convergence in 5G systems – an experimental approach. In: *2018 IEEE 23rd International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD)*, Barcelona, 2018, pp. 1-5.

## 5.3 Future Work

After complete the presented work and based on the results obtained, multiple lines of future work remain possible. The implemented system can be extended to incorporate other techniques that contribute to a more robust system, capable of achieving better levels of reliability, availability and latency. A main work efforts to improve the solution should be directed to (i) handovers trigger algorithms and (ii) other technique for exploit the system multi-connectivity.

Since the architecture bases its operation of user migrations on network-centric handover, the handover decision algorithms can be better exploited. The architecture already provides a solution where the mobility interruption time is minimized, however, the decision based only on SNR values perceived by the fixed stations is somewhat insufficient to make good decisions in the complex current wireless scenarios. By using new tools available for conventional WiFi cards, it is possible to obtain the status information of the wireless channel represented in attenuation and phase values for multiple path for the received signal. This physical layer information can be used to implement algorithms more aware of the physical state of transmissions, and handover controllers can perform migrations that improve the transmissions performance and end-to-end communication reliability. Although in the evaluation of the use case for Industry 4.0, a novel handover scheme that bases its migration decisions on contextual information offered by a computational vision system, information different from the location can also be used. The context aware networks can offer a large amount of information to be used in more efficient decisions and that can be adapted to the requirements of different types of applications, for which the machine learning and big data techniques can be implemented to help the orchestrators in these trigger algorithms.

The system's multi-connectivity can be used as support for the implementation and development of new routing multi-path protocols for WiFi wireless networks. As in broadband mobile networks, the use of packet duplication techniques can be used to increase the communication reliability in WiFi environments with low SNR conditions. The techniques of packages duplication however for scenarios with good propagation conditions can be inefficient, since the conditions in such scenarios allow reliable transmissions from one an access point. SDN orchestrators can then activate packet duplication during handover processes only for those access points involved in the process, guaranteeing maximum efficiency during the handover. But not only the reliability can be increased by means of the multi-connectivity, latency requirements for wireless transmissions can also be improved in this WiFi architecture. For this, the use of transmission strategies with information coding for sending it through several interfaces can be used, which means that users only need to receive a few packets of the message to be able to reconstruct it completely, decreasing the communication latency. While it is true that many times decoding processes can generate much complexity and delays to the systems, the use of simple encodings that require simple decoding processes would already represent an important advance to improve the WiFi networks performance. Finally, these strategies can be controlled and managed by SDN orchestrators, that with a general vision of the network can implement cooperation technique between the access points as it happens in some mobile broadband networks.

Currently some robotics research groups of the university, like the Assisted Technology Group, have adopted the SDN WiFi communication architecture for cloud robotic applications. The future developments of new applications that demand better levels of reliability in WiFi communications can be realized taking into account the WiFi SDN architecture presented here.

# Bibliography

[1] OSSEIRAN, A.; MONSERRAT, J. F.; MARSCH, P. *5G Mobile and Wireless Communications Technology*. [S.l.]: Cambridge University Press, 2016. 453 p.

[2] MARSCH, P. et al. *5G System Design: Architectural and Functional Considerations and Long Term Research*. [S.l.]: John Wiley  Sons Ltd, 2018. 608 p.

[3] SACHS, J. et al. 5g radio network design for ultra-reliable low-latency communication. *IEEE Network*, v. 32, n. 2, p. 24–31, March 2018.

[4] SIMSEK, M. et al. On the Flexibility and Autonomy of 5G Wireless Networks. *IEEE Access*, 2017.

[5] SANCHEZ, M.; OLIVA, A.; MANCUSO, V. Experimental evaluation of an sdn-based distributed mobility management solution. In: . [S.l.: s.n.], 2016. p. 31–36.

[6] HE, Y. et al. On wifi offloading in heterogeneous networks: Various incentives and trade-off strategies. *IEEE Communications Surveys Tutorials*, v. 18, n. 4, p. 2345–2385, Fourthquarter 2016.

[7] MISHRA, A.; SHIN, M.; ARBAUGH, W. An Empirical Analysis of the IEEE 802.11 MAC Layer Handoff Process. *ACM SIGCOMM Computer*, v. 33, n. 2, p. 93–102, 2003.

[8] MARIA, K. A. et al. Channel selectivity schemes for re-transmission diversity in industrial wireless system. In: *2017 International Symposium on Electronics and Smart Devices (ISESD)*. [S.l.: s.n.], 2017. p. 207–212.

[9] GAO, Y.; YANG, T.; HU, B. Improving the transmission reliability in smart factory through spatial diversity with arq. In: *2016 IEEE/CIC International Conference on Communications in China (ICCC)*. [S.l.: s.n.], 2016. p. 1–5.

[10] SWAMY, V. N. et al. Cooperative communication for high-reliability low-latency wireless control. In: *2015 IEEE International Conference on Communications (ICC)*. [S.l.: s.n.], 2015. p. 4380–4386.

[11] KALLE, R. K. Reliable and prioritized communication using polarization diversity for industrial internet of things. In: *2016 IEEE Conference on Wireless Sensors (ICWiSE)*. [S.l.: s.n.], 2016. p. 89–94.

[12] SWAMY, V. N. et al. Network coding for high-reliability low-latency wireless control. In: *2016 IEEE Wireless Communications and Networking Conference*. [S.l.: s.n.], 2016. p. 1–7.

[13] NIELSEN, J. J.; LIU, R.; POPOVSKI, P. Ultra-Reliable Low Latency Communication (URLLC) using Interface Diversity. *IEEE Transactions on Communications*, v. 6778, n. c, p. 1–12, 2017.

[14] QADIR, J. et al. Exploiting the power of multiplicity: A holistic survey of network-layer multipath. *IEEE Communications Surveys Tutorials*, v. 17, n. 4, p. 2176–2213, Fourthquarter 2015.

[15] MICHALOPOULOS, D. S.; VIERING, I.; DU, L. User-plane multi-connectivity aspects in 5g. In: *2016 23rd International Conference on Telecommunications (ICT)*. [S.l.: s.n.], 2016. p. 1–5.

[16] MCKEOWN, N. et al. OpenFlow: Enabling Innovation in Campus Networks. *ACM SIGCOMM Computer Communication Review*, v. 38, n. 2, p. 69, 2008.

[17] FONTES, R. D. R. et al. How Far Can We Go? Towards Realistic Software-Defined Wireless Networking Experiments. *Computer Journal*, v. 60, n. 10, p. 1458–1471, 2017.

[18] Bassi, L. Industry 4.0: Hope, hype or revolution? In: *2017 IEEE 3rd International Forum on Research and Technologies for Society and Industry (RTSI)*. [S.l.: s.n.], 2017. p. 1–6.

[19] Chernyshev, M. et al. Internet of things (iot): Research, simulators, and testbeds. *IEEE Internet of Things Journal*, v. 5, n. 3, p. 1637–1647, June 2018. ISSN 2327-4662.

[20] ITU-R Recommendation. *ITU-R M.2083 IMT Vision: Framework and overall objectives of the future development of IMT for 2020 and beyond*. 2015.

[21] LI, Z. et al. 5g urllc: Design challenges and system concepts. In: *2018 15th International Symposium on Wireless Communication Systems (ISWCS)*. [S.l.: s.n.], 2018. p. 1–6.

[22] BOCKELMANN, C. et al. Towards massive connectivity support for scalable mmtc communications in 5g networks. *IEEE Access*, v. 6, p. 28969–28992, 2018.

[23] 3GPP. *Technical Report 22.891. Study on new services and markets technology enablers*. [S.l.], 2016.

[24] HUSAIN, S. et al. The road to 5g v2x: Ultra-high reliable communications. In: *2018 IEEE Conference on Standards for Communications and Networking (CSCN)*. [S.l.: s.n.], 2018. p. 1–6.

[25] TALEB, T.; KSENTINI, A.; JANTTI, R. "anything as a service" for 5g mobile systems. *IEEE Network*, v. 30, n. 6, p. 84–91, November 2016.

[26] YOUSAF, F. Z. et al. Nfv and sdn—key technology enablers for 5g networks. *IEEE Journal on Selected Areas in Communications*, v. 35, n. 11, p. 2468–2478, Nov 2017.

[27] RANAWEERA, C. et al. 5g c-ran with optical fronthaul: An analysis from a deployment perspective. *Journal of Lightwave Technology*, v. 36, n. 11, p. 2059–2068, June 2018.

[28] WANG, R.; HU, H.; YANG, X. Potentials and challenges of c-ran supporting multi-rats toward 5g mobile networks. *IEEE Access*, v. 2, p. 1187–1195, 2014.

