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Regulations and Technical Advancements for Radio Spectrum Management: Technology Coexistence in Next-Generation Wireless Networks

Supervisor
Dr. Francesca Meneghello

Candidate
Francesca Tiengo

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Ai miei genitori, Simonetta e Renzo,
ai cui sacrifici devo tutto.
A Gina.

A Michele,
per farmi vedere il mondo con occhi diversi.

Abstract

The radio spectrum, a fundamental resource for wireless communications, is experiencing increasing demand due to the proliferation of wireless technologies and services, leading to the phenomenon of “spectrum scarcity” or “spectrum crunch”. Regulators face the challenge of efficiently managing this resource to accommodate different spectrum uses while ensuring fair access. This thesis examines the regulatory and technical aspects of spectrum management at the international, regional and national levels, with a focus on the US and Europe. In recent decades, spectrum-sharing techniques have become essential to allow multiple co-located services and applications to coexist in the same frequency bands. In particular, the unlicensed 2.4 and 5 GHz bands, traditionally used by popular consumer technologies such as Wi-Fi, have seen a rapid proliferation of devices and data-intensive applications. The congestion of these bands has prompted regulators to extend unlicensed operations to the 6 GHz bands. This expansion is seen as fundamental to providing high-throughput, and low-latency connectivity to support business and consumer activities. The decision raises issues relating to the protection of the rights of current authorised users of the band. Spectrum managers in the US and Europe conducted feasibility studies to determine the technical requirements to be imposed on unlicensed operations in the 6 GHz band to preserve the rights of licensed incumbents. The actions taken by regulators are reviewed and compared, also considering the results of the recent WRC-23. At the same time, this decision has encouraged the development of new standards and coexistence strategies, especially since this band was not previously occupied by any unlicensed technology. As a result, several unlicensed technologies are expected to emerge in the 6 GHz band. In particular, this thesis focuses on the technical tools to allow the coexistence of Wi-Fi and cellular technologies in the unlicensed spectrum, which present significant differences at the MAC layer and in the system architecture: while Wi-Fi uses a contention-based access protocol relying on distributed channel sensing, the 3GPP standards are based on a non-sensing scheme where the allocation of spectrum resources is managed centrally by base stations. An unlicensed version of 5G, 5G NR-U, has been developed to operate in the 6 GHz bands. Meanwhile, Wi-Fi 6E is the first 802-11-based standard to operate in this part of the spectrum. To achieve fair coexistence and efficient spectrum use, both technologies have adopted a contention-based protocol (LBT) over an OFDMA access scheme. Furthermore, this work highlights the importance of choosing homogeneous channel access parameters and mechanisms. In addition, novel approaches to technology coexistence, such as MIMO-Unlicensed and CoBeam, exploit MIMO and transmit beamforming techniques to achieve coexistence based on spatial diversity.

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Listing of acronyms

Symbols

3G Third Generation

3GPP Third Generation Partnership Project

4G Fourth Generation

5G Fifth Generation

5G NR Fifth Generation New Radio

6G Sixth Generation

A

AFC Automatic Frequency Coordination

AGCOM Italian Communications Regulatory Authority

AI Artificial Intelligence

AP Access Point

AR Augmented Reality

B

BAR Block ACK Request

BEREC Body of European Regulators for Electronic Communications

BRAN Broadband Radio Access Network

BS Base Station

BSR Buffer Status Report

BSRP Buffer Status Report Poll

C

CA Carrier Aggregation

CEPT European Conference of Postal and Telecommunications Administrations

CFR Code of Federal Regulations

CN Core Network

COT Channel Occupancy Time

CSI Channel State Information

CSMA/CA Carrier Sense Multiple Access with Collision Avoidance

CTS Clear To Send

D

DC Dual Connectivity

DL Downlink

DL-PPDU Downlink Protocol Data Unit

DOF Degree Of Freedom

E

E-UTRAN Evolved Universal Terrestrial Radio Access Network

EC European Commission

ECA European Common Allocation

ECC Electronic Communications Committee

ECO European Communications Office

ED Energy Detection

EDCA Enhanced Distributed Channel Access

EEA European Economic Area

EFIS European Frequency Information Table

EIRP Effective Isotropic Radiated Power

eLBT Enhanced LBT

EMC ElectroMagnetic Compatibility

EN European Norm

eNodeB Evolved Node B

EPC Evolved Packet Core

ERC European Radiocommunications Committee

ETSI European Telecommunications Standards Institute

EU European Union

F

FAA Federal Aviation Administration

FAT Frequency Allocation Table

FBI Federal Bureau of Investigation

FCC Federal Communications Commission

FS Fixed Service

FSS Fixed Satellite Service

G

gNB Next-Generation Node B

H

HetNet Heterogeneous Networks

I

I/N Interference-to-Noise Power

ICT Information and Communication Technologies

IDC International Data Corporation

IEC International Electrotechnical Commission

IEEE Institute of Electrical and Electronics Engineers

IEEE-SA Institute of Electrical and Electronics Engineers Standards Association

IFFT Inverse Fast Fourier Transform

IFS Interframe Spacing

IMT International Mobile Telecommunications

IP Internet Protocol

ISDN Integrated Services Digital Network

ISM Industrial, Scientific and Medical

ISO International Organization for Standardization

ITU International Telecommunication Union

ITU-R International Telecommunication Union Radiocommunication Sector

ITU-T International Telecommunication Union Telecommunication Standardization Sector

K

KPI Key Performance Indicator

L

LAA Licensed Assisted Access

LBE Load Base Equipment

LBT Listen Before Talk

LPI Low-Power Indoor

LTE Long Term Evolution

LTE-U LTE Unlicensed

LWA LTE-WLAN Aggregation

LWIP LTE-WLAN Integration over an IPSec Tunnel

M

MAC Medium Access Control

MIFR Master International Frequency Register

MIMIT Ministry of Enterprises and Made in Italy

MIMO Multiple Input Multiple Output

MISE Ministry of Economic Development

ML Machine Learning

mMIMO Massive MIMO

mMIMO-U MIMO-Unlicensed

MRT Maximum Ratio Transmission

MU Multi User

N

NN Antenna Radiation Null

NR-U New Radio Unlicensed

NTIA National Telecommunications and Information Administration

O

OFDM Orthogonal Frequency-Division Multiplexing

OFDMA Orthogonal Frequency-Division Multiple Access

P

PD Preamble Detection

PDCCH Physical Downlink Control Channel

PDCP Packet Data Convergence Protocol

PDSCH Physical Downlink Shared Channel

PSD Power Spectral Density

PSTN Public Switched Telephone Network

Q

QoS Quality of Service

R

RAN Radio Access Network

RAT Radio Access Technology

RF Radio Frequency

RFID Radio Frequency Identification

RLAN Radio Local Area Network

RR Radio Regulations

RTS Request To Send

RU Resource Unit

S

SC Small Cell

SC-FDMA Single-Carrier Frequency Division Multiple Access

SDO Standards Developing Organization

SDoC Supplier's Declaration of Conformity

SHF Super High Frequency

SIFR Short Interframe Space

SINR Signal-To-Interference-plus-Noise Ratio

SISO Single Input Single Output

SM Spatial Multiplexing

SRD Short-Range Device

STA WLAN Station

SU Single User

SVD Singular Value Decomposition

T

TCB Telecommunications Certification Body

TDD Time Division Duplex

TF Trigger Frame

TXOP Transmit Opportunity

U

U-NII Unlicensed National Information Infrastructure

UE User Equipment

UHF Ultra High Definition

UL Uplink

UMTS Universal Mobile Telecommunications System

UT User Terminal

UWB Ultra-wideband

V

VLP Very-Low-Power

VR Virtual Reality

W

WAS Wireless Access System

WLAN Wireless Local Area Network

WRC World Radiocommunication Conference

Z

ZF Zero-Forcing

1

Introduction

The **electromagnetic spectrum** is the entire distribution of electromagnetic radiation by frequency and wavelength. The **radio spectrum** is the part of the electromagnetic spectrum that supports radio transmissions and ranges from 3 kHz to approximately 300 GHz. The radio spectrum is a fundamental resource for all wireless communications, as electromagnetic radiation is an unguided transmission medium that connects a transmitter and a receiver without the need for a fixed and physical connection through cables [1]. The radio spectrum can be divided into different bands according to the specific operating frequency and, in turn, the wavelength of the transmitted waves. Each band has different characteristics in terms of the emission, transmission, and absorption of radio waves, which determines the use cases for which they are more suited. Super High Frequency (SHF), also called the centimetre band, is the International Telecommunication Union (ITU) designation for frequencies between 3 and 30 GHz, with wavelengths between 1 and 10 centimetres. The 6 GHz band, which is the focus of the regulatory and technical instruments described in this work, falls within this range. Due to their characteristics, the SHF bands occupy a “sweet spot” in the radio spectrum: the high frequencies make it possible to direct narrow beams in order to reduce interference with other nearby transmitters using the same frequency. On the other hand, the wavelength is still long enough not to suffer the same propagation losses as millimetre waves and above. This is why many heterogeneous radio services use the 6 GHz band. The radio spectrum is a resource that has to satisfy multiple and growing needs of the market, public administration and scientific research. The spectrum is considered a scarce resource as a large number of services are required to use it, especially certain parts. In addition, regulators recognise that the spectrum is a public good, fundamental to social and economic development. As such, regulatory authorities seek to manage it in the most efficient and equitable way. To deal with spectrum scarcity, regulators often implement spectrum-sharing measures, which consist of allocating more services and users in the same frequency bands and imposing technical and regulatory constraints to mitigate interference between spectrum users and allow a fair coexistence between them. Spectrum-sharing techniques are particularly important in the unlicensed spectrum, where technologies such as Wi-Fi can be deployed without an individual licence, provided that they do not cause harmful interference to other licensed users and cannot claim protection from interference from other devices. The low barrier to unlicensed spectrum access has led to widespread adoption of unlicensed devices.

In particular, global data traffic has grown exponentially over the last two decades. According to projections in the Cisco Annual Internet Report, the total number of internet users has grown from 3.9 billion in 2018 to 5.3 billion in 2023, representing 66% of the global population in 2023. Meanwhile, the number of devices connected to Internet Protocol (IP) networks is more than three times the 2023 global population, with consumers accounting for 74% of all devices, including both fixed and mobile ones [2]. Globally, the total number of mobile subscribers (those who subscribe to a cellular service) has increased from 5.1 billion in 2018 to 5.7 billion in 2023. Meanwhile, according to a report published by International Data Corporation (IDC) Research, a total of 19.5 billion Wi-Fi devices were in use in 2023, including access points, smartphones, laptops, security cameras and smart plugs [3].

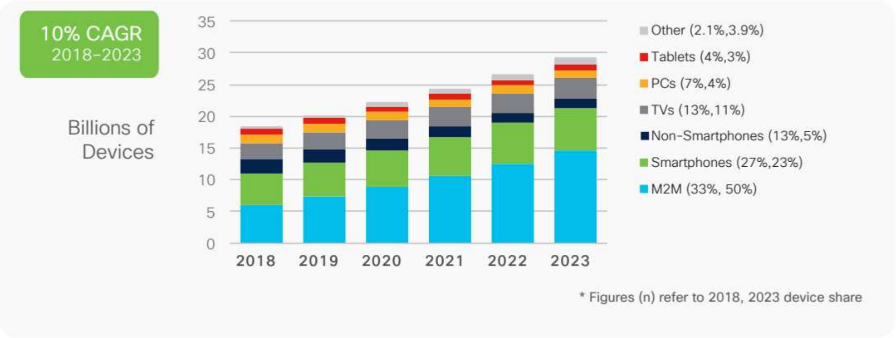


Figure 1.1: Global device and connection growth in the years 2018-2023 [2].

In addition, the growing popularity of data-intensive and mobile applications such as Ultra High Definition (UHF) video streaming, live streaming and video conferencing, as well as real-time applications such as Augmented Reality (AR)/Virtual Reality (VR) and online gaming, has increased the need for greater bandwidth to achieve gigabit speeds [4]. As a growing portion of the world's data traffic is delivered via unlicensed technologies, the traditional 2.4 and 5 GHz bands used by unlicensed standards such as Wi-Fi and Long Term Evolution (LTE)-Licensed Assisted Access (LAA) are not sufficient to meet the demand for unlicensed spectrum and higher Quality of Service (QoS)-requirements. This has led spectrum regulators to allow unlicensed operations in the 6 GHz bands. This decision was taken in view of the social and economic benefits of providing low-cost broadband connectivity to the population. It is also seen as a way of complementing the services provided by mobile operators through the licensed spectrum, thus offloading mobile data traffic to Wi-Fi and keeping cellular networks from being overwhelmed [5]. The 6 GHz band was already used by other licensed services and is expected to be used by various unlicensed technologies. Regulators had to carry out feasibility studies to determine the coexistence scenarios, the frequency ranges and the technical constraints to ensure the protection of the different licensed incumbents. At the same time, industry stakeholders and researchers have developed techniques to enable different co-located unlicensed technologies to share the same frequency bands.

In Chapter 2, this thesis describes the spectrum management process and the main regulatory authorities at international, regional and national levels, focusing on the US and European contexts. The aim is to define the powers and responsibilities of each authority, to understand the relationships that exist between the different levels of regulation, and to show how regulation can affect the development of technologies. In particular, the way unlicensed spectrum and devices are regulated is explained in the chapter. The chapter then analyses the measures taken by international and regional regulators to manage unlicensed use of the 6 GHz bands, highlighting the differences and similarities between the US and Europe.

Chapter 3 presents some of the most prominent technologies and strategies used to achieve coexistence between cellular technology and Wi-Fi in the unlicensed spectrum. As will be highlighted, this presents some challenges related to differences at the Medium Access Control (MAC) protocol layer and in the system architecture. To make this work self-contained, the system architecture of the Fourth Generation (4G) and the Fifth Generation (5G) of the Third Generation Partnership Project (3GPP) standards is presented, along with the deployment options for New Radio Unlicensed (NR-U). Other important building blocks for the technologies discussed are Multiple Input Multiple Output (MIMO), spatial diversity, spatial multiplexing and transmit beamforming techniques. In addition, comprehensive explanations of Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), Listen Before Talk (LBT) and Orthogonal Frequency-Division Multiple Access (OFDMA) are given as the main channel access schemes covered in this thesis. The 6 GHz unlicensed spectrum is often referred to as the *greenfield* spectrum, as these are the bands where neither Wi-Fi nor any 3GPP-based unlicensed Radio Access Technologys (RATs) have previously operated. This has provided many opportunities to develop new coexistence strategies that adapt to both technologies without favouring one or the other. Section 3.2 provides a background with the previous standards that have been developed to use cellular technologies in the 5 GHz unlicensed spectrum, such as LTE-LAA and LTE Unlicensed (LTE-U). Section 3.3.3 presents novel approaches using MIMO and transmit beamforming techniques to enable spatial frequency reuse. Finally, Section 3.4 introduces NR-U and Wi-Fi 6E as the first unlicensed standards to be deployed in the 6 GHz bands, together with some of the issues considered in defining the channel access techniques and parameters to allow fair coexistence between the two.

2

Regulations for Technology Coexistence

2.1 The Spectrum Management Process

The radio spectrum is a finite natural resource and it is paramount to use it efficiently without wasting precious resources for a bad management strategy. **Spectrum management** is the strategic use of the radio frequency spectrum. It requires the systematic organisation and allocation of finite frequency bands among different radio-communication services, such as radio, television, satellite and mobile wireless services. This involves balancing efficient use of the spectrum, fair access for different stakeholders, interference reduction, social needs, technological innovation and regulatory compliance. Due to its complexity, effective spectrum management relies on multidisciplinary approaches that integrate policy frameworks, legal provisions, standardisation and economic considerations.