[29] MUñOZ, R. et al. Sdn control and monitoring of sdm/wdm and packet transport networks for 5g fronthaul/backhaul. In: *2018 IEEE Photonics Society Summer Topical Meeting Series (SUM)*. [S.l.: s.n.], 2018. p. 151–152.

[30] MA, L. et al. An sdn/nfv based framework for management and deployment of service based 5g core network. *China Communications*, v. 15, n. 10, p. 86–98, Oct 2018.

[31] LI, X. et al. Network slicing for 5g: Challenges and opportunities. *IEEE Internet Computing*, v. 21, n. 5, p. 20–27, 2017.

[32] BARANDA, J. et al. Orchestration of end-to-end network services in the 5g-crosshaul multi-domain multi-technology transport network. *IEEE Communications Magazine*, v. 56, n. 7, p. 184–191, July 2018.

[33] GAMPALA, G.; REDDY, C. J. Massive mimo. beyond 4g and a basis for 5g. In: *2018 International Applied Computational Electromagnetics Society Symposium (ACES)*. [S.l.: s.n.], 2018. p. 1–2.

[34] AGRAWAL, S. K.; SHARMA, K. 5g millimeter wave (mmwave) communications. In: *2016 3rd International Conference on Computing for Sustainable Global Development (INDIACom)*. [S.l.: s.n.], 2016. p. 3630–3634.

[35] VOOK, F. W. et al. 5g new radio: Overview and performance. In: *2018 52nd Asilomar Conference on Signals, Systems, and Computers*. [S.l.: s.n.], 2018. p. 1247–1251.

[36] GOTSIS, A.; STEFANATOS, S.; ALEXIOU, A. Ultradense networks: The new wireless frontier for enabling 5g access. *IEEE Vehicular Technology Magazine*, v. 11, n. 2, p. 71–78, June 2016.

[37] ALLEVEN, M. *3GPP declares first 5G NR spec complete*. 2017. Disponível em: <https://www.fiercewireless.com/wireless/>.

[38] ALLEVEN, M. *3GPP puts finishing touch on Standalone version of 5G standard*. 2018. Disponível em: <https://www.fiercewireless.com/wireless/>.

[39] LIEN, S. et al. 5g new radio: Waveform, frame structure, multiple access, and initial access. *IEEE Communications Magazine*, v. 55, n. 6, p. 64–71, June 2017.

[40] CHEN, X. et al. Massive mimo beamforming with transmit diversity for high mobility wireless communications. *IEEE Access*, v. 5, p. 23032–23045, 2017.

[41] BUSARI, S. A. et al. Millimeter-wave massive mimo communication for future wireless systems: A survey. *IEEE Communications Surveys Tutorials*, v. 20, n. 2, p. 836–869, Secondquarter 2018.

[42] HUQ, K. M. S.; RODRIGUEZ, J. Backhauling 5g small cells with massive-mimo-enabled mmwave communication. In: _____. *Backhauling / Fronthauling for Future Wireless Systems*. [S.l.]: Wiley, 2016.

[43] AL-OGAILI, F.; SHUBAIR, R. M. Millimeter-wave mobile communications for 5g: Challenges and opportunities. In: *2016 IEEE International Symposium on Antennas and Propagation (APSURSI)*. [S.l.: s.n.], 2016. p. 1003–1004.

[44] ZHANG, S.; WANG, G.; I, C. Is mmwave ready for cellular deployment? *IEEE Access*, v. 5, p. 14369–14379, 2017.

[45] GUAN, K. et al. Towards realistic high-speed train channels at 5g millimeter-wave band—part ii: Case study for paradigm implementation. *IEEE Transactions on Vehicular Technology*, v. 67, n. 10, p. 9129–9144, Oct 2018.

[46] KAMEL, M.; HAMOUDA, W.; YOUSSEF, A. Ultra-dense networks: A survey. *IEEE Communications Surveys Tutorials*, v. 18, n. 4, p. 2522–2545, Fourthquarter 2016.

[47] KLESSIG, H. et al. From immune cells to self-organizing ultra-dense small cell networks. *IEEE Journal on Selected Areas in Communications*, v. 34, n. 4, p. 800–811, April 2016.

[48] PRAJAPATI, A.; SAKADASARIYA, A.; PATEL, J. Software defined network: Future of networking. In: *2018 2nd International Conference on Inventive Systems and Control (ICISC)*. [S.l.: s.n.], 2018. p. 1351–1354.

[49] LARA, A.; KOLASANI, A.; RAMAMURTHY, B. Network innovation using openflow: A survey. *IEEE Communications Surveys Tutorials*, v. 16, n. 1, p. 493–512, First 2014.

[50] LIYANAGE, M. et al. *Software Defined Mobile Networks (SDMN): Beyond LTE Architecture*. [S.l.]: Wiley Series on Communications Networking Distributed Systems, 2015.

[51] STANCU, A. et al. Enabling sdn application development using a netconf mediator layer simulator. In: *2017 Ninth International Conference on Ubiquitous and Future Networks (ICUFN)*. [S.l.: s.n.], 2017. p. 658–663.

[52] ZHANG, Y. *Network function virtualization: Concepts and applicability in 5G networks*. [S.l.: s.n.], 2017. 1-173 p.

[53] GRAY, K.; NADEAU, T. D. *Network Function Virtualization*. 1st. ed. San Francisco, CA, USA: Morgan Kaufmann Publishers Inc., 2016.

[54] ABDELWAHAB, S. et al. Network function virtualization in 5g. *IEEE Communications Magazine*, v. 54, n. 4, p. 84–91, April 2016.

[55] INTEL. *Intel 5G. Network, cloud and client.* [S.l.], 2016.

[56] SAMSUNG. *5G Vision.* [S.l.], 2015.

[57] HUAWEI. *5G Network Architecture. A High-level Perspective.* [S.l.], 2016.

[58] MARKETSANDMARKETS. Wi-Fi Hotspot Market by Components (Wireless Hotspot Gateways, Wireless Hotspot Controllers and Mobile Hotspot Devices), by Software, by Services, by End Users, by Verticals, by Regions - Global forecast to 2020. *Technical Report*, p. 1–171, 2015.

[59] SUN, W. et al. Wi-fi could be much more. *IEEE Communications Magazine*, v. 52, n. 11, p. 22–29, Nov 2014.

[60] GABRIEL, C.; FELLAH, M.-R. A. WBA Industry Report 2016. The Unlicensed Road to 5G. *Wireless Broadband Alliance*, p. 1–35, 2016.

[61] KINNEY, S. *The parallel development of 5G and Wi-Fi*. 2018. Disponível em: <https://www.rcrwireless.com/20180705/network-infrastructure/wi-fi/>.

[62] KINNEY, S. *Convergence marks 5G, Wi-Fi future, Boingo CTO says*. 2018. Disponível em: <https://www.rcrwireless.com/20180705/network-infrastructure/wi-fi/>.

[63] KINNEY, S. *For enterprises, Wi-Fi is here to stay, analyst says*. 2018. Disponível em: <https://www.rcrwireless.com/20180703/network-infrastructure/wi-fi/>.

[64] MEHMETI, F.; SPYROPOULOS, T. Performance analysis of mobile data offloading in heterogeneous networks. *IEEE Transactions on Mobile Computing*, v. 16, n. 2, p. 482–497, Feb 2017.

[65] ZHOU, H. et al. A survey on mobile data offloading technologies. *IEEE Access*, v. 6, p. 5101–5111, 2018.

[66] GAO, G. et al. Opportunistic mobile data offloading with deadline constraints. *IEEE Transactions on Parallel and Distributed Systems*, v. 28, n. 12, p. 3584–3599, Dec 2017.

[67] FAKHFAKH, E.; HAMOUDA, S.; TABBANE, S. Enhanced traffic offloading with d2d communications under noise rise constraint. In: *2016 IEEE Symposium on Computers and Communication (ISCC)*. [S.l.: s.n.], 2016. p. 1112–1116.

[68] PYATTAEV, A. et al. 3gpp lte traffic offloading onto wifi direct. In: *2013 IEEE Wireless Communications and Networking Conference Workshops (WCNCW)*. [S.l.: s.n.], 2013. p. 135–140.

[69] BENNIS, M. et al. When cellular meets wifi in wireless small cell networks. *IEEE Communications Magazine*, v. 51, n. 6, p. 44–50, June 2013.

[70] MIR, T. et al. Optimal femtocell density for maximizing throughput in 5g heterogeneous networks under outage constraints. In: *2017 IEEE 86th Vehicular Technology Conference (VTC-Fall)*. [S.l.: s.n.], 2017. p. 1–5.

[71] FORUM, S. C. Industry Perspectives, Trusted WLAN Architectures and Deployment Considerations for Integrated Small-Cell Wi-Fi (ISW) Networks . *Wireless Broadband Alliance. Small Cell Forum*, p. 1–53, 2016.