The spectrum management process involves the steps of frequency allocation, allotments, and assignments, followed by monitoring and review [6]. Frequency allocation is the process of dividing the spectrum into bands and designating them for one or more service categories, to harmonise the use of the spectrum in different countries. This approach has economic and social benefits as it allows equipment manufacturers to reach the wider market without the cost and time of adapting their products to different regulations. Once the spectrum has been allocated, the bands can be further subdivided according to a plan. The plan divides the bands into channels, the bandwidth of which depends on the technology and the capacity required by the system that will use it. The plan then defines which technologies are allowed in each band and how they are implemented [7]. The allotment of a radio frequency or channel is part of a plan that specifies which channels, or part of them, are available in a given geographical area and under what conditions [8]. It is useful to minimise cross-border interference and to facilitate band management between neighbouring countries [7] The final subdivision takes place through the assignment process, whereby the competent government administration assigns precise bands or channels to operators in specific geographical locations on the national territory through an assignment, authorisation or licence. Licences usually include technical and usage restrictions to ensure that harmful interference to other users is minimised and that legal obligations and international agreements are met [6]. All transmitters using spectrum require a licence to operate unless specifically exempted. Exemptions are generally granted for many low-power applications such as Wireless Local Area Network (WLAN) devices. The details of this topic are discussed in Section 2.2. National regulators may use different mechanisms to assign spectrum. All these procedures should be carried out with the aim of licensing users who are able to maximise economic and social benefits. In the past, the most common method was administrative assignment directly by the regulatory authorities. Most of these assignments were made on a first-come, first-served basis, with licences being assigned to applicants following the order of application. This is one of the simplest mechanisms and was appropriate when demand for spectrum did not exceed supply. With the increasing demand for spectrum and the need to use it efficiently, many regulators have adopted market-based mechanisms based on a competitive process to release frequency bands, such as beauty contests and auctions. In beauty contests, licences are awarded to applicants who, in the opinion of the regulator, submit the most convincing application based on a set of predetermined quantitative and/or qualitative criteria. Auctions consist of a bidding process in which the licence is granted to the bidder offering the highest bid. The underlying principle is that the user willing to invest a significant amount of money is more likely to have a sound business and to use the spectrum efficiently to recover the investment made. Spectrum monitoring activities are then carried out to assess spectrum usage, verify compliance with national regulations and specific licence conditions, and provide information on future spectrum use trends and needs. Finally, the review process uses the knowledge gained by spectrum managers to identify inefficient or unauthorised uses and take the necessary action, such as reallocating spectrum to other users or new services [6].

The spectrum management process can take place at three main geographical and regulatory levels: international, regional and national. The next sections provide an overview of the main actors, particularly those relevant to this work.

2.1.1 International RF Spectrum Management: ITU

Founded in Paris in 1865, ITU is a specialised agency of the United Nations for Information and Communication Technologiess (ICTs). At the global level, ITU develops the international regulatory framework for telecommunications through the Radio Regulations (RR). The main objective of ITU is to facilitate the coordination of radio spectrum usage to minimise interference and promote international connectivity [9]. The 1992 ITU Constitution and Convention were adopted by 193 countries, including all European Union (EU) Member States and the USA. These documents form the basis of its legal framework, organising its functioning and setting out the rights and obligations of Member States. The organisation also has a membership of more than 1000 companies, universities, and international and regional organisations [10]. The International Telecommunication Union Radiocommunication Sector (ITU-R) is responsible for the management of the radio spectrum and the approval of the RR. Its main tasks are to examine the frequency assignment and allocation notices submitted by national administrations, to record the assignments and coordinate the related procedures, and to process and publish the data. In particular, it manages the Master International Frequency Register (MIFR), which contains all internationally recognised assignments. The ITU RR regulates the electromagnetic spectrum from 9 kHz to 300 GHz at a global level and is an international treaty formally adopted by ITU Member States, making it a binding international instrument. The ITU Constitution affirms the sovereignty of states to regulate telecommunications on their territory as long as the regulations do not cause harmful interference to radio services operating in accordance with the RR. This document is revised approximately every four years at the World Radiocommunication Conferences (WRCs). The WRC is a decision-making forum for adapting international regulations and treaties to the requirements of technical progress and for discussing key issues that have a global impact on radio-communications, satellites and other related fields. WRCs are attended by delegates from ITU Member States and ITU-R Members representing international organisations, equipment manufacturers, network operators and industry forums as observers. WRCs agenda items are generally prepared at national and regional levels [7], [9]. ITU RR contains the international Frequency Allocation Table (FAT), the reference document that allocates radio spectrum to the regulatory services in the three ITU Regions. In fact, to ensure that the allocation process respects the differences among geographical regions, such as service requirements or legacy applications, ITU divides the world into three regulatory regions: Region 1: Europe, the Middle East, Africa; Region 2: North and South American continents and the Pacific; Region 3: Asian continent, Australia. The separation leads to different Radio Frequency (RF) allocations among them.

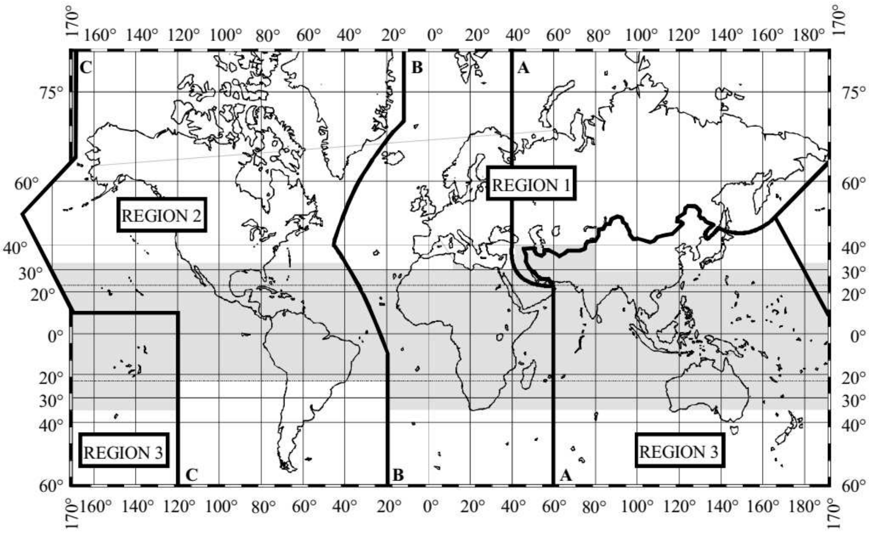


Figure 2.1: The Regions in the Radio Regulations. Region 1 covers Europe, Africa, the Middle East, Russian territories in Asia and republics bordering these countries. Region 2 covers the Americas. Region 3 covers Asia and Oceania [7].

Another important role of ITU is to coordinate national administrations to eliminate harmful interference between countries. ITU defines interference as “The effect of unwanted energy resulting from emissions, radiations or inductions on reception in a radio-communication system and manifested as degradation of performance, misinterpretation or loss of information that could be extracted in the absence of such unwanted energy", while harmful interference is defined as any interference that significantly degrades, obstructs or repeatedly interrupts a radio-communication service operating under RR. This can be caused by a technical fault or by an unauthorised station [8]. Since frequency assignment and licensing are national matters, if harmful interference occurs between stations under different administrations, they should cooperate to resolve the problem without direct ITU intervention. However, if States require a more detailed interpretation, the ITU Radiocommunication Bureau can act as a mediator to examine the case, determine the responsibilities of the States and propose means of resolving the problem [7].

2.1.2 Regional RF Spectrum Management: CEPT, EU and FCC

ITU Regions bring together countries with different economic and political backgrounds. As a result, RR may not adequately reflect the interests of all these countries. At the same time, the globalisation of businesses and consumers drives nations to cooperate to achieve harmonised spectrum management. This requires intermediary bodies between ITU and States. The benefits of such voluntary cooperation are many. For instance, initiatives supported by many countries have a greater chance of being recognised and adopted in international conventions. Others include the simplification and efficiency of spectrum management and the wider availability of equipment, allowing manufacturers to achieve economies of scale that also benefit consumers. A wider societal benefit is the use of emergency services across countries through interoperable bands. These bodies can be broadly divided into regional harmonisation bodies and supranational or intergovernmental organisations [6], [7]. The most relevant bodies for this thesis at the European level are European Conference of Postal and Telecommunications Administrations (CEPT) as the main regional harmonisation body and EU as the main supranational political organisation. In the US, the Federal Communications Commission (FCC) is the federal body that sets the rules and policies for spectrum management. CEPT and EU work closely together. Moreover, another important role in spectrum management is covered by Standards Developing Organizations (SDOs). The latter is outlined in Section 2.1.4, focusing on European Telecommunications Standards Institute (ETSI).

CEPT

CEPT was founded in 1959 in Switzerland as an organisation for dialogue between postal and telecommunications administrations in Europe. Today it has 46 European members, including all 27 EU countries, but also non-EU countries as it is an organisation independent of the EU. CEPT plays an active role in the ITU by preparing common European contributions to be presented at WRCs. It also plays an important role in dialogue with other regional bodies and contributes to global standardisation, although standardisation activities have been transferred to ETSI, created in 1988. CEPT has established the Electronic Communications Committee (ECC) (formerly European Radiocommunications Committee (ERC)) for radio-communications and telecommunications. The Committee deals with harmonisation activities and adopts recommendations and decisions. The European Communications Office (ECO) is the permanent office of CEPT, which supports its activities and provides the secretariat. ECO's tasks include updating CEPT documentation, in particular the European Frequency Information Table (EFIS), an information tool showing the European Common Allocation (ECA) table resulting from harmonisation between CEPT members, and their national tables. ECO also carries out studies and produces reports on strategic issues. These activities may also be mandated by the EC [7], [11]. CEPT/ECC decisions, recommendations and reports are not legally binding, as states are only invited to accept and implement them. In practice, almost all countries comply with CEPT policies. When these documents are produced in response to EC mandates, they can form the basis for EC measures which are legally binding on EU countries [9].

EU

The EU intervenes in the management of the radio spectrum as a means of developing the single market and harmonising services. The EU's objectives are to coordinate Member States' policies on the availability and efficient use of radio spectrum, which necessarily involves harmonisation procedures and improved exchange of information. This common approach brings significant benefits to consumers and contributes to economic development. In line with these objectives, the European Commission (EC) established the Body of European Regulators for Electronic Communications (BEREC) as a forum for cooperation between the national regulatory authorities of the 27 EU Member States and the EC. Moreover, the EU recognises the important role of CEPT. In particular, Article 4(2) of Decision 676/2002 (Radio Spectrum Decision) provides that the Commission may issue mandates to CEPT for the development of technical implementing measures which will make the substance of decisions imposed on Member States [7]. EC Decisions and Directives on spectrum management have a relevance for European Economic Area (EEA) countries, that is, all EU members together with Iceland, Norway and Liechtenstein [9].

USA

The US regulatory framework for communications systems is established by Congress and the FCC, the federal courts and the states [9]. The Congress approved the Communications Act of 1934, which created the FCC. The Congress can change the communication law through its legislative power and can change policy through its control of the FCC. The FCC exercises legislative authority through a statutory delegation granted by the Congress. For example, the Congress generally requires the FCC to issue licences for all private and non-federal uses. The FCC is the agency responsible for regulating interstate and international wired and wireless communications and operates only at the federal level, meaning that its jurisdiction covers the 50 US states, the District of Columbia and the US territories. However, it is important to distinguish its federal jurisdiction from the type of use it regulates. In fact, this agency manages the spectrum for private sector and non-federal use, i.e., state and local government use, commercial use, private internal business and personal use. This is in contrast with another agency, the National Telecommunications and Information Administration (NTIA), under the Department of Commerce, which manages the spectrum for federal use, such as by the Army, the Federal Aviation Administration (FAA), and the Federal Bureau of Investigation (FBI) [12]. FCC regulations can be found in Title 47 of the Code of Federal Regulations (CFR). Title 47 contains the International FATs for Region 2 and the US FATs, subdivided into the Federal and the non-Federal FATs. The Federal Table of Frequency is administered by the NTIA and the non-Federal Table is administered by the FCC. Except as specifically provided by FCC rules, spectrum licences and authorisations and the actual use of spectrum should be in accordance with the FATs [9]. Federal courts can review FCC decisions, while states exercise control over intrastate communications services. Since most wireless services, including Short-Range Devices (SRDs), are considered interstate because of their potential to cross state borders, only federal regulations apply [9].

2.1.3 National Spectrum Management

The ultimate managers of the spectrum are the national authorities. Each national government and its administration manages the spectrum resources in its territory. This should be done by developing long-term policies aimed at achieving efficient use of the spectrum, minimising harmful interference between users, serving national interests such as security and defence, and promoting innovation in infrastructure and services by facilitating spectrum access for new technologies. In doing so, each country must balance its political and socio-economic objectives with compliance with the decisions of the regional and international bodies to which it has chosen to adhere, thereby conceding part of its sovereignty [7], [9]. To achieve this objective, they have to define in a more precise way the allocation tables and the spectrum organisation and issue more detailed administrative and technical rules than those stated by ITU RR and regional provisions. Each country adopts and maintains a National FAT, which generally follows the ITU FAT but additionally provides all information necessary for operators to make practical use of spectrum resources in the national territory. They may also define unlicensed frequency bands and refer to the measures setting out the requirements for operating in them. The national FAT subdivides the spectrum for civil, governmental or shared use. National spectrum managers are also responsible for issuing licences to service users, protecting licensed stations and signing international agreements for frequency coordination with other states. To carry out this task, many countries created independent authorities or agencies in charge of implementing these regulations[6], [9].

Italy

In Italy, the Ministry of Enterprises and Made in Italy (MIMIT) (formerly Ministry of Economic Development (MISE)) and the Italian Communications Regulatory Authority (AGCOM) play a key role in radio spectrum management. The Ministry is responsible for defining the national policy for spectrum management, maintaining the National Frequency Allocation Plan, managing interference situations at national and international levels and representing Italy in the international and regional organisations to which it belongs (ITU, CEPT and EU). Italy, as a member of the EU, follows its decisions and directives to harmonise the use of frequencies within the internal market. Italy also is a member of CEPT and can decide to implement its decisions and recommendations if these are not in contrast with binding EU measures. Therefore, the measures taken by MIMIT follow the allocations of services and the technical requirements imposed by the EU and CEPT, which often coincide. MIMIT coordinates its planning activities with AGCOM and the Ministry of Defence. AGCOM is the independent authority responsible for the regulation and supervision of the communications and media sector, including spectrum management and frequency assignments. AGCOM also monitors spectrum use, ensuring that regulations and licence conditions are respected. MIMIT can provide AGCOM with guidelines and directives to achieve national and international spectrum objectives [13]. The frequency bands managed by MIMIT are allocated for civil use, while the Ministry of Defence manages the frequency bands allocated to meet the needs of law enforcement agencies and the army [14].

2.1.4 Standardisation

The creation of widely accepted standards is essential for technologies to work on a global scale. This is particularly true for wireless technologies, especially for low-cost and licence-exempt devices that can easily move across borders [9]. Standards can be defined as technical specifications approved and made publicly available by a recognised (international, regional or national) standards body. Compliance with standards is not mandatory. However, they support compatibility and interoperability. International Telecommunication Union Telecommunication Standardization Sector (ITU-T) is the main global SDO for telecommunications and radio-communications. Others are International Organization for Standardization (ISO), International Electrotechnical Commission (IEC) and, importantly for wireless equipment, 3GPP, Institute of Electrical and Electronics Engineers Standards Association (IEEE-SA) and the Wi-Fi Alliance. In Europe, the ETSI is the main SDO producing globally applicable standards for ICTs. In the US, the FCC's primary role is regulatory, but it also performs standard-setting functions by adopting standards developed by technical committees and incorporating them into regulations. Global SDOs have more influence in North America than in Europe, as the FCC relies more on these standards than on those of ETSI. ETSI cooperates with CEPT/ECC in the development of standards and technical specifications for ECC deliverables. As a result, ETSI standards are adopted and implemented in CEPT countries. In addition, the EC has mandated ETSI to produce harmonised standards or European Norms (ENs), which are developed in response to a request from the EC for a standard that can ensure compliance with legislation. EU national SDOs are required to transpose ENs into national standards and to withdraw any conflicting national standards. The use of harmonised standards in the EU is not mandatory, but if they are not used, regulatory compliance must be demonstrated in other ways. [9].

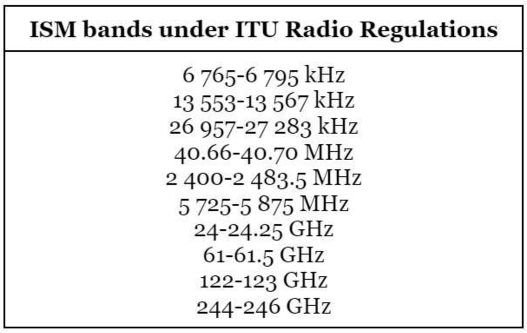
2.2 Short Range Devices and the Licence-Exempt RF Spectrum

The technologies considered in this thesis operate in the unlicensed spectrum. This section explains how this part of the spectrum is regulated and which devices are allowed to operate in it, commonly referred to as SRDs or licence-exempt devices. The term SRD is intended to cover low-power radio equipment that has a low ability to cause interference. These devices are used in a wide range of applications such as Radio Frequency Identification (RFID), medical devices and, most importantly, Wireless Access Systems (WASs), including Radio Local Area Networks (RLANs), also known as WLANs or wideband data transmission systems. [15]. WASs are broadband radio systems that can be deployed either inside or outside buildings, usually in geographically limited areas. Broadband RLANs, a subset of WASs, are the main type of equipment deployed today and are predominantly used inside buildings. These systems provide wireless access for public and private applications by connecting devices such as PCs, workstations, servers and other network equipment. Thus, WAS/RLANs eliminate the need for a physical connection and utilise low power levels due to the short distances typically encountered within buildings. More detailed information on broadband WAS/RLANs applications can be found in the ITU-R M.1450 Recommendation [16], [17]. RLANs include a range of technologies, such as Wi-Fi and newer technologies such as NR-U and LAA. In most cases, they are exempt from individual licensing, meaning that anyone can buy, install, possess and use the radio equipment without specific authorisation from the national administration. However, the equipment must still meet the requirements of national and regional regulatory authorities. These include the bands in which they may operate, maximum power levels, channel spacing, conditions for labelling and marketing of equipment, ElectroMagnetic Compatibility (EMC) and electrical safety requirements, among others. The technical regulation is necessary to ensure fair spectrum sharing with other incumbent services, and compliance is essential to obtain a general authorisation to operate and place SRDs on the market [15].

Power limits are defined to limit the service area of a particular radio system and prevent it from interfering with other systems. Indeed, the properties that determine the capability of a system to properly receive a message at a given location and time, are the signal strength (the received signal power), the noise power (the unwanted electric signal generated by the thermal and electric properties of the materials used in the radio circuits) and the interference (the unwanted signal coming from other users that use the same radio resources or neighbouring frequencies, in the same area of the receiver). To express the maximum power levels, regulations often use Effective Isotropic Radiated Power (EIRP) or Power Spectral Density (PSD). PSD is the amount of power emitted over a given bandwidth and can be expressed as dBm/MHz. EIRP is based on the assumption that real antennas do not radiate power uniformly, but rather radiate more power in a particular direction, i.e., the strongest beam or main lobe of the antenna. EIRP is the power that an isotropic antenna (a theoretical antenna that radiates power equally in all directions) would have to radiate to have the same signal strength as an actual antenna in the direction of its main lobe. This parameter is often expressed in dBm and is used to limit the maximum power that can be radiated by the antennas of a particular system [7].

2.2.1 International SRDs Regulation

Depending on the specific application and geographical region, SRDs can operate on different frequencies. SRDs mainly operate on the bands internationally designated by ITU RR for Industrial, Scientific and Medical (ISM) applications. These are shown in Figure 2.2.



ISM bands under ITU Radio Regulations
6 765-6 795 kHz
13 553-13 567 kHz
26 957-27 283 kHz
40.66-40.70 MHz
2 400-2 483.5 MHz
5 725-5 875 MHz
24-24.25 GHz
61-61.5 GHz
122-123 GHz
244-246 GHz

Figure 2.2: ISM bands under ITU Radio Regulations Nos. 5.138 and 5.150 [8].

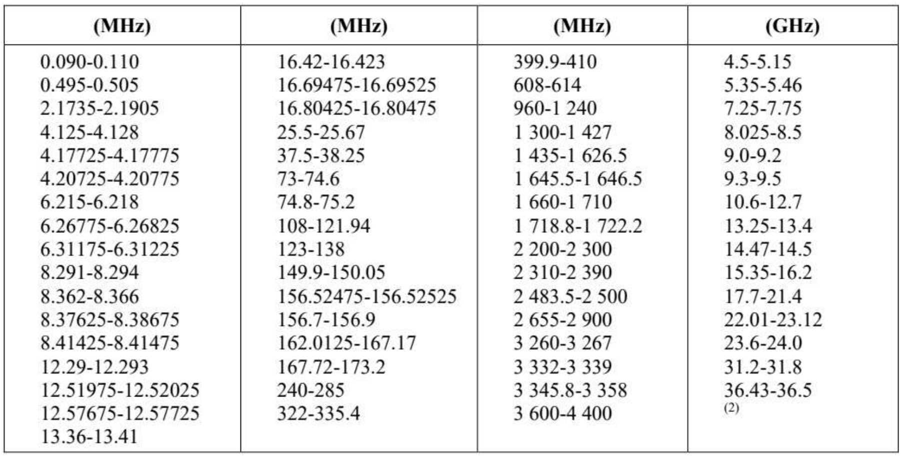
ITU RR defines ISM applications as the operation of equipment for industrial, scientific, medical, domestic or similar purposes, excluding telecommunications applications. As a result, the availability of the ISM bands for telecoms cannot be guaranteed and unlicensed equipment operating in these bands must accept harmful interference caused by ISM applications [8]. The choice of these bands for SRDs is based on the fact that ISM equipment also operates on a non-protected and non-interference level. ISM bands have become the focus for WAS/RLANs and similar systems, particularly for wireless standards such as Wi-Fi and Bluetooth. Among these, the 2400-2483.5 MHz band is the globally harmonised band for WLANs [9]. However, due to the high congestion in these bands, other non-ISM frequency bands have been identified for WAS/RLANs operations to ensure higher reliability and data rates [18]. At global level, Resolution 229 of WRC-03 (revised at WRC-19) allocated the non-ISM bands 5 150-5 250, 5 250-5 350 MHz and 5 470-5 725 MHz to the mobile service on a primary basis for the implementation of WAS/RLANs. The Resolution specifies that these services should respect certain parameters and implement techniques to protect incumbent services and cannot claim protection from them [19]. However, the precise conditions at which licence-exempt devices can operate are defined by regional and national regulators.

2.2.2 European SRDs Regulation: CEPT and EU

Within ITU Region 1, CEPT and ECC drafted ERC Recommendation 70-03 “Relating to the Use of Short Range Devices (SRD)”, which provides detailed implementation information for CEPT countries. Rec 70-03 defines parameters for each application and frequency range considered. For WASs, the relative requirements are defined in Annex 3, dedicated to wideband data transmission systems, and in Annex A for applications operating under the general authorisation regime (exempt from individual licensing). The requirements for the latter are defined in specific ECC/ERC Decisions. The main parameters are related to the transmit power or magnetic field strength, the required spectrum access and mitigation techniques, the occupied bandwidth and the possible specific ECC/ERC deliverables applied to each allocation [20]. Annex 3 allocates the 2400-2485 MHz band to WASs and specifies the limits and requirements for this application. Annex A allocates to WASs the non-ISM 5150-5350 and 5470-5725 MHz bands by ECC Decision (04)/08 and the recently opened non-ISM 5945-6425 MHz band by ECC Decision (20)/01. The details of the latter are examined in Section 2.3. In addition to these bands, WAS/RLANs use is also possible in the ISM 5725-5875 MHz band, under the parameters defined in Annex 1 "Non-specific SRDs", valid for all types of applications [16]. To facilitate conformity assessment with the many technical and non-technical standards, ERC Recommendation 70-03 includes references to the relevant ENs for each provision. Some SRDs applications may also be subjected to EU regulations. When EC decisions conflict with CEPT regulations, the former prevails only for EU members. Nevertheless, for WLANs, CEPT and EU measures are developed and harmonised in close cooperation [9]. EU members must also comply with the Radio Equipment Directive (2014/53/EU), the aim of which is to establish a common internal market by laying down certain essential requirements with which all radio equipment must comply in order to be placed on the market and to ensure mutual recognition of its conformity between Member States. The simplest way of demonstrating conformity is to comply with the applicable harmonised standards developed by ETSI. The Directive also regulates the CE marking, which indicates a product's compliance with EU legislation and allows free movement within the EEA [21].

2.2.3 USA SRDs Regulation: FCC

In the USA, the main regulations are contained in FCC CFR Title 47 Part 15 "Radio Frequency Devices". Some US terms used for SRDs are Radio Frequency Devices, Part 15 Devices, Low Power Transmitters and Unlicensed National Information Infrastructure (U-NII) Devices. Operators in the USA must obtain FCC authorisation to legally import or market a Part 15 Device in the USA. The authorisation ensures that they comply with FCC technical standards. The main difference between CEPT and U-NII regulations is that the former specifies the permitted ranges for each application, whereas the FCC allows operation on all frequencies above 9 kHz, subject to general emission limits, except some restricted bands where low-power unlicensed transmitters are not allowed because they are intended for sensitive radio communications. The restricted bands are shown in Figure 2.3 [15]. Moreover, there may be some exceptions to the general limits for certain types of use, such as the 5925-7250 MHz band used for WASs, details of which are given in Section 2.3 [15]. Part 15 also governs the approval process that ensures telecom equipment complies with applicable technical standards and FCC rules. The Commission has two approval procedures, Certification and Supplier's Declaration of Conformity (SDoC), depending on the type of equipment being approved. SDoC requires the responsible party to guarantee that the equipment complies with FCC rules, while certification requires the manufacturer to go through



(MHz)	(MHz)	(MHz)	(GHz)
0.090-0.110	16.42-16.423	399.9-410	4.5-5.15
0.495-0.505	16.69475-16.69525	608-614	5.35-5.46
2.1735-2.1905	16.80425-16.80475	960-1 240	7.25-7.75
4.125-4.128	25.5-25.67	1 300-1 427	8.025-8.5
4.17725-4.17775	37.5-38.25	1 435-1 626.5	9.0-9.2
4.20725-4.20775	73-74.6	1 645.5-1 646.5	9.3-9.5
6.215-6.218	74.8-75.2	1 660-1 710	10.6-12.7
6.26775-6.26825	108-121.94	1 718.8-1 722.2	13.25-13.4
6.31175-6.31225	123-138	2 200-2 300	14.47-14.5
8.291-8.294	149.9-150.05	2 310-2 390	15.35-16.2
8.362-8.366	156.52475-156.52525	2 483.5-2 500	17.7-21.4
8.37625-8.38675	156.7-156.9	2 655-2 900	22.01-23.12
8.41425-8.41475	162.0125-167.17	3 260-3 267	23.6-24.0
12.29-12.293	167.72-173.2	3 332-3 339	31.2-31.8
12.51975-12.52025	240-285	3 345.8-3 358	36.43-36.5
12.57675-12.57725	322-335.4	3 600-4 400	(2)
13.36-13.41			

Figure 2.3: Restricted bands for the operation of short-range devices in the USA, according to FCC [15].

a multi-step administrative process. The core of the process is the submission of a certification application to a Telecommunications Certification Body (TCB), providing all product information. If the TCB determines that the product complies with FCC rules, it issues a certificate of approval to the FCC's Equipment Authorisation Electronic System. In both processes, products are marked with the FCC Mark, which includes the required customer information [15].

2.3 The Authorisation of Unlicensed Operations in the 6 GHz Frequency Band

Global data traffic relying on wireless connectivity continues to grow, as does the number of unlicensed devices used for WAS/RLANs. This has led to congestion in the bands traditionally used by RLANs, a problem that is exacerbated by the growing importance of applications (such as videoconferencing, online learning and gaming, AR/VR, telemedicine) that require high-throughput, high-reliability connectivity [5]. Different strategies can be followed to acquire new spectrum for a given application. In the past, it was easier for regulators to use a free band, or to remove a previous application from a band and repurpose it for a new application. Today, as most bands are already in use, the most common option is spectrum sharing, i.e., adding a service or application in a band already occupied by other services [6]. Spectrum sharing always requires an assessment of potential interference between the new and existing equipment. The new service should be able to function properly without harming other protected services operating in the same bands. To achieve this objective, the most common method used by regulators is to impose some technical restrictions, such as maximum radiated power or EIRP and indoor/outdoor confinement [7]. In addition, regulators often consider unlicensed spectrum as a common resource and may impose other conditions to facilitate coexistence with existing or planned unlicensed users to conserve this resource and achieve the objective of promoting innovation [9]. Following this latter strategy, in order to meet the growing demand for unlicensed spectrum, the FCC in the US and the EC in Europe commissioned studies to determine the feasibility of unlicensed operations in the 6 GHz band. This band has already been used by other licensed users and is expected to accommodate various unlicensed technologies. As discussed later in this Section and in Chapter 3, the coexistence of unlicensed devices with both incumbent protected users and other unlicensed RATs presents significant challenges. There are several anticipated benefits that regulators have cited to justify their decision. First, devices using Wi-Fi or other unlicensed standards are essential to provide low-cost wireless connectivity, a way to bring broadband to all citizens, especially those in rural or underserved areas. In addition, making more spectrum available can reduce existing and potential congestion, which in turn can lead to higher throughput and lower latency, benefiting consumers and businesses that need to use real-time applications. This decision has also stimulated service and technology innovation, as demonstrated by the development of new Wi-Fi and unlicensed 5G standards discussed in Chapter 3 [18], [22]. This section shows how unlicensed operations in the 6 GHz band have been regulated in the United States and Europe. The legislation focuses mainly on coexistence scenarios that allow existing licensed users to be protected. The next chapter, Chapter 3 focuses on coexistence between unlicensed operators.

2.3.1 USA: the FCC's 6 GHz band Report and Order

In the US, the FCC began exploring the possibility of expanding the unlicensed spectrum with the Notice of Proposed Rulemaking 18-147 in October 2018, which sought comments on opening the 5.925-7.125 GHz band to unlicensed access. This was followed by the adoption of Report and Order 20-51 (6 GHz Order) in April 2020. The Order opened up 1.2 GHz for unlicensed use, which was divided into four sub-bands: U-NII-5 (5.925-6.425 GHz), U-NII-6 (6.425-6.525 GHz), U-NII-7 (6.525-6.875 GHz) and U-NII-8 (6.875-7.125 GHz), based on the prevalence and characteristics of the incumbent licensed services operating in them.