[72] SUH, D.; KO, H.; PACK, S. Efficiency analysis of wifi offloading techniques. *IEEE Transactions on Vehicular Technology*, v. 65, n. 5, p. 3813–3817, May 2016.

[73] FORTETSANAKIS, G.; PAPADOPOULI, M. How beneficial is the wifi offloading? a detailed game-theoretical analysis in wireless oligopolies. In: *2016 IEEE 17th International Symposium on A World of Wireless, Mobile and Multimedia Networks (WoWMoM)*. [S.l.: s.n.], 2016. p. 1–10.

[74] 3GPP. *Technical Specification 22.234. Requirements on 3GPP system to Wireless Local Area Network (WLAN) interworking*. [S.l.], 2006.

[75] BAYHAN, S.; GÜR, G.; ZUBOW, A. The future is unlicensed: Coexistence in the unlicensed spectrum for 5g. *CoRR*, 2018.

[76] MARKOVA, E. et al. Performance assessment of qos-aware lte sessions offloading onto laa/wifi systems. *IEEE Access*, v. 7, p. 36300–36311, 2019.

[77] LASELVA, D. et al. 3gpp lte-wlan aggregation technologies: Functionalities and performance comparison. *IEEE Communications Magazine*, v. 56, n. 3, p. 195–203, March 2018.

[78] HAQUE, I. T.; ABU-GHAZALEH, N. Wireless software defined networking: A survey and taxonomy. *IEEE Communications Surveys Tutorials*, v. 18, n. 4, p. 2713–2737, Fourthquarter 2016.

[79] RAGHAVENDRA, R. et al. Understanding Handoffs in Large IEEE 802 . 11 Wireless. *Wireless Networks*, p. 333–338, 2007.

[80] ZEHL, S.; ZUBOW, A.; WOLISZ, A. BIGAP - A seamless handover scheme for high performance enterprise IEEE 802.11 networks. *Proceedings of the NOMS 2016 - 2016 IEEE/IFIP Network Operations and Management Symposium*, n. Noms, p. 1015–1016, 2016.

[81] MOURA, H. et al. Ethanol: Software defined networking for 802.11 Wireless Networks. *2015 IFIP/IEEE International Symposium on Integrated Network Management (IM)*, p. 388–396, 2015.

[82] SURESH, L. et al. Towards programmable enterprise wlans with odin. *HotSDN'12 - Proceedings of the 1st ACM International Workshop on Hot Topics in Software Defined Networks*, 08 2012.

[83] GILANI, S. M. M. et al. Mobility management in ieee 802.11 wlan using sdn/nfv technologies. *EURASIP Journal on Wireless Communications and Networking*, v. 2017, n. 1, p. 67, Apr 2017.

[84] GOWDA, M.; DHEKNE, A.; CHOUDHURY, R. R. The Case for Robotic Wireless Networks. *Proceedings of the 25th World Wide Web Conference (WWW 2016)*, p. 1317–1327, 2016.

[85] 3GPP. *Service requirements for next generation new services and markets.* [S.l.], 2018. Rev. 16.3.0.

[86] UUSITALO, M. *Wireless for Verticals.* [S.l.], 2017.

[87] POCOVI, G. et al. Achieving Ultra-Reliable Low-Latency Communications: Challenges and Envisioned System Enhancements. *IEEE Network*, IEEE, v. 32, n. 2, p. 8–15, 2018. ISSN 08908044.

[88] CHO, Y. S. et al. *MIMO-OFDM Wireless Communications with MATLAB.* [S.l.]: Wiley Publishing, 2010.

[89] PAYAMI, S.; TUFVESSON, F. Delay spread properties in a measured massive mimo system at 2.6 ghz. In: *2013 IEEE 24th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*. [S.l.: s.n.], 2013. p. 53–57.

[90] GONçALVES, J. V. O.; SIQUEIRA, G. L. Delay spread calculation from coherence bandwidth measurements on a ofdm based mobile communication system. In: *2009 SBMO/IEEE MTT-S International Microwave and Optoelectronics Conference (IMOC)*. [S.l.: s.n.], 2009. p. 253–256.

[91] TSE, D.; VISWANATH, P. *Fundamentals of Wireless Communication.* New York, NY, USA: Cambridge University Press, 2005.

[92] SILVA, J. A. L.; CARTAXO, A. V. T.; SEGATTO, M. E. V. A papr reduction technique based on a constant envelope ofdm approach for fiber nonlinearity mitigation in optical direct-detection systems. *J. Opt. Commun. Netw.*, OSA, v. 4, n. 4, p. 296–303, Apr 2012.

[93] TJHUNG, T. T. Error probability performance of ofdm-adsl systems. In: *IEEE GLOBECOM 1998*. [S.l.: s.n.], 1998. v. 6, p. 3326–3331 vol.6.

[94] QIU, K. et al. Ofdm-pon optical fiber access technologies. In: *2011 Asia Communications and Photonics Conference and Exhibition (ACP)*. [S.l.: s.n.], 2011. p. 1–9.

[95] COURA, D. J. C.; SILVA, J. A. L.; SEGATTO, M. E. V. A bandwidth scalable OFDM passive optical network for future access network. *Photonic Network Communications*, v. 18, n. 3, p. 409, 2009.

[96] KSHETRIMAYUM, R. *Fundamentals of MIMO Wireless Communications*. [S.l.]: Cambridge University Press, 2017.

[97] SHANKAR, P. M. *Fading and Shadowing in Wireless Systems*. [S.l.]: Springer-Verlag New York, 2014. 1-464 p.

[98] XIE, Y.; LI, Z.; LI, M. Precise power delay profiling with commodity wifi. In: *Proceedings of the 21st Annual International Conference on Mobile Computing and Networking*. [S.l.]: ACM, 2015. (MobiCom '15), p. 53–64.

[99] SARANGI, A. K.; DATTA, A. Capacity comparison of siso, simo, miso mimo systems. In: *2018 Second International Conference on Computing Methodologies and Communication (ICCMC)*. [S.l.: s.n.], 2018. p. 798–801.

[100] AHAMED, I.; VIJAY, M. Comparison of different diversity techniques in mimo antennas. In: *2017 2nd International Conference on Communication and Electronics Systems (ICCES)*. [S.l.: s.n.], 2017. p. 47–50.

[101] LEE, J. et al. Generalized co-phasing for multiple transmit and receive antennas. *IEEE Transactions on Wireless Communications*, v. 8, p. 1649 – 1654, 05 2009.

[102] SAKARELLOS, V. et al. Cooperative diversity performance of selection relaying over correlated shadowing. *Physical Communication*, v. 4, n. 3, p. 182–189, 2011.

[103] YANG, H.-C.; ALOUINI, M.-S. *Order Statistics in Wireless Communications: Diversity, Adaptation, and Scheduling in MIMO and OFDM Systems*. 1st. ed. [S.l.]: Cambridge University Press, 2011.

[104] HALPERIN, D. et al. 802.11 with multiple antennas for dummies. *Computer Communication Review*, v. 40, p. 19–25, 2010.

[105] DAVOODI, A. G.; JAFAR, S. A. Transmitter cooperation under finite precision csit: A gdof perspective. *IEEE Transactions on Information Theory*, v. 63, n. 9, p. 6020–6030, Sep. 2017.

[106] LU, Y.; ZHANG, W. Water-filling capacity analysis in large mimo systems. In: *2013 Computing, Communications and IT Applications Conference (ComComAp)*. [S.l.: s.n.], 2013. p. 186–190.

[107] TAROKH, V.; JAFARKHANI, H.; CALDERBANK, R. Space-time block coding for wireless communications: Performance results. *Selected Areas in Communications, IEEE Journal on*, v. 17, p. 451 – 460, 04 1999.

[108] LIU, J.; ZHAO, H. The comparison between space-time blocks codes and trellis codes under maximum likelihood sequence estimator. In: *2009 International Conference on Wireless Networks and Information Systems*. [S.l.: s.n.], 2009. p. 23–26.

[109] ROH, J. C.; RAO, B. D. Design and analysis of mimo spatial multiplexing systems with quantized feedback. *IEEE Transactions on Signal Processing*, v. 54, n. 8, p. 2874–2886, Aug 2006.

[110] GETU, B. N.; ANDERSEN, J. B. Mimo systems in random uncorrelated, correlated and deterministic radio channels. *Wireless Personal Communications*, v. 30, n. 1, p. 27–61, Jul 2004.

[111] YADAV, B. K.; SINGH, R. K.; MOHANTY, S. Performance analysis of efficient and low complexity mimo-ofdm using stbc and v-blast. In: *2016 International Conference on Emerging Trends in Electrical Electronics Sustainable Energy Systems (ICETEESES)*. [S.l.: s.n.], 2016. p. 204–207.

[112] MROCZEK, J. J.; GANS, M. J.; JOINER, L. L. Performance of frequency hopping d-blast mimo architecture using ldpc and bpsk. In: *MILCOM 2015 - 2015 IEEE Military Communications Conference*. [S.l.: s.n.], 2015. p. 860–865.

[113] KUHESTANI, A.; MOHAMMADI, A. Diversity-multiplexing trade-off of linear dispersion coded multi-input–multi-output systems. *IET Communications*, v. 9, n. 1, p. 55–61, 2015.

[114] ZHANG, K. et al. The study of multi-user diversity technology over the mimo-ofdm system. In: *2008 4th International Conference on Wireless Communications, Networking and Mobile Computing*. [S.l.: s.n.], 2008. p. 1–4.

[115] NIU, J. et al. Scheduling exploiting frequency and multi-user diversity in lte downlink systems. *IEEE Transactions on Wireless Communications*, v. 12, n. 4, p. 1843–1849, April 2013.

[116] BIGLIERI, E. et al. *Principles of Cognitive Radio*. [S.l.]: Cambridge University Press, 2012.

[117] GUEGUEN, C.; BAEY, S. Compensated proportional fair scheduling in multiuser ofdm wireless networks. In: . [S.l.: s.n.], 2008. p. 119 – 125.

[118] ZARBOUTI, D. A. et al. Ofdma multicell systems with opportunistic beamforming. In: *21st Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*. [S.l.: s.n.], 2010. p. 1407–1412.

[119] MURRAY, B. P.; ZAGHLOUL, A. I. A survey of cognitive beamforming techniques. In: *2014 United States National Committee of URSI National Radio Science Meeting (USNC-URSI NRSM)*. [S.l.: s.n.], 2014. p. 1–1.

[120] Lee, S. J. Comparison of open loop and closed loop schemes for multiple transmit antennas in ofdma systems. *Electronics Letters*, v. 44, n. 8, p. 536–537, April 2008. ISSN 0013-5194.

[121] RAO, J.; VRZIC, S. Packet duplication for urllc in 5g: Architectural enhancements and performance analysis. *IEEE Network*, v. 32, n. 2, p. 32–40, March 2018.

[122] VIDHYA, R.; KARTHIK, P. Dynamic carrier aggregation in 5g network scenario. In: *2015 International Conference on Computing and Network Communications (CoCoNet)*. [S.l.: s.n.], 2015. p. 936–940.

[123] MAHMOOD, N. H. et al. Reliability oriented dual connectivity for urllc services in 5g new radio. In: *2018 15th International Symposium on Wireless Communication Systems (ISWCS)*. [S.l.: s.n.], 2018. p. 1–6.

[124] ANTONIOLI, R. et al. Dual connectivity for lte-nr cellular networks. In: *XXXV BRAZILIAN SYMPOSIUM ON TELECOMMUNICATIONS AND SIGNAL PROCESSING - SBrT2017*. [S.l.: s.n.], 2017.

[125] ZAKRZEWSKA, A. et al. Dual connectivity in lte hetnets with split control- and user-plane. In: *2013 IEEE Globecom Workshops (GC Wkshps)*. [S.l.: s.n.], 2013. p. 391–396.

[126] European Telecommunications Standards Institute. *5G; Service requirements for next generation new services and markets (3GPP TS 22.261 version 15.5.0 Release 15)*. [S.l.], 2018. 53 p. Disponível em: <https://portal.etsi.org/TB/ETSIDeliverableStatus.aspx>.

[127] RENTSCHLER, M.; HEINE, H. The parallel redundancy protocol for industrial ip networks. In: *2013 IEEE International Conference on Industrial Technology (ICIT)*. [S.l.: s.n.], 2013. p. 1404–1409.

[128] NIELSEN, J. J.; LIU, R.; POPOVSKI, P. Ultra-reliable low latency communication using interface diversity. *IEEE Transactions on Communications*, v. 66, n. 3, p. 1322–1334, March 2018.

[129] FARZANEH, M. H.; KNOLL, A. Time-sensitive networking (tsn): An experimental setup. In: *2017 IEEE Vehicular Networking Conference (VNC)*. [S.l.: s.n.], 2017. p. 23–26.

[130] IEEE Standard for Local and metropolitan area networks–Frame Replication and Elimination for Reliability. *IEEE Std 802.1CB-2017*, p. 1–102, Oct 2017.

[131] CENA, G.; SCANZIO, S.; VALENZANO, A. Seamless link-level redundancy to improve reliability of industrial wi-fi networks. *IEEE Transactions on Industrial Informatics*, v. 12, n. 2, p. 608–620, April 2016.

[132] AIJAZ, A. Packet duplication in dual connectivity enabled 5g wireless networks: Overview and challenges. *Computing Research Repository CoRR*, 2018.

[133] FAROOQI, M. et al. A survey on network coding: From traditional wireless networks to emerging cognitive radio networks. *Journal of Network and Computer Applications*, v. 46, p. 166–181, 11 2014.

[134] FRAGOULI, C. et al. Wireless network coding: Opportunities challenges. In: *MILCOM 2007 - IEEE Military Communications Conference*. [S.l.: s.n.], 2007. p. 1–8.

[135] GHANEM, S. A. M. Network coded handover in ieee 802.11. *Computing Research Repository CoRR*, 2018.

[136] JOUILI, I.; HASSINE, K.; FRIKHA, M. A network coding based solution to minimize packet loss during handover in lte-a systems: Highway scenario. In: *2016 International Wireless Communications and Mobile Computing Conference (IWCMC)*. [S.l.: s.n.], 2016. p. 458–462.

[137] POPOVSKI, P. et al. Wireless access for ultra-reliable low-latency communication: Principles and building blocks. *IEEE Network*, v. 32, n. 2, p. 16–23, March 2018.

[138] VENKATESAN, S.; LOZANO, A.; VALENZUELA, R. Network mimo: Overcoming intercell interference in indoor wireless systems. In: *2007 Conference Record of the Forty-First Asilomar Conference on Signals, Systems and Computers*. [S.l.: s.n.], 2007. p. 83–87.

[139] CLERCKX, B.; OESTGES, C. *MIMO Wireless Networks: Channels, Techniques and Standards for Multi-Antenna, Multi-User and Multi-Cell Systems*. 2nd. ed. [S.l.]: Academic Press, Inc., 2013.

[140] YU, X.; CUI, Q.; HAENGGI, M. Coherent joint transmission in downlink heterogeneous cellular networks. *IEEE Wireless Communications Letters*, v. 7, n. 2, p. 274–277, April 2018.

[141] TANBOURGI, R. et al. Analysis of non-coherent joint-transmission cooperation in heterogeneous cellular networks. In: *2014 IEEE International Conference on Communications (ICC)*. [S.l.: s.n.], 2014. p. 5160–5165.

[142] GESBERT, D. et al. Multi-cell mimo cooperative networks: A new look at interference. *IEEE Journal on Selected Areas in Communications*, v. 28, n. 9, p. 1380–1408, December 2010.

[143] GEIRHOFER, S.; GAAL, P. Coordinated multi point transmission in 3gpp lte heterogeneous networks. In: *2012 IEEE Globecom Workshops*. [S.l.: s.n.], 2012. p. 608–612.

[144] HOLMA, H.; TOSKALA, A. *LTE Advanced: 3GPP Solution for IMT-Advanced*. 1st. ed. [S.l.]: Wiley Publishing, 2012.

[145] LI, Q. C. et al. 5g network capacity: Key elements and technologies. *IEEE Vehicular Technology Magazine*, v. 9, n. 1, p. 71–78, March 2014.

[146] TORNATORE, M.; CHANG, G.-K.; ELLINAS, G. *Fiber-Wireless Convergence in Next-Generation Communication Networks: Systems, Architectures, and Management*. 1st. ed. [S.l.]: Springer Publishing Company, Incorporated, 2017.

[147] BASSOY, S. et al. Coordinated multi-point clustering schemes: A survey. *IEEE Communications Surveys Tutorials*, v. 19, n. 2, p. 743–764, Secondquarter 2017.

[148] QAMAR, F. et al. A comprehensive review on coordinated multi-point operation for lte-a. *Computer Networks*, v. 123, 05 2017.

[149] PABNA, C. P. Handoff / handover mechanism for mobility improvement in wireless communication by liton. In: . [S.l.: s.n.], 2014. v. 13, n. 16.

[150] JAVED, S.; NAEEM, B. Reduction of ping-pong effect in cognitive radio spectrum handoffs using fuzzy logic based inference. In: *2018 UKSim-AMSS 20th International Conference on Computer Modelling and Simulation (UKSim)*. [S.l.: s.n.], 2018. p. 9–13.