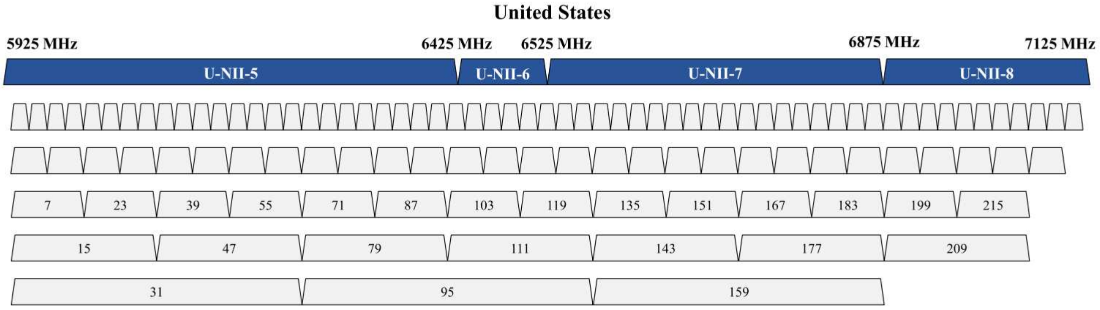
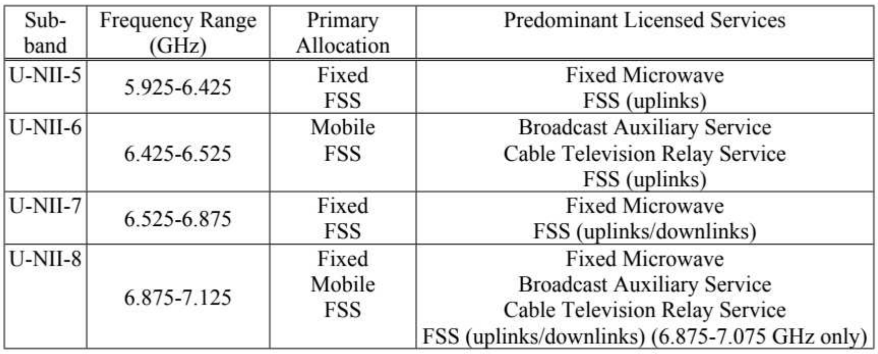


Figure 2.4: The 6 GHz channels for unlicensed access in the US [4].

The regulation of each of these sub-bands takes these characteristics into account to preserve the rights and operativity of each incumbent category. The ITU primarily allocates the 6 GHz band to Fixed Services (FSs), Fixed Satellite Services (FSSs) and Mobile Services in all three ITU Regions, with some predominant licensed services in each allocation [22]. U-NII-5 and U-NII-7 host the majority of fixed microwave point-to-point services used to provide backhaul links for critical services such as police, energy resource control and power grid management. Due to the safety value of these links, they have very high reliability requirements and therefore require the highest possible protection against harmful interference. Moreover, these links are used to provide backhaul for cellular mobile networks, e.g., the links between the base stations of a LTE/5G network and its core network. Due to the fixed nature of these services, the position of incumbents is predictable and new incumbents rarely enter the market. The U-NII-6 and U-NII-8 bands are home to Broadcast Auxiliary Services and Cable Television Relay Services, which operate on a mobile basis in the U-NII-6 band and on a fixed and mobile basis in the U-NII-8 band. These services are used by television pick-up stations to transmit content from special events or remote locations to the studio or other central receiving locations. In this case, the location of licensees may change frequently depending on where they need to transmit from. Therefore, it is not possible to limit their licence to geographical areas. Other incumbents are the Earth-to-Space FSSs, which are allocated in all sub-bands except U-NII-8. The main use of these frequencies is to distribute content for radio and television broadcasters and to provide feeder links for mobile satellite services. However, as the receivers of these applications (i.e., satellites) are located far from the unlicensed devices, they are unlikely to cause interference. Finally, the U-NII-6 band is also used by low-power Ultra-wideband (UWB) and wideband systems that are highly susceptible to external interference. These are Part 15 devices that operate as real-time locating systems with a variety of applications such as tool tracking and worker safety in industrial environments and robotics applications. FCC refused to take specific action to protect them because they operate on an unprotected basis and are not entitled to this level of interference protection [4], [22]. A summary of the predominant uses of the 6 GHz bands is in Figure 2.5.



Sub-band	Frequency Range (GHz)	Primary Allocation	Predominant Licensed Services
U-NII-5	5.925-6.425	Fixed FSS	Fixed Microwave FSS (uplinks)
U-NII-6	6.425-6.525	Mobile FSS	Broadcast Auxiliary Service Cable Television Relay Service FSS (uplinks)
U-NII-7	6.525-6.875	Fixed FSS	Fixed Microwave FSS (uplinks/downlinks)
U-NII-8	6.875-7.125	Fixed Mobile FSS	Fixed Microwave Broadcast Auxiliary Service Cable Television Relay Service FSS (uplinks/downlinks) (6.875-7.075 GHz only)

Figure 2.5: Predominant uses of the 6 GHz bands in the USA [22].

Regulation

In Report and Order 20-51 FCC allows three types of unlicensed operation:

- Standard power Access Points (APs) using an Automatic Frequency Coordination (AFC) system;
- Indoor Low-power operations;
- Very Low-power operations.

Clients can only operate in this band when paired with an AP. Direct client-to-client communication is not allowed as this could make it difficult to enforce the restrictions imposed and to identify and resolve interference. In addition, the EIRP's limit for clients is 6 dB lower than for the corresponding APs. This is mainly due to the need to reduce the transmission range and ensure that clients operate close to the APs. First, the Commission had to define an interference protection criterion to determine the power limits of the equipment. The criterion used is the Interference-to-Noise Power (I/N), which is the ratio between the signal received from the interfering unlicensed device and the background noise level at the licensed receiver. The specific criterion is I/N= -6 dB [22]. A summary of the unlicensed devices allowed to operate in the 6 GHz bands in the US can be found in Figure 2.6.

STANDARD-POWER

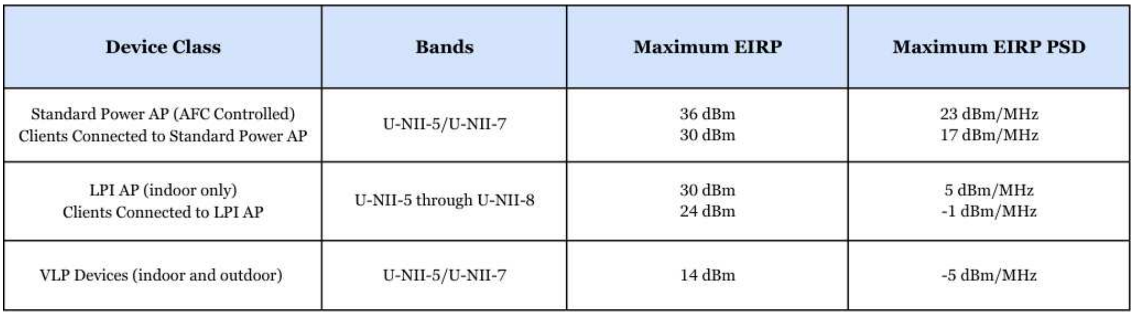
The FCC 6 GHz Order authorises unlicensed standard power APs in the U-NII-5 (5.925-6.425) and U-NII-7 (6.525-6.875) bands. The APs can operate at a maximum EIRP of 36 dBm with a maximum PSD of 23 dBm/Mhz. The client connected to this type of AP can have a maximum EIRP of 30 dBm and a maximum PSD of 17 dBm/Mhz. These devices operate at the same power levels permitted in the 5 GHz U-NII-1 and U-NII-3 bands (5.150-5.250 GHz and 5.725-5.850 GHz, respectively), enabling combined use of the 5 GHz and 6 GHz bands and promoting unlicensed broadband deployment. The standard power APs can operate both outdoors and indoors using an AFC system which, together with the technical and operational rules, allows incumbents to be protected from harmful interference. The AFC system essentially calculates the exclusion zones, i.e., the regions around the incumbent receiver where the unlicensed operation does not meet the interference protection criteria of I/N= -6dBm. Before starting transmission, the AP contacts the AFC database. Depending on the exclusion zones calculated, the AFC returns a list of authorised frequencies on which the AP can transmit. It also calculates a set of allowed transmit power levels for the AP depending on the distance from the defined licensed receiver (the smaller the distance, the lower the power). The allowed frequencies depend on the power level selected by the AP. The exclusion zones are calculated taking into account the technical and operational characteristics of both licensed and unlicensed users and the interference protection parameters. An important piece of information is the location, which requires the AP to have a geolocation capability. Instead, the AFC relies on the Universal Licensing System database to obtain the location and other relevant information from the incumbent. This type of operation is possible in these bands because of the constant and predictable location of the licensed users.

INDOOR LOW-POWER

The FCC allows the operation of low-power APs (maximum EIRP of 30 dBm and maximum PSD of 5 dBm/MHz) and clients (maximum EIRP of 24 dBm and maximum PSD of -1 dBm/MHz) throughout the 6 GHz band. However, in the U-NII-6 (6.425 - 6.525 GHz) and U-NII-8 (6.875 - 7.125 GHz) bands, it is difficult to determine the location of incumbents, so coexistence based on geolocation would be ineffective. Therefore, to enable operation in all bands, devices must operate on a low-power basis, be restricted to indoor operation and use a contention-based protocol, that is, the protocol enables multiple users to share the same spectrum by specifying actions to take when multiple transmitters try to access the same channel simultaneously and establishing rules by which a transmitter provides fair opportunities for other transmitters to operate [22]. Restricting devices to low-power indoor operation is considered sufficient by the FCC as interference is significantly attenuated when passing through the walls of a building. To ensure that such APs operate only indoors, the FCC has imposed three restrictions: Low-Power Indoor (LPI) APs cannot be weather resistant, they must have integrated antennas, and they cannot be battery-powered. The use of a contention-based protocol for APs and clients avoids co-channel interference with incumbent services in the band and limits the amount of time each unlicensed device can transmit. As described in Chapter 3, it is also necessary to provide fair access to the spectrum for all unlicensed users.

VERY LOW POWER

The FCC approved a third type of unlicensed device in the U-NII-5 and U-NII-7 bands in the Second Report and Order 23-86 of October 2023. These are very low-power devices that can operate at a maximum EIRP of 14 dBm and up to -5 dBm/MHz PSD and are allowed to operate both indoors and outdoors without the need for an AFC system. The decision to allow this type of operation was motivated by the fact that Very-Low-Powers (VLPs) are considered essential for wearable devices such as smartphones, glasses, watches and earphones, personal area networks and in-vehicle applications [23].



Device Class	Bands	Maximum EIRP	Maximum EIRP PSD
Standard Power AP (AFC Controlled) Clients Connected to Standard Power AP	U-NII-5/U-NII-7	36 dBm 30 dBm	23 dBm/MHz 17 dBm/MHz
LPI AP (indoor only) Clients Connected to LPI AP	U-NII-5 through U-NII-8	30 dBm 24 dBm	5 dBm/MHz -1 dBm/MHz
VLP Devices (indoor and outdoor)	U-NII-5/U-NII-7	14 dBm	-5 dBm/MHz

Figure 2.6: Unlicensed devices allowed to operate in the 6 GHz band in the US [22].

2.3.2 Europe and the Unlicensed 6 GHz band: CEPT and EU measures

In Europe, the EC has been the driving force behind the feasibility studies for the unlicensed 6 GHz band. An important difference with the US is that only half the bandwidth is available in Europe, as only the 5925-6425 MHz band has been opened, while the opening of the 6425-7125 MHz band is under consideration. This choice is partly justified in Section 2.3.3.

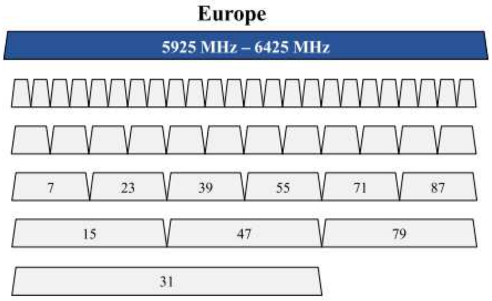


Figure 2.7: The 6 GHz channels for unlicensed access in Europe [4].

The EC issued a mandate to CEPT in December 2017 with two main tasks:

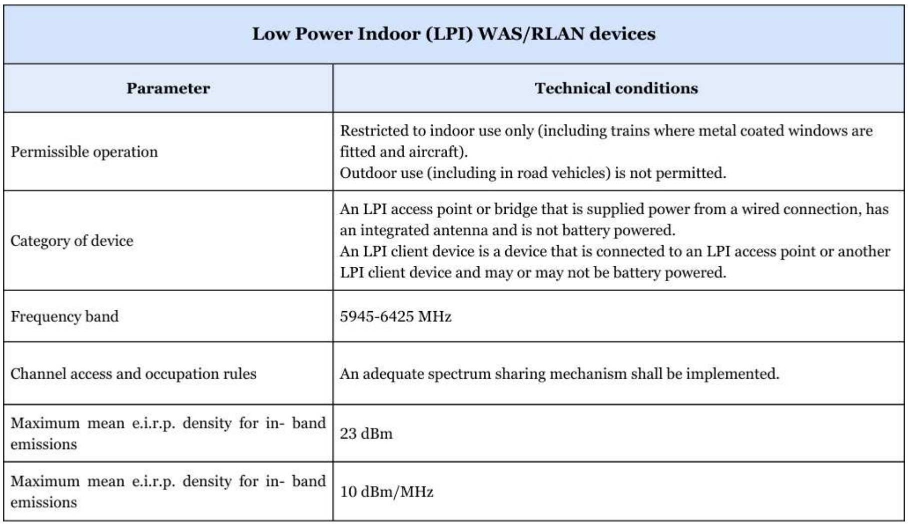
1. To study the regulatory and technical feasibility of introducing WAS/RLANs in the 5925-6425 MHz band.
2. To develop the harmonised technical conditions for fair compatibility and coexistence of WAS/RLANs with the protected incumbents [18].

The existing users operating in the 6 GHz bands in Europe and the US are very similar, as are the permitted classes of equipment, the restrictions and the solutions for allowing unlicensed systems to coexist with incumbent systems [4], [24]. The EC's decision was in line with the European Gigabit Society's broadband targets of 1 gigabit per second connectivity for all socio-economic drivers and digital-intensive businesses, and at least 100 megabits per second download speed for all households by 2025. The EC considered it necessary to increase the spectrum available to these systems to meet the new capacity, speed and coverage requirements [18].