[151] VIERING, I. et al. Zero-zero mobility: Intra-frequency handovers with zero interruption and zero failures. *IEEE Network*, v. 32, n. 2, p. 48–54, March 2018.

[152] PARK, H. S. et al. Handover mechanism in nr for ultra-reliable low-latency communications. *IEEE Network*, v. 32, n. 2, p. 41–47, March 2018.

[153] KHATTAB, O. Vertical handover study on 4g category vs 5g category for 3gpp generation mobile systems and non-3gpp wireless networks. *Transactions on Networks and Communications*, v. 6, n. 2, 2018.

[154] RIZKALLAH, J.; AKKARI, N. Sdn-based vertical handover decision scheme for 5g networks. In: *2018 IEEE Middle East and North Africa Communications Conference (MENACOMM)*. [S.l.: s.n.], 2018. p. 1–6.

[155] BIJWE, A.; DETHE, C. Rss based vertical handoff algorithms for heterogeneous wireless networks -a review. *International Journal of Advanced Computer Science and Applications*, v. 1, 08 2011.

[156] ZHANG, X. et al. Multi-slot coverage probability and sinr-based handover rate analysis for mobile user in hetnet. *IEEE Access*, v. 6, p. 17868–17879, 2018.

[157] NARAYANA, A.; DUTT, V.; RAO, G. Bandwidth based handover probability analysis for beyond 4g heterogeneous wireless networks. *Journal of Scientific and Industrial Research (JSIR)*, v. 76, p. 690–693, November 2017.

[158] CHECHI, R.; KHANNA, R. Qos based handover in heterogeneous networks. In: *2011 International Conference on Multimedia Technology*. [S.l.: s.n.], 2011. p. 5021–5024.

[159] ZHAO, P. et al. Context-aware multi-criteria handover with fuzzy inference in software defined 5g hetnets. In: *2018 IEEE International Conference on Communications (ICC)*. [S.l.: s.n.], 2018. p. 1–6.

[160] VY, L. L.; TUNG, L.; LIN, B. P. Big data and machine learning driven handover management and forecasting. In: *2017 IEEE Conference on Standards for Communications and Networking (CSCN)*. [S.l.: s.n.], 2017. p. 214–219.

[161] MELLO, R. et al. Towards a new generation of smart devices for mobility assistance: Cloudwalker, a cloud-enabled cyber-physical system. In: *2018 7th IEEE International Conference on Biomedical Robotics and Biomechatronics (Biorob)*. [S.l.: s.n.], 2018. p. 439–444.

[162] RIBEIRO, M. R. N. 5g research and testbeds in brazil. In: *Optical Fiber Communication Conference (OFC) 2019*. [S.l.]: Optical Society of America, 2019. p. M3G.4.

[163] GAST, M. S. *802.11 Wireless Networks: The Definitive Guide, Second Edition*. [S.l.]: O'Reilly Media, Inc., 2005.

[164] IEEE Standard for Information Technology - Telecommunications and information exchange between systems - Local and Metropolitan networks - Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY)

specifications: Higher Speed Physical Layer (PHY) Extension in the 2.4 GHz band. *IEEE Std 802.11b-1999*, p. 1–96, Jan 2000.

[165] IEEE Standard for Telecommunications and Information Exchange Between Systems - LAN/MAN Specific Requirements - Part 11: Wireless Medium Access Control (MAC) and physical layer (PHY) specifications: High Speed Physical Layer in the 5 GHz band. *IEEE Std 802.11a-1999*, p. 1–102, Dec 1999.

[166] IEEE Standard for Information Technology- Telecommunications and Information Exchange Between Systems- Local and Metropolitan Area Networks- Specific Requirements Part Ii: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. *IEEE Std 802.11g-2003 (Amendment to IEEE Std 802.11, 1999 Edn. (Reaff 2003) as amended by IEEE Stds 802.11a-1999, 802.11b-1999, 802.11b-1999/Cor 1-2001, and 802.11d-2001)*, p. i–67, 2003.

[167] IEEE Standard for Information technology– Local and metropolitan area networks– Specific requirements– Part 11: Wireless LAN Medium Access Control (MAC)and Physical Layer (PHY) Specifications Amendment 5: Enhancements for Higher Throughput. *IEEE Std 802.11n-2009 (Amendment to IEEE Std 802.11-2007 as amended by IEEE Std 802.11k-2008, IEEE Std 802.11r-2008, IEEE Std 802.11y-2008, and IEEE Std 802.11w-2009)*, p. 1–565, Oct 2009.

[168] IEEE Standard for Information technology– Telecommunications and information exchange between systemsLocal and metropolitan area networks– Specific requirements– Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications–Amendment 4: Enhancements for Very High Throughput for Operation in Bands below 6 GHz. *IEEE Std 802.11ac-2013 (Amendment to IEEE Std 802.11-2012, as amended by IEEE Std 802.11ae-2012, IEEE Std 802.11aa-2012, and IEEE Std 802.11ad-2012)*, p. 1–425, Dec 2013.

[169] RAVINDRANATH, N. S. et al. Study of performance of transmit beamforming and mu-mimo mechanisms in ieee 802.11ac wlans. In: *2017 International Conference on Inventive Communication and Computational Technologies (ICICCT)*. [S.l.: s.n.], 2017. p. 419–429.

[170] KHOROV, E. et al. A tutorial on ieee 802.11ax high efficiency wlans. *IEEE Communications Surveys Tutorials*, v. 21, n. 1, p. 197–216, Firstquarter 2019.

[171] KHOROV, E. et al. A tutorial on ieee 802.11ax high efficiency wlans. *IEEE Communications Surveys Tutorials*, p. 1–1, 2018. ISSN 1553-877X.

[172] HOEFEL, R. P. F. Ieee 802.11ax: On performance of multi-antenna technologies with ldpc codes. In: *2018 IEEE Seventh International Conference on Communications and Electronics (ICCE)*. [S.l.: s.n.], 2018. p. 159–164.

[173] DENG, D. et al. Ieee 802.11ax: Highly efficient wlans for intelligent information infrastructure. *IEEE Communications Magazine*, v. 55, n. 12, p. 52–59, Dec 2017.

[174] WANG, K.; PSOUNIS, K. Scheduling and resource allocation in 802.11ax. In: *IEEE INFOCOM 2018 - IEEE Conference on Computer Communications*. [S.l.: s.n.], 2018. p. 279–287.

[175] AFAQUI, M. S.; GARCIA-VILLEGAS, E.; LOPEZ-AGUILERA, E. Ieee 802.11ax: Challenges and requirements for future high efficiency wifi. *IEEE Wireless Communications*, v. 24, n. 3, p. 130–137, June 2017.

[176] KHOROV, E.; KIRYANOV, A.; LYAKHOV, A. Ieee 802.11ax: How to build high efficiency wlans. In: . [S.l.: s.n.], 2015.

[177] IEEE Standard for Information technology–Telecommunications and information exchange between systems–Local and metropolitan area networks–Specific requirements-Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 3: Enhancements for Very High Throughput in the 60 GHz Band. *IEEE Std 802.11ad-2012 (Amendment to IEEE Std 802.11-2012, as amended by IEEE Std 802.11ae-2012 and IEEE Std 802.11aa-2012)*, p. 1–628, Dec 2012.

[178] NGUYEN, K. et al. Empirical investigation of ieee 802.11ad network. In: *2017 IEEE International Conference on Communications Workshops (ICC Workshops)*. [S.l.: s.n.], 2017. p. 192–197.

[179] NITSCHE, T. et al. Ieee 802.11ad: directional 60 ghz communication for multi-gigabit-per-second wi-fi [invited paper]. *IEEE Communications Magazine*, v. 52, n. 12, p. 132–141, December 2014.

[180] GHASEMPOUR, Y. et al. Ieee 802.11ay: Next-generation 60 ghz communication for 100 gb/s wi-fi. *IEEE Communications Magazine*, v. 55, n. 12, p. 186–192, Dec 2017.

[181] ZHOU, P. et al. IEEE 802.11ay-Based mmWave WLANs: Design challenges and solutions. *IEEE Communications Surveys and Tutorials*, 2018.

[182] IEEE Standard for Information Technology–Telecommunications and information exchange between systems Local and metropolitan area networks–Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 3: Enhancements for Very High Throughput to Support Chinese Millimeter Wave Frequency Bands (60 GHz and 45 GHz). *IEEE Std 802.11aj-2018 (Amendment to IEEE Std 802.11-2016 as amended by IEEE Std 802.11ai-2016 and IEEE Std 802.11ah-2016)*, p. 1–306, April 2018.

[183] MILLIMETER Wave Propagation: Spectrum Management Implications. *FEDERAL COMMUNICATIONS COMMISSION*, Bulletin, n. 70, July 1997.

[184] HAIMING, W. et al. Ieee 802.11aj (45ghz): A new very high throughput millimeter-wave wlan system. *China Communications*, v. 11, n. 6, p. 51–62, June 2014.

[185] HONG, W. An Overview of China Millimeter-Wave Multiple Gigabit Wireless Local Area Network System. *IEICE Transactions on Communications, VOL.E101–B, NO.2*, 2018.

[186] IEEE Standard for Information technology - Telecommunications and information exchange between systems - Local and metropolitan area networks - Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 5: Television White Spaces (TVWS) Operation. *IEEE Std 802.11af-2013 (Amendment to IEEE Std 802.11-2012, as amended by IEEE Std 802.11ae-2012, IEEE Std 802.11aa-2012, IEEE Std 802.11ad-2012, and IEEE Std 802.11ac-2013)*, p. 1–198, Feb 2014.

[187] FLORES, A. B. et al. Ieee 802.11af: a standard for tv white space spectrum sharing. *IEEE Communications Magazine*, v. 51, n. 10, p. 92–100, October 2013.

[188] MATSUMURA, T. et al. Prototype of ieee 802.11af-based baseband ic enabling compact device for wireless local area network systems in tv white-spaces. *IEEE Transactions on Cognitive Communications and Networking*, v. 3, n. 3, p. 450–463, Sep. 2017.

[189] IEEE Standard for Information technology–Telecommunications and information exchange between systems - Local and metropolitan area networks–Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 2: Sub 1 GHz License Exempt Operation. *IEEE Std 802.11ah-2016 (Amendment to IEEE Std 802.11-2016, as amended by IEEE Std 802.11ai-2016)*, p. 1–594, May 2017.

[190] AKEELA, R.; ELZIQ, Y. Design and verification of ieee 802.11ah for iot and m2m applications. In: *2017 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops)*. [S.l.: s.n.], 2017. p. 491–496.

[191] DOMAZETOVIć, B.; KOčAN, E.; MIHOVSKA, A. Performance evaluation of ieee 802.11ah systems. In: *2016 24th Telecommunications Forum (TELFOR)*. [S.l.: s.n.], 2016. p. 1–4.

[192] AUST, S.; PRASAD, R. V.; NIEMEGEERS, I. G. M. M. Outdoor long-range wlans: A lesson for ieee 802.11ah. *IEEE Communications Surveys Tutorials*, v. 17, n. 3, p. 1761–1775, thirdquarter 2015.

[193] IEEE Standard for Information technology– Local and metropolitan area networks– Specific requirements– Part 11: Wireless LAN Medium Access Control (MAC) and

Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments. *IEEE Std 802.11p-2010 (Amendment to IEEE Std 802.11-2007 as amended by IEEE Std 802.11k-2008, IEEE Std 802.11r-2008, IEEE Std 802.11y-2008, IEEE Std 802.11n-2009, and IEEE Std 802.11w-2009)*, p. 1–51, July 2010.

[194] EZE, E. C.; ZHANG, S.; LIU, E. Vehicular ad hoc networks (vanets): Current state, challenges, potentials and way forward. In: *2014 20th International Conference on Automation and Computing*. [S.l.: s.n.], 2014. p. 176–181.

[195] MIR, Z. H.; FILALI, F. Lte and ieee 802.11p for vehicular networking: a performance evaluation. *EURASIP Journal on Wireless Communications and Networking*, v. 2014, n. 1, p. 89, May 2014.

[196] TABASSAM, A. A. et al. Fast and seamless handover for secure mobile industrial applications with 802.11r. In: *2009 IEEE 34th Conference on Local Computer Networks*. [S.l.: s.n.], 2009. p. 750–757.

[197] AHMED, H.; HASSANEIN, H. A performance study of roaming in wireless local area networks based on ieee 802.11r. In: *2008 24th Biennial Symposium on Communications*. [S.l.: s.n.], 2008. p. 253–257.

[198] IEEE Draft Standard for Information technology-Telecommunications and information exchange between systems-Local and metropolitan area networks-Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Amendment to IEEE P802.11-REVmc(TM)/D4.0: Fast Initial Link Setup. *IEEE P802.11ai/D8.0, June 2016*, p. 1–188, Jan 2016.

[199] ONG, E. H. Performance analysis of fast initial link setup for ieee 802.11ai wlans. In: *2012 IEEE 23rd International Symposium on Personal, Indoor and Mobile Radio Communications - (PIMRC)*. [S.l.: s.n.], 2012. p. 1279–1284.

[200] IEEE Standard for Information technology–Telecommunications and information exchange between systems Local and metropolitan area network–Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 5: Preassociation Discovery. *IEEE Std 802.11aq-2018 (Amendment to IEEE Std 802.11-2016 as amended by IEEE Std 802.11ai-2016, IEEE Std 802.11ah-2016, IEEE Std 802.11aj-2018, and IEEE Std 802.11ak-2018)*, p. 1–69, Aug 2018.

# A IEEE 802.11 Standards Evolution

During the 90's decade, the scientific community started to make important efforts to allow access to data in local area networks satisfying the mobility characteristics of users. This new approach offered clear advantages over wired networks, increasing productivity for users, thanks to the flexibility that wireless accesses provide in various scenarios. At the same time, it possible to reduce costs with rapid and simple network deployments, because the need for cabling of the areas served by these networks was eliminated.

## A.1 WiFi: First Steps

In 1997, the first 802.11 standard was completed by the IEEE 802.11 Working Group, which specifies the operation of the physical layers and data link layer for WLAN [163]. This first standard was developed so that the equipment operates in the two options of Spread Spectrum, with Frequency Hopping (DSFH) and Direct Sequence (DSSS), both reaching rates of 1 Mbps and 2 Mbps. The standard was developed to operate in the Industrial, Scientific and Medical band (ISM band) at 2.4 GHz with 20 MHz bandwidth channels, frequency band free of licenses, which has been a fundamental characteristic of its successors.

Only two years later, the 802.11b [164] and 802.11a [165] standards were made official, both using 20 MHz channels.The first, operating in the 2.4 GHz band, allows to reach theoretical transmission rates of 11 Mbps using a Direct Sequence Spread Spectrum (DSSS) modulation, being the direct evolution of the first standard. The second, which uses the same protocol core as its predecessor, operates in the 5 GHz band using Orthogonal Frequency Division Multiplexing (OFDM) modulation for the first time in this technology, allowed to reach rates up to 54 Mbps. The use of the 5 GHz band offers great advantages to reach more data rate transmissions and nowadays over the current saturation of the existing 2.4 GHz spectrum that can cause frequent connection losses and services degradation. On the other hand, the use of OFDM offers considerable improvements for transmissions in multipath wireless channels, combating the effects of fading through the simultaneous transmissions of data into narrowband channels. However, the high cost of equipment to work in the 5 GHz band at that time meant that this standard was not widely adopted, betting on a new 2.4 GHz solution that offered the same advantages and transmission rates as 802.11a. Thus, they formalized in 2003 the 802.11g [166] standard that introduces OFDM in 2.4 GHz maintaining rates of 54 Mbps.

Undoubtedly one of the greatest achievements of WiFi in the search for higher transmission rates to accompany the development of new data services occurred in 2009 when the 802.11n standard was published [167]. The main feature introduced was the increase in throughput, where to achieve it, and unlike its predecessors that only focused on the physical layer (PHY) modifications, 802.11n implemented new techniques also at the Medium Access Control layer (MAC). This version integrated the possibility of operation in both frequency bands (2.4 GHz and 5 GHz), and the new techniques used in this solution allow theoretical transmission rates of 600 Mbps, considered as the first High Throughput WiFi standard. At the physical layer level, the first technique implemented was MIMO in transmitters and receivers. These techniques allow four times higher throughput increments thanks to the use of four parallel radio chains for transmissions and receptions, exploiting the benefits of Spatial Multiplexing (SM). To get beyond the limits that MIMO offers another interesting feature is introduced in the physical layer, the Channel Bonding, that basically consists of creating wider communication channels through the union of smaller channels. With this, 802.11n doubled the throughput by implementing channels of 40 MHz bandwidth, from the 20 MHz channels already used by this family of protocols. Also at the physical level, the reduction of the transmission time of the OFDM symbols reducing the size of the guard interval (GI) in each symbol for more throughput and in addition to the use of more efficient low-density parity check (LDPC) codes.