Reports and Decisions

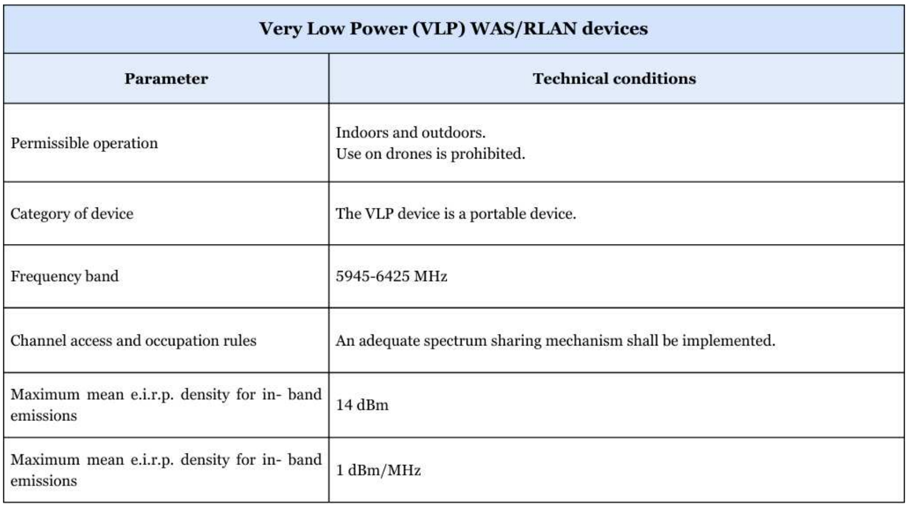
The EC mandate set in motion a series of measures by CEPT and the EU. Following Task 1, the ECC produced Report 302 which included studies on sharing and compatibility between WAS/RLANs and existing incumbents in the 5925-6425 MHz and adjacent bands. It evaluated the coexistence scenarios, considering different EIRP levels and indoor/outdoor options, and identified the technical conditions for their feasibility [24]. CEPT Report 73 (also Report A) drew some conclusions based on these technical studies. It defined two interference protection criteria: I/Ns -10 dB and I/Ns -20 dB, depending on how WAS/RLANs are considered. The details of this decision can be found in [25]. In response to Task 2, CEPT Report 75 of November 2020 (also

Report B) carried out complementary studies and identified two main use cases for WAS/RLANs and the associated technical requirements. These are LPI devices (maximum EIRP of 23 dBm and PSD of 10 dBm/MHz) for indoor use only, and VLP devices (maximum EIRP of 14 dBm and a PSD of 1 dBm/MHz) which can operate both indoors and outdoors. In both deployments, an appropriate spectrum-sharing mechanism should be implemented. This regulation has some differences from the US requirements. Firstly, European LPI devices have a lower power limit and VLPs are allowed to operate at a higher PSD. Authorisation to use higher power devices (equivalent to US standard power) indoors and outdoors is currently under review as it may require a solution similar to the AFC system. The other major difference is that in Europe VLP devices are intended to be portable devices that can communicate directly in small areas or form ad hoc networks, whereas in the US client-to-client communication is not currently permitted [17]. Report 75 was adopted in conjunction with ECC Decision 20(01). The Decision aims is to harmonise the use of the 5925-6425 MHz band in the CEPT area and to allow the free circulation and use of WAS/RLAN equipment that complies with the requirements set out in the Decision, which reflect those outlined in Report 75. CEPT specified that administrators should regulate such equipment so that it remains on a non-exclusive, non-protected, non-interference basis and is exempt from individual licensing [26]. Finally, the EC adopted Decision 1067 in June 2021. This is a legally binding act with EEA relevance. The objective of the Decision is to harmonise the regulatory framework for the 6 GHz bands in the Union to benefit the internal market by creating large economies of scale and to achieve the EU's objectives for high-quality connectivity and services. The Decision recalls the content of ECC Decision 02(01) and requires compliance with the same technical parameters [5]. The unlicensed operations allowed in the 6 GHz band in Europe are summarised in Figure 2.8 and 2.9.



Low Power Indoor (LPI) WAS/RLAN devices	
Parameter	**Technical conditions**
Permissible operation	Restricted to indoor use only (including trains where metal coated windows are fitted and aircraft). Outdoor use (including in road vehicles) is not permitted.
Category of device	An LPI access point or bridge that is supplied power from a wired connection, has an integrated antenna and is not battery powered. An LPI client device is a device that is connected to an LPI access point or another LPI client device and may or may not be battery powered.
Frequency band	5945-6425 MHz
Channel access and occupation rules	An adequate spectrum sharing mechanism shall be implemented.
Maximum mean e.i.r.p. density for in- band emissions	23 dBm
Maximum mean e.i.r.p. density for in- band emissions	10 dBm/MHz

Figure 2.8: Technical conditions imposed on Low-Power Indoor (LPI) devices in Europe [26].



Very Low Power (VLP) WAS/RLAN devices	
Parameter	**Technical conditions**
Permissible operation	Indoors and outdoors. Use on drones is prohibited.
Category of device	The VLP device is a portable device.
Frequency band	5945-6425 MHz
Channel access and occupation rules	An adequate spectrum sharing mechanism shall be implemented.
Maximum mean e.i.r.p. density for in- band emissions	14 dBm
Maximum mean e.i.r.p. density for in- band emissions	1 dBm/MHz

Figure 2.9: Technical conditions imposed on Very-Low Power (VLP) devices in Europe [26].

2.3.3 ITU World Radiocommunication Conference 2023

The recent WRC-23 held in Dubai made significant changes to the RR for the 6 GHz band. One item on the WRC-23 agenda was the identification of additional bands for International Mobile Telecommunications (IMT) evolution. IMT is the term used by ITU to describe mobile broadband systems. ITU-R develops and adopts the international regulations and technical references on which these systems are based, to achieve global harmonisation. These include IMT-2000, IMT-Advanced, IMT-2020 and the latest IMT-2030, corresponding to Third Generation (3G), 4G, 5G and Sixth Generation (6G) standards, respectively [27]. These systems are favoured for ultra-reliable and low-latency communications and are considered fundamental to economic and social development by regulators, as they provide global access to a wide range of telecommunication services such as Public Switched Telephone Network (PSTN)/Integrated Services Digital Network (ISDN) and high-bit-rate Internet access [27][19]. The reason why unlicensed operations have not been allowed in the 6425-7125 MHz band in Europe is strictly related to other studies carried out in this band to implement the terrestrial components of IMT in Region 1. In the Provisional Final Acts of WRC-23, Resolution COM4/7 decided that administrations in Region 1 can implement IMT in the 6425-7025 MHz band on a primary basis, but also mandated ITU-R and administrations to undertake the necessary technical studies to determine the conditions that would ensure the protection of existing licensed incumbents. This Resolution applied also to some countries in Region 3 (Cambodia, Lao P.D.R. and the Maldives) and Region 2 (Brazil and Mexico). At the same time, ITU recognised that the 6 GHz band is also used for the implementation of WAS/RLANs [27]. The allocation of this band to the mobile service for IMT poses significant challenges and risks, as identified by stakeholders. First, Wi-Fi cannot operate co-channels with IMT. As a result, the decision creates a significant global fragmentation of spectrum use between regions that prioritise IMT allocations and those where Wi-Fi operates in the full 6 GHz band, such as the US [28]. [29] argues that this decision may have a negative impact on fostering innovation such as Wi-Fi 7 and future versions of other unlicensed technologies. Besides, without access to the whole band, the open unlicensed spectrum will not be sufficient in a few years to avoid congestion and provide the wider channels needed for data-intensive services. Generally, it is argued that this decision benefits neither consumers nor manufacturers [30].

3

Technical Strategies for Technology Coexistence

3.1 Introduction

In 2021, the European Commission and the US Federal Communication Commission released new portions of the radio spectrum for unlicensed use. The new portion is referred to as *6 GHz band* and enables unlicensed devices to transmit in a third unlicensed portion of the spectrum in addition to the traditional 5 GHz and 2.4 GHz bands. The 6 GHz bands provide additional 1.2 GHz and 500 MHz spectrum for unlicensed use in the US and Europe respectively, enabling the introduction of features and mechanisms to support QoS-sensitive applications. Industry stakeholders are accelerating their efforts in research and development of new strategies to exploit this part of the radio spectrum [4]. The main issue in using the 6 GHz portion of the radio spectrum is that such frequencies are currently in use by licensed devices. This requires developing strategies for a fair share of the available spectrum resources among the devices. It is possible to envision different options of coexistence in the unlicensed spectrum. Among them, the objective of current 3GPP and Institute of Electrical and Electronics Engineers (IEEE) designs is to enable the operation of Wi-Fi and cellular technologies in the same geographical areas, sharing the spectrum, without causing harmful interference to each other [31]. Concerning Wi-Fi technology, it is important to note that “Wi-Fi Certified” is the trademark used by the Wi-Fi Alliance to identify products that have been certified to meet the industry-standard interoperability, backward compatibility and security protections [32]. Nowadays, it is used as a synonym of WLAN and it is based on the IEEE 802.11 family standards. The first generation of Wi-Fi devices capable of operating in the 6 GHz band is based on the 802.11ax standard, also called Wi-Fi 6E. The other RAT that will work in the 6 GHz band is 5G NR-U, a standard developed by 3GPP in Release 16 [33]. 3GPP is a consortium established in 1998 by the standards organisations of Japan, Korea, China, Europe and the USA to develop standards for mobile telecommunications systems and it is responsible for the development and maintenance of standards such as Universal Mobile Telecommunications System

(UMTS), LTE and Fifth Generation New Radio (5G NR) [34]. Achieving coexistence between Wi-Fi and 5G NR-U is challenging due to their differences at the MAC layer. Typically, IEEE 802.11-based technologies operate exclusively in the unlicensed spectrum, usually with higher bandwidths and are based on a CSMA/CA scheme. In contrast, 3GPP-based technology follows a non-sensing scheme. It relies on interference management and coordination, which are critical to optimise the use of the limited and valuable licensed spectrum resources. Moreover, cellular networks have a centralised architecture in which the base station schedules access for the mobile stations, whereas Wi-Fi has a decentralised channel access mechanism [31], [35]. Despite their inherent differences, both RATs are now converging to use large bandwidths very efficiently, as will be discussed in Section 3.4. Novel methods for enabling technology coexistence in unlicensed bands involve the utilisation of MIMO technology and beamforming. These strategies will be outlined in Section 3.3.4.

3.2 Background

The expansion of 3GPP technologies to unlicensed operations began in 2015 with the 4G of wireless communication networks, LTE Release 13. The unlicensed variants of the standard are referred to as LAA and LTE-U and work with frequencies on the 5 GHz bands. Other approaches used by 3GPP to use the unlicensed portions of the radio spectrum are LTE-WLAN Aggregation (LWA) and LTE-WLAN Integration over an IPSec Tunnel (LWIP). They consist of the integration of WLAN and LTE radio links, where only WLAN devices have access to the unlicensed spectrum. In LWA the Base Station (BS) aggregates the traffic flows for the communication channel at the Packet Data Convergence Protocol (PDCP) in the LTE protocol stack, whereas with LWIP the integration occurs at the IP protocol layer. More information about LWA and LWIP can be found in [36]. LAA and LTE-U were developed to operate directly in the unlicensed bands, which were previously dominated by Wi-Fi devices. The 3GPP in TR36.889 defined fair coexistence as “the ability of an LAA network not to impact Wi-Fi networks operating on a carrier more than an additional Wi-Fi network operating on the same carrier, in terms of throughput and latency”. As a result, these technologies had to focus primarily on the protection of the performance of existing unlicensed technologies, as required also by the regulations of the 5 GHz bands in certain regions. For instance, in Europe, accessing the unlicensed channel requires the use of LBT for Clear Channel Assessment [35]. LTE-LAA uses LBT, the details of which are discussed in Section 3.3.1, while the LTE-U most common deployment manages transmissions using duty cycles, which are based on various parameters such as interference, traffic type, and path load [37]. Both of these LTE unlicensed versions are based on Carrier Aggregation (CA). CA aims to increase the data rate, capacity, and user throughput by expanding the bandwidth through the combination of several component carriers: a primary carrier supports essential control signalling, while one or more secondary carriers located in the unlicensed spectrum carry user data. At least one licensed carrier must be present as the primary carrier, as it is the anchor of the CA. The MAC entity manages the aggregation and the data distribution across the secondary carriers [38], [39].

The main change in the unlicensed 6 GHz band is that it is no longer dominated by Wi-Fi devices. Therefore, the *greenfield* 6 GHz spectrum provides an opportunity to design novel coexistence mechanisms that do not require NR-U to be strictly aligned with legacy Wi-Fi standards [4]. Nevertheless, the NR-U MAC layer and associated protocols are derived from LAA, in part to meet the technical requirements for appropriate spectrum sharing in the 6 GHz band imposed by European and US regulations [22], [26]. Before delving into the characteristics of these technologies and strategies, it is important to outline the basic building blocks and key elements of the 4G LTE, the 5G NR System Architecture and of Small Cells (SCs).

3.2.1 4G LTE and 5G NR: System Architecture

The coverage area of a cellular system is divided into distinct cells, each utilising a specific set of channels. Operating on the principle of frequency reuse, this allows the same channel set to be employed in cells located some distance apart, as illustrated in Figure 3.1 [40].

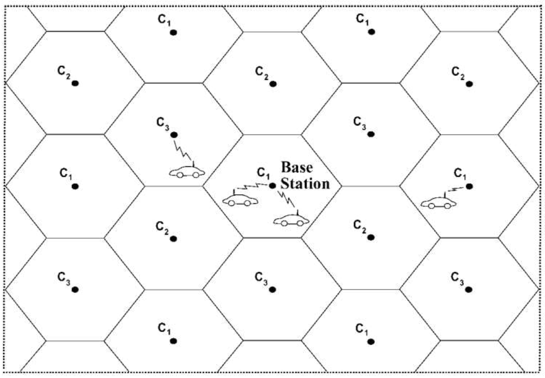


Figure 3.1: The cellular system [40].

A cellular network system contains three major network components: User Equipments (UEs); the Radio Access Network (RAN) and the Core Network (CN). The LTE RAN, also known as Evolved Universal Terrestrial Radio Access Network (E-UTRAN) is structured as a system of logical nodes Evolved Node B (eNodeB) representing the E-UTRAN BSs. Each eNodeB provides services to one or more cells. The RAN is responsible for managing the delivery of data or voice calls from the CN to specific mobile devices (the Downlink (DL)) and establishing connections for mobile devices when they initiate similar activities (the Uplink (UL)). The “last mile” connectivity between the UEs and the BS is provided through the air or radio interface. The RAN handles resource allocation and management for this function, utilising data channels for user data, i.e., data plane, and control channels to provide and manage connectivity, i.e., control plane. The Evolved Packet Core (EPC) or Core Network connects the RAN to external networks, providing the data and voice services that users require.

The 5G system architecture is shown in Figure 3.3. The 5G standards provide various deployment options for operators, some of which are based on Dual Connectivity (DC) for UEs. This feature enables the device to simultaneously connect and communicate with two different base stations,

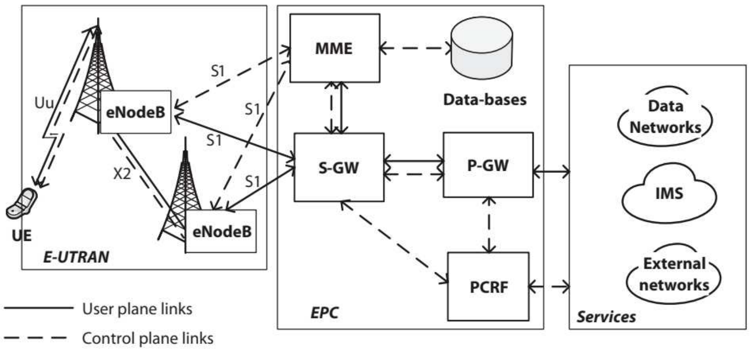


Figure 3.2: The LTE system architecture [6].

even from different cellular generations. Additionally, the architecture allows for 5G RAN, LTE RAN, and other wireless technologies to connect to the 5G core. In contrast to LTE, 5G NR has a native capability to operate in the unlicensed spectrum. A distinction can be made between stand-alone and non-stand-alone systems, depending on whether the 5G UEs solely use the 5G RAN and core, or are supported by the 4G RAN and core.

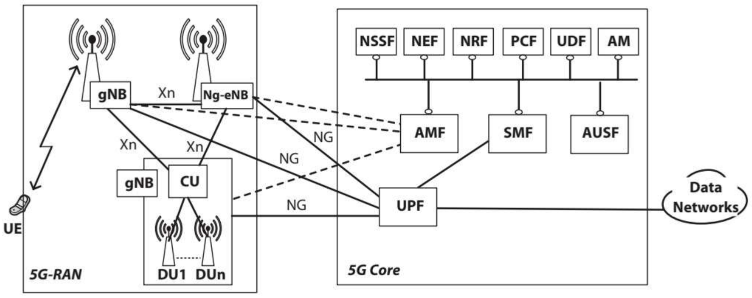


Figure 3.3: The 5G system architecture [6].

One of the critical network architecture improvements to provide capacity enhancement to 5G and support NR-U operations is the implementation of dense small-cell deployments. SCs have a smaller coverage area and are served by low-transmit-power base stations compared to macro base stations. They are commonly classified into three categories – microcells, picocells, and femtocells – based on their range of transmit power. Small-cell deployments offer several advantages, including improved indoor coverage and enhanced network capacity. In the context of a multi-tier cellular network, also known as Heterogeneous Networks (HetNet), various types of SCs or relays coexist alongside traditional macrocells [6]. The 3GPP proposes various NR-U deployments, which can be based on DC or CA. Unlike LAA, NR-U can also have a standalone deployment that consists of one or more unlicensed carriers served by a NR-U cell. In this case, a licensed primary carrier is not required for operations and the NR-U network is directly connected to the 5G CN. This allows NR-U networks to be deployed by any party, similar to Wi-Fi AP deployments [41].

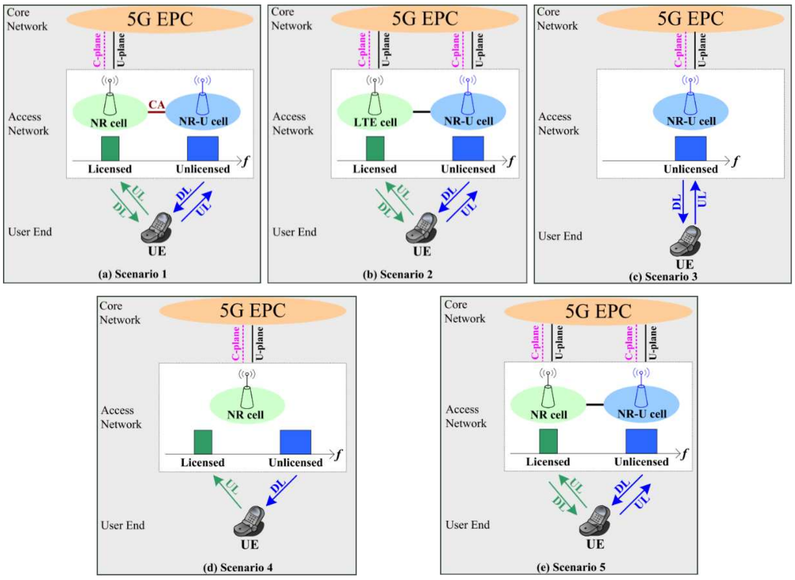


Figure 3.4: NR-U deployment scenarios. (a) Scenario 1: NR/NR-U CA; (b) Scenario 2: LTE/NR-U DC; (c) Scenario 3: NR-U Standalone; (d) Scenario 4: NR/NR-U UL/DL; (e) Scenario 5: NR/NR-U DC. U-plane defines User Plane; C-plane defines Control Plane [42].

3.3 Channel Access Techniques for Spectrum Sharing

This chapter will go deeper into the details of channel access techniques for spectrum sharing. The following approaches will be detailed:

- Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and Listen Before Talk (LBT);
- Orthogonal Frequency-Division Multiple Access (OFDMA);
- Multiple Input Multiple Output (MIMO);
- CoBeam and Massive MIMO Unlicensed.

3.3.1 Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and Listen Before Talk (LBT)

The MAC layer of IEEE 802.11-based systems rely on Enhanced Distributed Channel Access (EDCA) to coordinate channel access among devices. EDCA is based on CSMA/CA, with exponential backoff. Essentially, devices listen for ongoing transmissions in the channel before transmitting, to avoid collisions. When the channel is occupied, the device must wait, and when it is idle, devices initiate the exponential backoff phase to compete for access. Devices can use the channel if it remains idle for a certain defer time. To reduce the possibility of collisions, devices back off for a different period, defined by a certain amount of time slots. The number of slots is randomly sampled and depends on the contention window size. If the transmission fails, the contention window is increased. After the defer time, the devices can use the channel for a period known as Channel Occupancy Time (COT) or Transmit Opportunity (TXOP). In previous Wi-Fi generations, this scheme meant that only one device could transmit on the same channel at any given time. LAA and NR-U are using LBT, which is based on the same idea of CSMA/CA. There are 4 categories of LBT, the most relevant for this thesis are Category 2, in which the NR-U device must sense the channel for a fixed time duration and Category 4 or Load Base Equipment (LBE), basically equivalent to CSMA/CA since devices need to use exponential backoff [41].

3.3.2 OFDMA: Orthogonal Frequency Division Multiple Access

OFDMA is at the basis of the MAC protocols used in the 4G and 5G DL, while a variation of it, Single-Carrier Frequency Division Multiple Access (SC-FDMA) is used for the UL. Among the 802.11-based standards, Wi-Fi 6E is the first one to use OFDMA [6]. Section 3.4 discusses the impact of this convergence on the coexistence. OFDMA is a multiple access scheme that subdivides the available channel into smaller sub-channels or sub-carriers in the frequency domain, through a mathematical function known as an Inverse Fast Fourier Transform (IFFT). These sub-carriers are orthogonal to each other, meaning that when each sub-carrier is sampled at the peak of its signal, all other sub-carriers have zero value. This ensures that they do not interfere with each other, despite the lack of guard bands between them. Each sub-carrier is then individually modulated using the most suitable digital modulation technique [6].

BSs in cellular networks and APs in WLANs allocate the radio resources into Resource Units (RUs). Each RU consists of one time slot and one or a set of contiguous sub-carriers, depending on the bandwidth requirements of the user [43]. In contrast to Orthogonal Frequency-Division Multiplexing (OFDM) (a multiplexing technique in which all the sub-carriers within a particular time slot can only be assigned to one specific user), OFDMA allows dynamic allocation of sub-carriers to any user at any time by exploiting both time and frequency domains. For instance, more sub-carriers could be assigned to different users at a specific time and one sub-carrier can be assigned to the same user for several time slots. An example of this can be seen in Figure 3.5. Thanks to OFDMA, multiple stations can transmit frames concurrently to different receivers, without having collisions.

3.3.3 MIMO: Multiple-Input Multiple-Output

MIMO is a physical layer technology used in wireless communications characterised by multiple antennas at both transmitter and receiver. It was first introduced in Wi-Fi with the IEEE 802.11n version, while the first widespread integration in 3GPP standards came with LTE [43], [6]. MIMO exploits spatial diversity to convey simultaneous data streams using the same time and frequency resources. Spatial diversity is a consequence of multipath fading, a wireless channel propagation phenomenon where signals may reflect off objects, scatter, refract, or diffract. As a result, the communication paths between individual transmitting and receiving antennas vary in arrival time, angle of arrival, and signal attenuation and each antenna element receives a unique version of the

Figure 3.5: Example of a OFDMA (left) and OFDM (right) transmission over time for 802.11ax and 802.11n/ac, respectively. [43].

transmitted signal. For this to happen, there needs to be more than half-wavelength of space between multiple transmitting antennas. The separation between antennas is necessary for the fading effects in the channel to result in statistical independence among the channel gains [6]. MIMO and spatial diversity make possible transmission techniques such as space diversity techniques, spatial multiplexing, and transmit beamforming. Space diversity techniques use multipath to increase the robustness of the signal to fading. It consists of sending the same data stream over multiple independent fading channels, using techniques such as applying different weights to the data stream at each transmitting antenna. This allows the receiver to combine the signals in a way that reduces the fading of the resulting signal, as independent paths are unlikely to experience deep fading simultaneously. Spatial Multiplexing (SM)-MIMO techniques consist in sending multiple independent spatial streams (also called data streams) from different transmit antennas, each of them carrying unique data. This approach enables the utilisation of the same time/frequency resources across the data streams, leading to enhanced spectral efficiency. Furthermore, it contributes to increase both capacity and throughput without requiring additional transmit power or channel bandwidth, compared to a Single Input Single Output (SISO) system. A SM-MIMO system involving M transmitters and N receivers and a set of fading channels between each transmit and receive antenna can be represented as: $y = Hx + n$. In this equation, y denotes the received symbols in a vector of length N, x represents the transmit vector of length M, which undergoes multiplication by the channel matrix H, and n is the vector of noise samples at the receiver with length N. The matrix H is an $N \times M$ complex channel matrix of the transfer coefficients that consider the attenuation and phase adjustments occurring in the transmitted signal as it propagates over the spatial channels [44]. The approach of simultaneously transmitting data from all antennas does not involve the use of any pre-coding. However, at the receiver end, it becomes necessary to decouple the data streams through spatial demultiplexing. This involves recovering the original transmitted signals by multiplying the receive vector y by the inverse channel matrix. To execute this operation, the receiver needs knowledge about the fading channels, typically obtained from reference signals sent by the transmitter. In SM techniques, the calculation of the inverse channel matrix is commonly performed using methods such as MMSE (Minimum Mean Square Error) equalisation or ZF (Zero Forcing) equalisation [6].

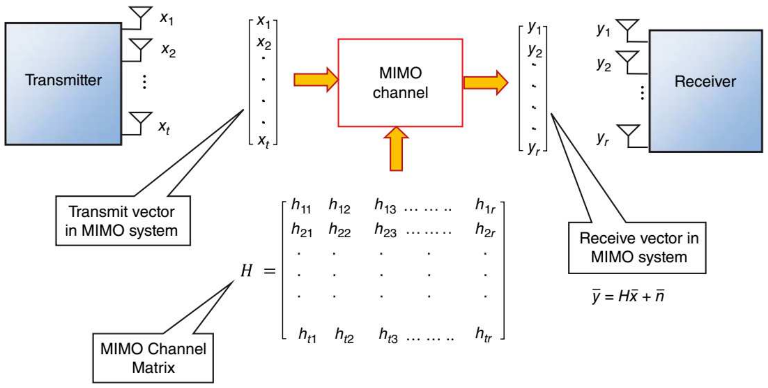


Figure 3.6: Simplified channel matrix model in MIMO system [44].
h_{ij} represents the channel coefficient between i^{th} transmit antenna and j^{th} receive antenna; n is the additive white Gaussian noise.

MIMO transmissions are classified into Single User (SU)-MIMO or Multi User (MU)-MIMO. In a SU-MIMO system using SM multiple data streams are sent to just one device at a time, since the multiple receiving antennas are all located on the same device. In a MU-MIMO system using SM multiple spatial streams can be sent to multiple receiving devices. In this case, each receiver can have only a single antenna, as long as the receiving antennas are distributed over multiple devices. MU-MIMO provides a capacity increase as multiple users can share the same resources. Note, however, that for efficient MU-MIMO, the interference between users must be kept low. This can be achieved by using transmit beamforming techniques [45].

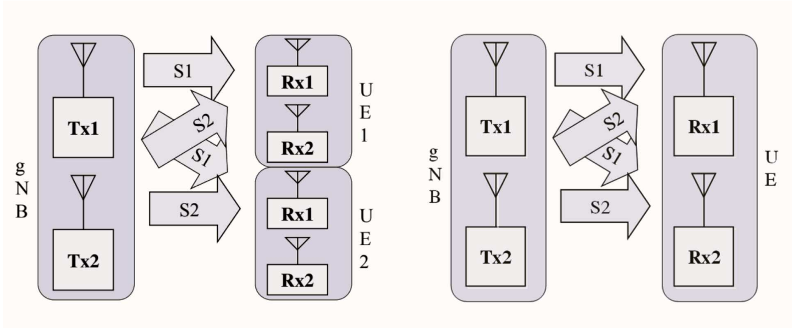


Figure 3.7: Example of a MU-MIMO system (left) and a SU-MIMO system (right) in a cellular network [46].

Transmit beamforming is a complementary technology to MIMO that allows antenna beams to be focused in a specific direction, rather than being broadcast omnidirectionally. This technique relies on phased antenna arrays, which consist of multiple antenna elements that can change the shape and direction of the radiation pattern without physically moving the antenna. Also, multiple beams can be generated in different directions by dividing the radiating elements into sub-arrays. The beams are shaped by adjusting the phase difference between the antenna elements. The phase shift is calculated to provide constructive interference in the desired direction, where signals with the same phase reinforce each other resulting in higher gain, and to create destructive interference in other directions by sending out-of-phase signals [44]. Phase refers to the timing or position within the cycle of a radio frequency signal. A waveform, such as a sine wave, completes a cycle as it oscillates from its starting point through positive and negative amplitudes, and back to the beginning. Gain is a measure of the ability of an antenna to direct or concentrate its radiated power in a particular direction compared to an isotropic antenna (an idealised antenna radiating uniformly in all directions). There are three basic architectures for antenna beamforming: analogue, digital and hybrid beamforming. Analogue beamforming uses a single RF chain in the transmitter to feed all the antenna elements as shown in Figure 3.8. The output of the RF chain is split among several antenna elements using a power splitter, and each antenna has an analogue phase shifter, which adjusts the phase of the signal in each antenna element to direct the beam. In this type of beamforming, one beam is sent at a time. In digital beamforming, each antenna is equipped with an individual RF chain and it employs a digital signal processor to execute a beamforming algorithm. Unlike analogue beamforming, which directs physical antenna beam patterns in a predetermined manner, digital beamforming aims to direct information through parallel singular channels using a linear pre-coding operation carried out at the transmitter. In this case, multiple beams can be sent simultaneously and the phase shift is applied in the digital domain. This ability to simultaneously direct different beams can be exploited to realise more precise MU-MIMO systems [44], [47].

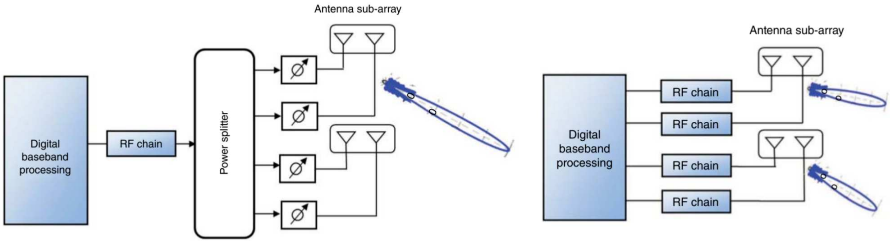


Figure 3.8: Illustration of analogue beamforming (left) and digital beamforming (right) in a wireless transmitter [44].

Digital beamforming can be seen as a combination of spatial multiplexing and space diversity techniques, as it can be used to multiplex several data streams while exploiting diversity. As shown in Figure 3.9, multiple data streams are sent from the transmitter and each transmit antenna sends a combination of the weighted data streams. In digital beamforming, the data streams are multiplied by a set of pre-coding weights to obtain independent fading channels. The results of the pre-coding are then combined at each transmit antenna. The pre-coding weights are calculated by performing an estimation of the channel matrix H and its decomposition. Then, the output signal from each transmit antenna takes a different path to each receive antenna. Therefore, as long as the antennas are at least half a wavelength apart, the signal has been modified by different channel coefficients. Moreover, the weighting is such that signals destined for a particular receiver arrive in-phase at that receiver and out-of-phase at the others. On the other hand, each receiving antenna receives all the weighted combinations modified by the channel conditions encountered along the way. The receiver must estimate the channel matrix and perform its inversion to decouple the data streams and reverse the coding process to obtain the original data. In this technique, the exchange of feedback signals between the transmitter and receiver is fundamental for accurate channel estimation. The channel matrix decomposition is done through Singular Value Decomposition (SVD), which decomposes H as: $H = U\Lambda V^H$, where U and V are matrices comprising the left- and right-singular vectors and Λ is the $N \times M$ diagonal matrix of singular values. The singular vectors capture the directions along which the channel matrix H has a significant influence. Λ represents the attenuation experienced in each direction. The matrix V is applied at the transmit side, while the matrix U is applied at the receiver side to adjust the received signal based on the characteristics of the channel, to recover the data stream intended for that specific antenna [6].