To improve the operating efficiency of the protocol, mainly in the inefficient use of the air time, some modifications were introduced in the MAC layer. The size of the data frames in 802.11n was increased by means of a frame aggregation scheme. This technique reduces the overhead in the transmission because the protocol is able to send several MAC frames in a same physical layer package. The overhead is also reduced with the incorporation of ACK blocks, which unlike the previous versions that sent an acknowledgment for each transmitted frame, in 802.11n the acknowledging frames are made in blocks. In addition to the modifications to improve efficiency, the protocol is able to coexist in solutions with legacy equipment.

# B New Generation of IEEE 802.11 Standards

Nowadays, as a fundamental part of the evolution and standardization of WiFi, the works are being focused almost completely on technology that can be able to satisfy communication requirements such as reliability, latency and throughput, very similar to what the 5G network paradigm aims to achieve. This is mainly due to the fact that the WiFi community believes and bet strongly that the evolution of 5G should be hand in hand with WiFi as a key element in the integration of wireless access technologies and unlicensed spectrum bands. So then it has begun to talk about the new generation of WiFi standards, most of them that comply in one way or another some requirements of 5G networks such as high throughput, high reliability, low latency, and large ranges of coverage for address IoT solutions deployed in wide areas.

## B.1 High throughput WiFi

In January 2014 the 802.11ac [168] protocol was approved as a direct evolution of its 802.11n predecessor, and it shares many of the techniques for increasing throughput. This new version called Very High Throughput VHT WiFi can reach up to the theoretical 6.93 Gbps, also through the application of new techniques in PHY layer and MAC layer. Again the use of MIMO in PHY layer allows the increase in transmission rates, this time doubling the throughput of 802.11n using up to 8 radio chains in the transmitters and receivers. In this version, the great contribution to increase throughput is offered by channel bonding, which on this occasion increases throughput by up to 4 times with the use of channels with a bandwidth of 160 MHz, resulting from the merger of two 80 MHz channel, which is the same as the use of four 40 MHz channels that implements 802.11n. In addition, a new modulation index was introduced, a 256-QAM modulation that is more aggressive than the previous ones, obtaining a eight-bit mapping of on each sub-carrier for increasing the capacity of the link.

In the MAC layer, the modifications are focused on supporting the new PHY layer. Regarding the frames aggregation, 802.11ac implements the scheme so that all transmitted frames are aggregated, even if only one frame are to be transmitted. With this scheme, the MAC layer is responsible for all the framing in the transmissions. Two other features differentiate 802.11ac from its predecessor, the first is that the protocol only operates in the 5 GHz band, and the second is that MIMO techniques are use to introduce beamforming and Mutiple User MIMO (MU-MIMO) techniques on 802.11ac [169]. With beamforming the AP manages the signal strength in a specific space region to increase the data rate in the receivers. On the other hand 802.11ac can use eight spatial streams, four more compared to 802.11n, that streams can be used to transmit to several clients simultaneously. The MU-MIMO feature can influence how WiFi networks are projected because it allows spatial reuse for interference reduction.

The official publication of the 802.11ax standard [170] is planned for 2019, which will define a very high efficiency standard for WiFi networks that will undoubtedly revolutionize WLAN communications. At the end of 2018, the WiFi Alliance announced that, starting from this new standard, a new nomenclature for the IEEE 802.11 standards would be used so that it becomes easier to identify by its users. Thus the new IEEE 8002.11ax standard will be identified as WiFi 6, and at the same time they were assigned the same nomenclature to their predecessors, 802.11ac as WiFi 5 and 802.11n as WiFi 4. The WiFi-friendly community strongly believes that WiFi 6 will be the technology that will dominate wireless communications in unlicensed spectrum bands, which makes evident the need for integration between this new standard and 5G network technologies. The standard aims to achieve high spectral efficiency and throughput per area in high density device scenarios, reducing the overlap areas to avoid collisions in the transmissions of the stations. WiFi 6 not only directs its efforts to the search of high transmission rates, but is also focused on implementing a better spatial reuse to combat and reduce interference through an efficient user access scheme [171].

In the 802.11ax standard the operation will be again in the 2.4 and 5 GHz frequency bands as well as 802.11n. In the physical layer several modifications are introduced, the use of LDPC as an error correction scheme for channel boding in large bandwidths transmissions and maintains the convolutional binary coding schemes in narrowband transmissions [172]. Maintaining the pattern of adaptive modulations adopted by 802.11, new Modulation and Coding Schemes (MCS) are used introducing 1024-QAM modulation to improve the spectral efficiency of the transmissions. It also implements a novel scheme of dual sub-carrier modulation [173] that takes advantage of the frequency diversity of OFDM systems, transmitting the same information on two separate sub-carriers to increase the transmissions reliability in low Signal-to-Noise Ratio (SNR) regions with interference. Implementing an OFDM with an FFT size bigger than 802.11ac, it increases the throughput of indoor communications and increases the robustness of outdoor communications. In physical layer, a scheduling function for multiuser access is also implemented, which contributes to increase the spectral efficiency, through OFDM access in the frequency domain and MU-MIMO in the spatial domain [174].

Several techniques are implemented in the MAC layer to achieve improvements in spatial reuse. In scenarios of high user density, it can happen that users always determine occupation in the channel for transmissions. To avoid this effect, a dynamic sensitivity control algorithm [175] is introduced to modify the module in charge of detecting the channel state in the 802.11 solutions. This new algorithm performs a dynamic adjustment of the carrier detection threshold, decreasing its value so that stations within the same Basic Service Set (BSS) can transmit without considering the busy medium. Another new scheme to increase throughput is the so-called BSS color, which allows the stations to know which BSS is generating the transmission without the need to completely decode the frames, and thus the station that receives frames from a neighboring BSS can assume a inactive channel to make a transmission on your BSS.

In the MAC layer is also defined a scheme to operate with two Network Allocation Vectors (NAV) [176] in each station. This means that a virtual carrier detector shows an estimate of how long the channel will be virtually occupied. In addition to the regular NAV, the 802.11ax stations will implement an independent NAV for the BSS, which will only be increased or restored for frames belonging to the BSS in question, in order to increase the spatial reuse. With these features, the 802.11ax standard is an excellent proposal for WLAN communications with high rates of transmission in homes and offices, but also the spatial reuse characteristics and the energy efficiency techniques such as Target Wake Time [175] make it a strong candidate to face the challenges in IoT sensor networks.

## B.2 WiFi in mmWave Band

Although the WiFi protocols operating in the mmWave band could be regarded as high throughput protocols, they are analyzed here independently to highlight their operational characteristics in the frequency bands above 6 GHz. The most important, without any doubt to date is the IEEE 802.11ad standard [177] also known as ”WiGig” because it was the result of a collaboration with Wireless Gigabit Alliance, and was published in December 2012. This is the first WiFi standard that operates in the mmWave bands, with which it enjoys the advantages of operating on these frequencies, as well as facing its limitations. The standard, which is designed to work at 60 GHz, offers transmission rates in the order of Gbps, taking advantage of the wider bandwidths available for transmissions on mmWave bands.

The communication in these frequencies is severely affected by path loss and signal attenuation phenomena due to the very small wavelengths of the signals (approximately 5mm), with which communications are limited to short distances between one and ten meters. This high degree of attenuation has the advantage that interference from adjacent transmissions is quite unlikely allowing spatial reuse. The small wavelengths on the other hand allow the construction of devices with smaller dimensions to implement MIMO techniques with beamforming. These techniques will allow high-directionality beams to achieve better channel capabilities and be able to support both LoS communications and No-Line-of-Sight (NLOS) communications.

The 802.11ad standard works by default on channel 2 of the 60 GHz band, between 60.48 GHz and 62.64 GHz, which means a bandwidth for transmissions over 2 GHz allowing to reach transmission rates of 8 Gbps in transmissions using Single Input Single Output systems. In physical layer, several operation modes are available through different MCS [178], meeting the requirements of high throughput and robustness. The first one, the PHY Control mode (CPHY) is used for exchange signaling and control messages, allowing the establishment and monitoring of connections between devices. The second operation mode is the Single Carrier Mode (SC PHY) that can reach theoretical 4,620 Gbps, with a subsequent extension to reach more than 8 Gbps. This mode has the Low Power SC PHY variant that is very similar to the SC PHY, but implements energy optimization for small battery devices.

Due to the aforementioned communications characteristics in these frequency bands, the standard implements two interesting techniques, Directional Multi-Gigabit (DMG) channel access and DMG Beamforming Training (BFT) [179]. The DMG channel access is implemented because the stations for this standard can not simultaneously listen to the access point as a consequence of the directionality in the transmissions. For this reason the area around an access point is divided into sectors, and the stations in a sector compete for the channel only during the time assigned for that sector. For its part, the DMG BFT aims to mitigate the strong path-loss effects in the 60 GHz band. Although BFT is a key piece of this standard, if the process takes a long time to establish the direction of the communication, it can generate a delay that significantly affects the quality of experience (QoE) of the users.

In Febrary 2019 the latest draft of the 802.11ay was published, a direct evolution of the 802.11ad standard. This standard is expected to be the future of WiFi communications in the mmWave band to reach 20 Gbps through multiple independent data flows and a greater channel bandwidth. To do this, like the high throughput sub 6 GHz standards, the use of channel bonding where a single waveform covers at least two contiguous 2.16 GHz channels and channel aggregation with a separate waveform for each added channel are two key techniques [180]. The other important feature is the use of MU-MIMO in the downlink that allows the distribution of capacity to multiple stations simultaneously. In 802.11ad the DMG stations only provides beamforming gain but no multiplexing gain because the transmissions are assigned in a space of time for each station. To address this problem and increase the performance of communications, 802.11ay implements MIMO transmission schemes with a maximum number of eight spatial flows per station and allows downlink links from the access point to eight stations.

As for the beamforming techniques employed by 802.11ay, thoses are very similar to the ones used by 802.11ad, incorporating more efficient methods to optimize beamforming performance [181]. In the operation in these bands, the difficulties to maintain the directionality of the beams increases with the path-loss phenomenon, blocking and the stations mobility. To deal with this issue, both standards, 802.11ad and 802.11ay, implement a Fast Session Transfer method (FST) that allows communications established at 60 GHz to go to the 2.4 GHz / 5 GHz bands in order to guarantee the continuity of the communication with transmission rates in the order of Gbps. A second method that fights the set of problems is the so-called beam tracking which tries to find another pair of available beams to continue the transmission in case of blockage. The 802.11ad and 802.11ay, are expected to provide Ultra High Transmission rates to meet the communication requirements demanded by applications in the new smart cities and smart industries scenarios.

Also part of the mmWave communications are the China millimeter-wave multiple gigabit (CMMG) wireless systems. This system, standardized since April 2018 as IEEE 802.11aj [182], is available in some regions of the world operating in the 45 GHz frequency band, reaching up to 15 Gbps. The selection of the 45 GHz band is more attractive than the 60 GHz band and it is expected to be more efficient for high transmission rates communications due to the signal propagation characteristics in the mmWave band. For the same open space propagation conditions, the 60 GHz band experiences an attenuation peak due to the absorption of the radio signal by oxygen, which represents almost five times the attenuation of dB/Km compared with the attenuation suffered in the 45 GHz band [183].

The CMMG standard supports three transmission modes, the Control mode in charge of guaranteeing coverage, and the Single Carrier and OFDM modes that, like in 802.11ad, are used for different requirements in different environments [184]. Both the SC mode and the OFDM mode are capable of supporting MIMO transmission schemes by implementing diversity and spatial multiplexing. In 802.11aj is also introduced a new packet coding scheme based on LDPC which adds a new cyclic redundancy check sub-block for each block of bits information to be encoded. Despite adding new operations during the coding process, an improvement in packet error rate (PER) performance is obtained through a gain of 0.6 dB compared to the traditional LDPC coding scheme [185].

## B.3 WiFi for IoT

The new revolution of WiFi standards has also sought to satisfy the requirements for IoT solutions, a paradigm that is expected to be key in the socio-economic development of modern society. An essential feature of IoT networks is the large deployment of sensor device in wide areas, so wireless communications technologies that support these networks must provide coverage for long-range extensions. The two 802.11 standards designed to meet these objectives operate in the sub 1 GHz spectrum area, which allows communications with acceptable transfer rates for distances greater than one kilometer and low power consumption. It is worth noting that these standards are also interesting for wireless backhauling solutions in places of difficult access for mobile operators.

In February 2014, the IEEE 802.11af standard was published, which defines the PHY layer and MAC layer functionalities for the use of WiFi wireless systems in the White

Space Television (TVWS) [186]. The TVWS are spectrum resources not used at specific times and spaces, allowing them to be shared between the so-called white space devices (WSD), where 802.11af is located, and licensed users of the TV band. It is in these band spaces where 802.11af operates, and according to the specific spectrum regulations for each country, the band occupied by the standard is adjusted in the Very High Frequency (VHF) and Ultra High Frequency (UHF) bands. For this reason, one of the main elements that integrates the 802.11af architectures is the White Space Database (WSDB), which stores the available frequencies and transmission requirements for a specific geographic location. The WSD, which in 802.11af represent access points and stations, are secondary users in TVWS communications, so they need to consult this database before starting a transmission and thus avoid interfering with broadcasts of television stations, primary users in this band [187].

In the PHY layer the 802.11af standard implements the high throughput TV specification that can operate in two modes. These modes are differentiated by the channel bandwidth that can be used by the standard, the first for bandwidths of 6 and 7 MHz which can reach rates of 26 Mbps, and a second mode with 8 MHz bandwidth for achieve rates of 35 Mbps, both using 256-QAM modulation [188]. The radio interface employs OFDM and is capable of implementing channel aggregation of up to 4 channels to increase throughput, in addition supports four MU-MIMO transmissions. In the physical layer, one part is responsible for the signal processing functions during the generation of data frames and control frames and another part is responsible for the exchange of device information and channel information between the access points and the WSDB.

The other important standard that bases its operation on the sub 1 GHz frequency bands is the IEEE 802.11ah standard, published in May 2017 [189]. This standard, also known as WiFi HaLow, is much more focused on the IoT scenarios and machine to machine (M2M) communications, to support long-range wireless networks with a high density of wireless stations. To meet this objective, 802.11ah operates in the 900 MHz band, thus building long-range and low-power wireless sensor networks (WSN) and other massive multi-node wireless networks [190]. The standard can implement transmission modes in short bursts of data packets with low power, offering short operating times for remote sensors with band and battery restrictions.

The 802.11ah physical layer is also based on OFDM technology with operation on 1 MHz, 2 MHz, 4 MHz, 8 MHz and 16 MHz channels, and data equally distributed over sub-carriers as in traditional OFDM schemes [191]. For its part, the MAC layer offers a high degree of scalability in the number of nodes it can handle, being able to attend up to 6000 nodes in a 1 km area with a high energy efficiency. Through a restricted access window function, the conflict-free access periods are implemented for the access of group-based sensors [192]. In this layer are implemented the mechanisms that allow coexistence with RFID, ZigBee and IEEE 802.15.4 devices that also operate at 900 MHz.

## B.4 Other useful WiFi Standards

Vehicle communications have also been addressed by the IEEE 802.11 family of protocols. In 2010, the 802.11p standard [193] was published and became one of the main standards in wireless access technology in vehicular environments (WAVE) to address communications in vehicular ad-hoc networks (VANETs) [194]. In PHY layer, the protocol is very similar to 802.11a with the characteristic that the communication channel bandwidth was reduced to 10 MHz, while in MAC layer Enhanced Distributed Channel Access is implemented to increase the possibilities of sending the high priority traffic [195]. The 802.11p is a standard for short-range communications capable of serving communications for mobile elements that travel at high speeds like in vehicle to vehicle (V2V) communications. Also the standard introduces an interesting modification to eliminate the need for association and authentication for the exchange of data in the V2V communications and in the communications between vehicles and roadside stations (V2I).

To achieve more reliable communications and maintain small interruption times during the handover, mainly in industrial wireless applications, the standard 802.11r was published in 2008 [196]. This standard implements rapid transitions of the stations between two access points, minimizing the amount of steps necessary for station re-association with a new access point. For this purpose, when a new station joins the network, it exchanges with the AP a Pairwise Master Keys set, which in turn is shared among all the APs in the network to reduce the re-association latency. These times can also be reduced through a resource reservation mechanism in the AP that is done before the handover during the re-association process [197].

Continuing the logic of optimization and performance improvement for communication establishment between stations and access points, more recently the standards 802.11ai and 802.11aq were published. In June of 2017 was published 802.11ai, standard focused on making a quick configuration of the initial link for wireless stations [198]. In networks with high density of stations and AP, the new stations may experience delays in the establishment of the communication higher than those allowed by the station, which results in a failure in the establishment of the data link. This is where the 802.11ai standard tries to reduce the time that the stations must wait to complete the establishment of the communication, by reducing the time of discovery of the network and the APs [199]. For this, the standard uses more efficient scanning methods that use context information in the discovery process, and optimizing the times of authentication, association, and assignation of IP addresses by means of information exchange concurrently. On the other hand, the 802.11aq standard was published in August 2018 to allow WiFi users make the best AP selection for better link conditions through a service discovery mechanism made before the association. [200]. Through the exchange of information between the wireless access point and the user's device, users can quickly and effortlessly discover what types of services are compatible before making the decision to connect, which simplifies the process of selecting the network and improves the user experience.