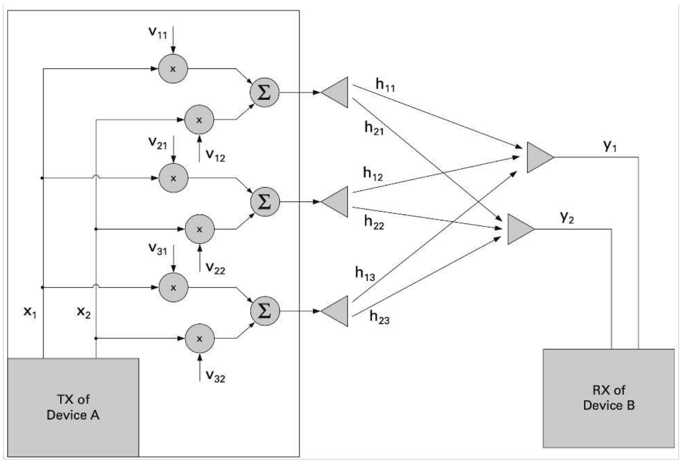


Figure 3.9: A MIMO system with 3 transmit antennas and 2 receive antennas using digital beamforming techniques to transmit 2 data streams. [48].

Another particular deployment option for MIMO is Massive MIMO (mMIMO), which can be defined as a transmit station with many antenna arrays, each of them having a massive amount of antenna elements. Increasing the number of elements in an antenna array results in the possibility of creating narrower beams and having a higher gain. This capability is strictly related to antenna directivity and it is expressed in terms of Degree Of Freedoms (DOFs) or the degrees to which the radiated power is focused in a single direction. Since mMIMO provides a high number of DOFs, MU-MIMO can serve a large number of receiving stations.

3.3.4 Novel approaches for technology coexistence

Coexistence in the unlicensed spectrum through LBT is based on discontinuous transmissions, meaning that it does not allow simultaneous use of the same frequency resources in the same coverage area, resulting in sub-optimal spectrum utilisation and data rates, especially in dense deployment scenarios. These problems are overcome by techniques that exploit MIMO together with spatial multiplexing and beamforming techniques. In the following, two approaches recently proposed in the literature will be analysed.

Massive MIMO Unlicensed

A proposed approach to enforce technology coexistence in the unlicensed bands is MIMO-Unlicensed (mMIMO-U), based on mMIMO capabilities [39]. mMIMO-U is an application of MIMO where BSs equipped with a large antenna array operate in the unlicensed bands. Due to the large number of antennas, there are more spatial DOFs than the number of User Terminals (UTs) to be served per time-frequency resource. This high spatial resolution can be exploited by placing radiation nulls during the Enhanced LBT (eLBT) phase to suppress mutual interference between the BSs and the WLAN devices sharing the spectrum in the same area. This system is based on Time Division Duplex (TDD) channel reciprocity, which means that the BS does not transmit or receive signals to/from a particular direction where the nulls are placed, i.e., they are placed in both directions.

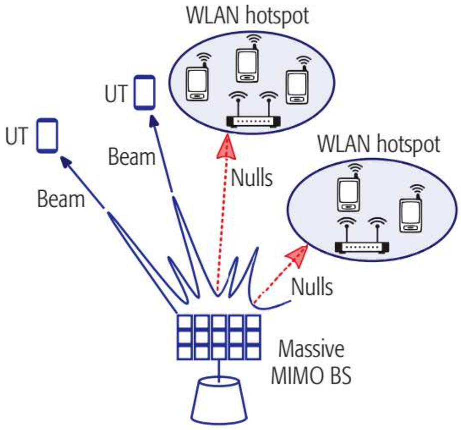


Figure 3.10: Illustration of a mMIMO-U system: A BS multiplexes UTs in the unlicensed band while spatially suppressing interference at neighbouring WLAN devices [39].

In order to place the radiation nulls in the direction of potential WLAN interferers, each BS periodically performs a channel covariance estimation procedure in which it remains silent and receives a signal consisting of all transmissions from active WLAN devices. This procedure allows the calculation of the eigendirections of the channel matrix, i.e., the primary paths through which signals travel in the channel subspace occupied by nearby WLAN devices. The calculation involves estimating how the characteristics of this channel portion change over time. From this estimation, the BS gains spatial awareness and creates a baseband filter that places radiation nulls towards the dominant WLAN channel eigendirections. In the eLBT phase, a BS monitors transmissions in the unlicensed bands and calculates the total received signal power filtered through the radiation nulls. If enough nulls are assigned and properly positioned, WLAN transmissions do not cause interference to BS transmissions. A successful eLBT phase enables the BS to utilise the channel for DL transmissions even when WLAN devices are transmitting, enhancing spectrum reuse in the spatial domain. This channel assessment at the BS allows to suppress the mutual BS-to-WLAN interference, but it does not affect the WLAN-to-UT interference, which may also compromise the mMIMO-U DL at the targeted UT. To avoid this, it is necessary to implement a UL scheduling process where UTs are selected based on their proximity to WLAN devices. One way of doing this is for the UTs to send reports to the BSs containing information about the received signal strength between the UT and one or more WLAN APs, allowing the BS to determine which UTs are far from WLAN devices and should be scheduled for transmission. To serve UTs located near WLAN hotspots, different strategies can be used, such as scheduling the UTs to use a different frequency resource. Alternatively, sharing the same channel but waiting for its conditions to change or periodically switching to a conventional LBT. Another option could be scheduling the transmission on a licensed band.

Figure 3.11 shows the coexistence improvements provided by mMIMO-U. The graph compares the mMIMO-U approach with the conventional LBT considering different numbers of antenna elements at the antenna array (NA). In Fig. 3.11(a), the area enclosed by the red lines represents the region where the interfering power is below the WLAN detection threshold of -62 dBm and coexistence is feasible. Fig. 3.11(b) shows the area where the interference from WLAN devices is below the cellular BS energy detection threshold of -72 dBm. In both graphs, it can be seen that the higher the number of antenna elements at the BSs, the lower the detected interference, allowing coexistence in the same coverage area.

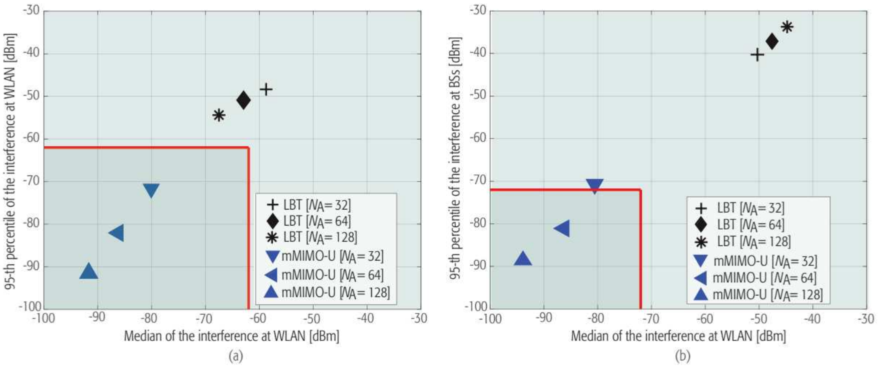


Figure 3.11: Coexistence in the unlicensed spectrum in the presence of two active WLAN hotspots per sector as seen by: a) WLAN devices; b) cellular BSs, considering different numbers of antenna elements at antenna array (NA) [39].

An inherent challenge of mMIMO-U is that the placement of the radiation nulls is equivalent to dedicating a number of spatial DOF to interference suppression. This leads to a trade-off, since on the one hand it increases the channel access and spectrum reuse opportunities, but on the other hand, it reduces the mMIMO beamforming gain.

Figure 3.12 shows the impact of this trade-off by considering the average DL data rates per cell sector as a function of the number of Antenna Radiation Nulls (NNs) placed. The figure shows how a conventional system based only on LBT and 0 NNs would not be able to access the channel while WLAN devices are active. Instead, as the number of NNs increases, the mMIMO-U BSs are able to transmit because the eLBT phase is more likely to be successful. At the same time, it can be observed that the placement of a large number of radiation nulls leads to a reduction in the data rate, as fewer DOFs are available to provide MU beamforming. Furthermore, Fig. 3.12 shows that the data rate decreases as the number of WLAN hotspots increases, which is a consequence of the greater interference generated by the WLAN devices towards the UTs and of the fact that more WLAN devices lead to the need to place more radiation nulls.

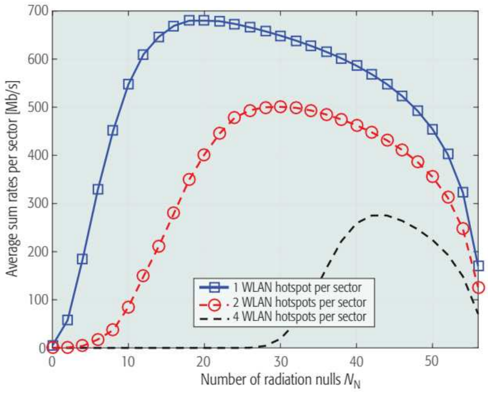


Figure 3.12: Cellular mMIMO-U rates versus number of radiation nulls (NN) in the presence of 1, 2, and 4 active WLAN hotspots per sector on average [39].

CoBeam

Another spectrum-sharing paradigm recently proposed in the literature, called CoBeam, is based on cognitive beamforming. CoBeam uses beamforming techniques and spatial diversity to enable multiple co-located wireless technologies to simultaneously access the same part of the spectrum [49]. Approaches such as mMIMO-U [39] present a MIMO-based scheme that requires signalling exchanges or modifications to the protocol stack, such as the necessary eLBT phase. Instead, CoBeam aims to achieve throughput maximisation and fairness between coexisting systems based on different spectrum access techniques, without explicit cross-technology signalling schemes, which often require significant modifications to the protocol stack. This is achieved by working at the lower layers of the protocol stack, particularly at the physical layer. This design choice allows backward compatibility and transparency to both the intended receivers and other interfering systems. In [49] the considered scenario consists of spectrum sharing between Wi-Fi and LTE in unlicensed bands, assuming Wi-Fi as the primary system (incumbent wireless network) and LTE as the secondary system (intending to access the medium), where Cobeam is deployed on secondary transmitters. In this setup, the primary system consists of a set K of single-antenna transceivers communicating with each other. On the other hand, the secondary system consists of an N-antenna transceiver that aims to communicate with a set S of single-antenna secondary receivers, where N represents the set of antenna elements available at the secondary transmitter. Figure 3.13 illustrates the channel coefficients between the primary and secondary systems. Here, $\mathbf{h}_s$ represents the channel of the secondary system between the secondary transmit antennas in

N and the secondary receiver s in S. Meanwhile, $\mathbf{g}_k$ represents the channel that interferes with the primary system between the secondary transmit antennas in N and the primary user $k \in \mathcal{K}$. In addition, $\mathbf{q}_j$ denotes the channel of the primary system between a primary transmitter $k \in \mathcal{K}$ and a primary receiver $j \in \mathcal{K}/k$, and $\mathbf{q}_s$ stands for the channel that interferes with the secondary system between a primary transmitter and a secondary receiver s in S.

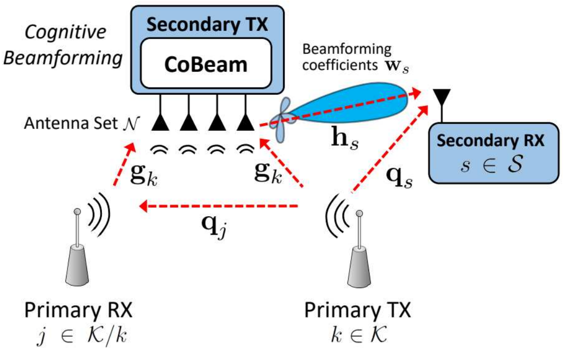


Figure 3.13: Beamforming-based spectrum sharing between primary and secondary technologies co-located on the same spectrum bands [49].

The primary objective of CoBeam is to determine, during each time interval, the secondary transmitter beamforming vectors W_s that can ensure satisfactory Signal-To-Interference-plus-Noise Ratio (SINR) levels at the secondary receivers to both maximise spectrum utilisation and maintain high fairness to primary receivers. This is accomplished by collecting data on ongoing transmissions within the primary system and using this information to perform beamforming-based transmissions. The architecture of CoBeam is shown in Figure 3.14. As can be seen, it consists of three primary modules: the Programmable Physical Layer Driver, the Cognitive Sensing Engine and the Beamforming Engine.

For each available antenna, the Programmable Physical Layer Driver implements the transmit and receive chains for the secondary system, along with an additional receive chain capable of capturing and demodulating primary user traffic. Within the receive chains, it demodulates incoming signals and forwards them to the Cognitive Sensing Engine. In the transmit chain, it accesses the spectrum by pre-coding and modulating the data for transmission. Pre-coding is performed using beamforming coefficients calculated by the Beamforming Engine. The Cognitive Sensing Engine extracts information about the channel characteristics between the secondary transmitter where Cobeam is operating and a primary or secondary user. This information, which takes into account the effects of distance, path loss, small and fast fading on the wireless channels, can be estimated based on a priori knowledge of the transmitted signals. By estimating channel gains, it can also detect the presence of ongoing traffic within the primary system and analyse it. The output of the Cognitive Sensing Engine is the Channel State Information (CSI) and the Key Performance Indicator (KPI) that indicates the level of surrounding Wi-Fi activity. The Beamforming Engine is fed by the Cognitive Sensing Engine with the channel gain information and a KPI of the primary user traffic. KPI indicates whether there is ongoing traffic within the primary

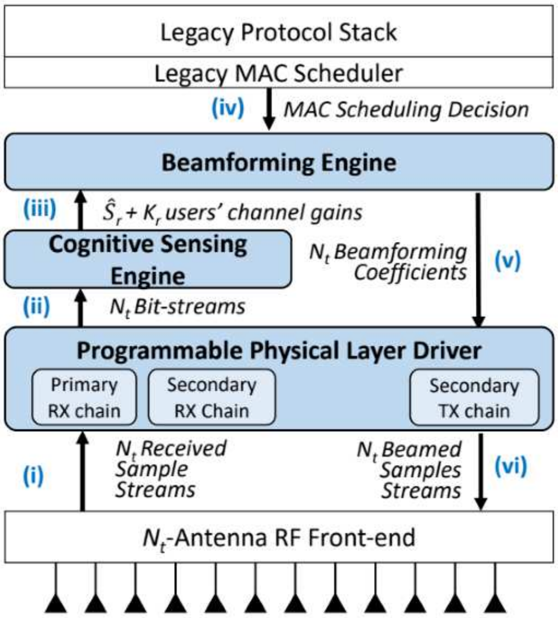


Figure 3.14: CoBeam architecture design overview [49].

system, evaluates its impact on the secondary transmitter where CoBeam is deployed and the interference from secondary transmissions to primary users. Based on these inputs, the Beamforming Engine selects the most appropriate beamforming technique. It may choose Maximum Ratio Transmission (MRT), which maximises the use of the spectrum in favour of the secondary system and is therefore preferred when Wi-Fi traffic loads are low. Alternatively, it can choose Zero-Forcing (ZF) beamforming, which minimises interference to the primary system by nullifying received power at primary users. This approach is preferred in situations with intense primary user channel activity. Subsequently, taking into account the secondary user selection performed by the MAC scheduler, the beamforming engine constructs optimal beamforming coefficient vectors, denoted as $\mathbf{W}_s$ in Figure 3.13. These coefficients are then passed to the Physical Layer Driver, which uses them to precode the user data bit streams in each of the N secondary system transmit chains before modulation. Figure 3.15 illustrates the throughput of the secondary system (LTE) and the corresponding interference to the primary system (Wi-Fi) in a small-scale topology scenario. The setup includes five LTE users (four transmitters and one receiver) and two Wi-Fi users (one AP and one STA). The analysis considers four different beamforming schemes: (a) TX-1Ant (single-antenna omnidirectional), (b) ZF-2Ant (Zero-Forcing Beamforming with two antennas), (c) ZF-4Ant (Zero-Forcing Beamforming with four antennas), and (d) MRT-4Ant (Maximum Ratio Transmission Beamforming with four antennas). The results indicate that the use of beamforming techniques reduces interference levels compared to single-antenna omnidirectional transmissions. As can be seen, ZF-based beamforming achieves the best balance between throughput of the interfering system and interference to the primary system. The experiment confirmed that the effectiveness of a precoding scheme also depends on the DOFs determined by the ratio between the number of antenna elements at the secondary transmitter and the total number of users involved in the construction of the precoder, i.e., the intended secondary receivers plus the number of primary users. In ZF-4Ant, a higher ratio improves the beamforming efficiency. In addition, experiments with different topologies and secondary receiver locations showed an average throughput gain of 169% for coexisting Wi-Fi/LTE networks compared to single omnidirectional antennas, with guaranteed fairness across technologies.

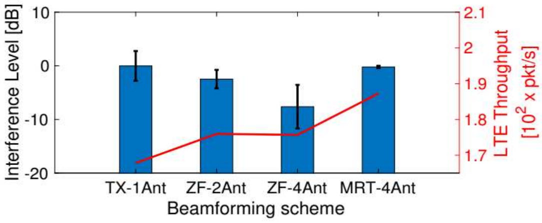


Figure 3.15: Throughput of LTE (curve) and corresponding caused interference levels (bars) in Scenario 1 for different beamforming schemes [49].

3.4 6 GHz band: Wi-Fi 6E and 5G NR-U Coexistence

Various aspects related to the coexistence of Wi-Fi and NR-U in the 6 GHz bands are currently under study, including MAC protocols, channel contention parameters, duration of unlicensed transmissions, and detection mechanisms [4]. In order to achieve a fair coexistence and maintain the benefits brought by OFDMA, the MAC access scheme used by both technologies is OFDMA over a Category 4 LBT-based contention. For DL transmissions, the NR-U Next-Generation Node B (gNB) and the Wi-Fi 6E AP contend for channel access and win a TXOP for the entire frame exchange. Then, they transmit packets to the designated UEs/WLAN Stations (STAs) on specific RUs. For UL transmissions, the NR-U gNB/Wi-Fi 6E AP will first contend for the channel, then schedule a certain number of RUs to specific UEs/STAs.

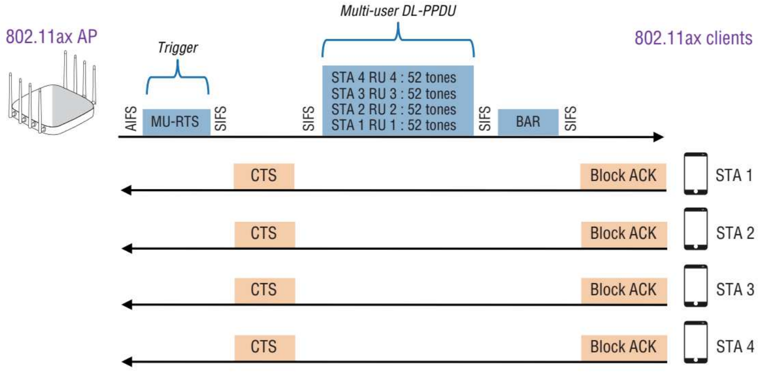


Figure 3.16: Downlink OFDMA between 802.11ax AP and 802.11ax clients [43].

As for Wi-Fi 6E, both DL and UL are started by the AP sending a Trigger Frame (TF), after winning of the TXOP. In the downlink, the TF is used to allocate the RUs to each STA and to synchronise the UL Clear To Send (CTS) client responses. CTS is part of the Request To Send (RTS)/CTS mechanism, which is used to manage the contention process and reduce collisions. After receiving the TF and waiting a period called the Short Interframe Space (SIFR), if the STA is ready to receive the data and the channel is clear, it responds with a CTS frame. After waiting an amount of time equal to the SIFR, the AP starts a multi-user Downlink Protocol Data Unit (DL-PPDU) transmission. Then, the AP will send a Block ACK Request (BAR) frame followed by the clients replying with Block ACKs in parallel. Acknowledgements are needed by the AP to check the successful reception of the packets [43]. In the uplink, after winning the TXOP, the AP sends first a Buffer Status Report Poll (BSRP) to solicit Buffer Status Report (BSR) from the clients. These inform the AP about the client's buffered data and the QoS category of data. After receiving the BSR and waiting for a SIFR, the AP will send a MU-RTS frame to allocate the RUs and to synchronise client transmissions. The 802.11ax clients will send a CTS frame. Finally, a third basic trigger frame informs the clients to begin their parallel uplink transmissions. Each STA performs a channel sensing without exponential back-off before transmitting, i.e., it waits for a SIFR, since the channel availability may be different at the STA [50]. Once the uplink data is received from the clients, the AP will send a single multi-user Block ACK. The signal strength received at the AP from different STAs may fluctuate, and interference from nearby RUs can hinder the reception of signals from distant STAs. To solve this problem, the 802.11ax standard mandated UL transmit power control for users employing OFDMA. This measure is implemented to guarantee that signal strength differences are minimised, thereby enhancing the successful reception of packets across all RUs [41]. The basic trigger frame also contains power control information so that individual clients can increase or decrease their transmit power [43].

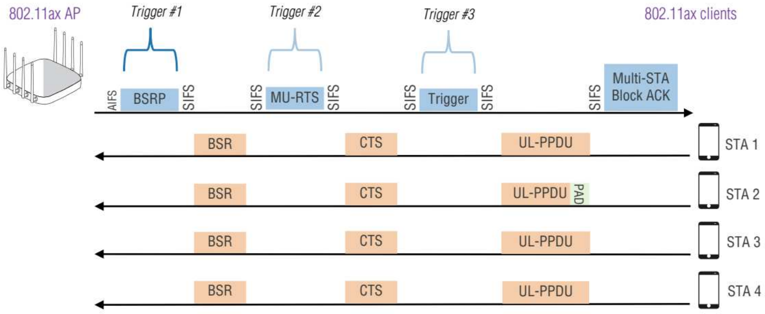


Figure 3.17: Uplink OFDMA between 802.11ax clients and 802.11ax AP [43].

Concerning NR-U, the UL process is similar to Wi-Fi 6E. The gNB sends the resource allocation information for the UL transmissions through the Physical Downlink Control Channel (PDCCH), which is the DL logical control channel in 5G, while the Physical Downlink Shared Channel (PDSCH) is the logical channel for data transmissions. The assigned UEs transmit after sensing the medium using Category 2 LBT. NR-U implements transmit power control, too [50]. Figure 3.18

represents uplink MU OFDMA transmissions in Wi-Fi 6E and NR-U. The image also represents a SU transmission for Wi-Fi, which is the channel access mode based on the legacy contention mechanism.

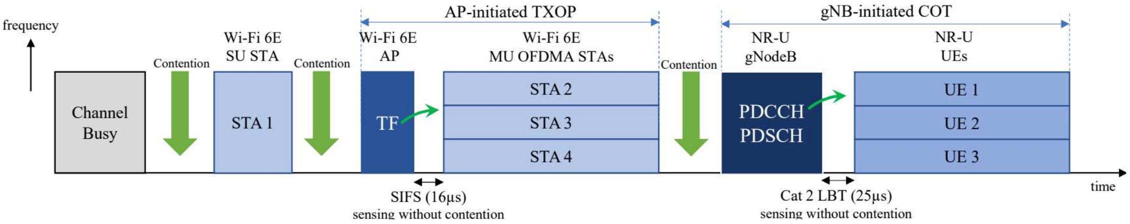


Figure 3.18: SU and MU OFDMA transmissions in Wi-Fi 6E and NR-U transmissions. Packet ACKs are not shown. [50].

3.4.1 Channel Access Parameters

The effectiveness of each RAT depends on the specific MAC protocols used and their associated parameters, which need to be defined to facilitate the coexistence and optimal performance of devices in shared environments. In MU-OFDMA over LBT-based contention, the device must wait when the channel is occupied, while when the channel is idle the devices initiate the exponential backoff phase to compete for access. The contention parameters include the fixed wait time following channel idle status (Interframe Spacing (IFS) or defer time), and the contention window. These parameters depend on the packet priority, determined by the QoS of the application generating the packets. Both NR-U and Wi-Fi categorise packets into four classes: voice, video, best-effort and background, in decreasing order of priority. After gaining channel access, devices can transmit uninterruptedly for a defined period, the COT or TXOP. This duration depends on the access category of the packets. It is essential for an equitable coexistence that the packet classification and the values of the parameters are consistent across technologies [4].

Arguably, the most influential factor impacting the coexistence performance of NR-U and Wi-Fi 6E lies in the selection of the method for devices to detect each other and the corresponding detection threshold. These two parameters are linked since the chosen detection threshold has implications on which mechanism is eventually chosen by the RATs to detect each other. Two possible mechanisms exist for the detection of wireless signals in the air: 1) Energy Detection (ED) 2) Preamble Detection (PD). In ED the detector compares the measured energy in the channel with a threshold value to decide whether the channel is available. In PD devices need to monitor the presence of preambles in the channel. Preambles are a specific set of signals transmitted at the beginning of a data transmission [43]. If the chosen detection threshold is set too low (e.g., -82 dBm), the only viable method for Wi-Fi and NR-U devices to detect each other is through PD. At present, there is no consensus on the choice between ED and PD as the detection mechanism for inter-RAT transmissions in the 6 GHz bands. ED proves straightforward to implement in both NR-U and Wi-Fi devices. Moreover, ED is technology-neutral, eliminating the need for NR-U (and potential future RATs) to transmit and decode an arbitrary preamble signal. Conversely, if PD is employed, a suitable common preamble must be selected, considering its accuracy of detection across both technologies, spectral efficiency, and potential effectiveness for new RATs operating in the 6 GHz bands. PD's advantages lie in its ability to infer the duration of the transmission upon decoding the preamble and in the fact that it can reliably be used for threshold values up to -82 dBm, while for values lower than -72 dBm ED is often unreliable. In the 5 GHz bands Wi-Fi utilises a different threshold to detect other Wi-Fi signals (-82 dBm) and non-Wi-Fi signals (-62 dBm). The LTE-LAA design opted for a fixed energy detection threshold of -72 dBm to detect transmissions within and between RATs. This choice was motivated by the fact that Wi-Fi devices were already ubiquitous in the 5 GHz bands and it was impossible to change the detection threshold used by them. However, this choice is no longer justified in the 6 GHz band. The vast majority of contributions to the IEEE Coexistence Standing Committee and ETSI Broadband Radio Access Network (BRAN) have argued for a technology-neutral and common threshold to be used in the 6 GHz bands [41]. Another solution is to use a hybrid approach where a common detection threshold is used across different RATs (i.e., for NR-U to detect Wi-Fi signals and vice versa) and an adjustable threshold can be used by each RAT for intra-RAT detections (e.g. detection of Wi-Fi signals at a Wi-Fi transmitter) to maximise their respective performance through spatial reuse. In this case, it would be possible to use a lower threshold and the PD mechanism for intra-RAT transmissions, and a higher threshold and the ED mechanism for inter-RAT transmissions. In [50] the effect of the chosen detection threshold is studied. Figure 3.19 shows the performance of NR-U and Wi-Fi, assuming that both use the same detection parameters used in the 5 GHz band: to detect inter-RAT transmissions, the threshold for NR-U is set at -72 dBm, while Wi-Fi uses a higher threshold of -62 dBm.

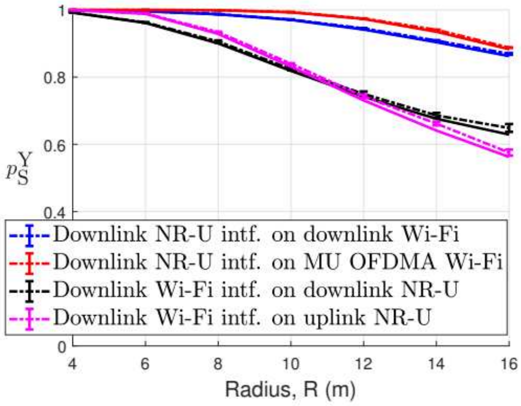


Figure 3.19: Impact of the detection thresholds used in the 5Ghz bands, considering: DL NR-U interfering on DL and UL Wi-Fi 6E, in MU OFDMA mode; DL Wi-Fi interfering on DL and UL NR-U.[50]
p_S^Y = probability that transmission is successful; Radius (m)= the radius R of the circular region where all devices are located.
$\beta_N W$ = -62 dBm = threshold used by Wi-Fi to detect NR-U; $\beta_W N$ = -72 dBm = threshold used by NR-U to detect Wi-Fi.
M_W^T=M_N^T= 3 = number of active Wi-Fi and NR-U users for UL transmissions.

The red and blue lines represent Wi-Fi performance when NR-U is interfering, while the pink and black lines represent NR-U performance in the presence of Wi-Fi interference. As the radius R of the circular region in which all devices are randomly placed increases, the probability of hidden nodes increases, with a negative impact on performance. Hidden nodes are active transmitters on the same channel that are not perceived or are unable to sense ongoing transmissions. Devices belonging to different RATs are considered to be hidden from each other if the strength of the signal received from one RAT is lower than the detection threshold set by the other RAT, which is unable to detect the channel occupation. Because of the difference in the detection thresholds, the performance of NR-U is lower than that of Wi-Fi. Intuitively, a higher detection threshold used by Wi-Fi results in a higher probability of incorrectly detecting the channel as idle, when it is being used by a NR-U device. This reinforces the need to use the same threshold for all coexisting technologies in the 6 GHz bands.

3.4.2 The benefits of MU-OFDMA over LBT-based contention on the coexistence

The impact of MU-OFDMA on coexistence is examined in [50], where the performance of the coexisting RATs with Wi-Fi utilising OFDMA is compared against a scenario in which Wi-Fi employs a contention mechanism based only on CSMA/CA, referred to as SU mode, since a single device accesses the channel, occupying the entire bandwidth. To assess the implications of MU-OFDMA, the success probability of a RAT's transmissions is analysed, considering it was the first to gain channel access. The second RAT that secures access is regarded as a potential interferer to the first RAT. An essential consideration in sensing-based channel access schemes is the existence of hidden nodes. In their presence, the interfering RAT will consider the channel idle and start transmitting, causing collisions that result in loss or corruption of the transmitted data, thus reducing the probability of successful transmission for the first RAT. When all RATs use MU-OFDMA over LBT to access the channel, in the DL the inference can only come from one device (the AP or the gNB) belonging to the interfering RAT.

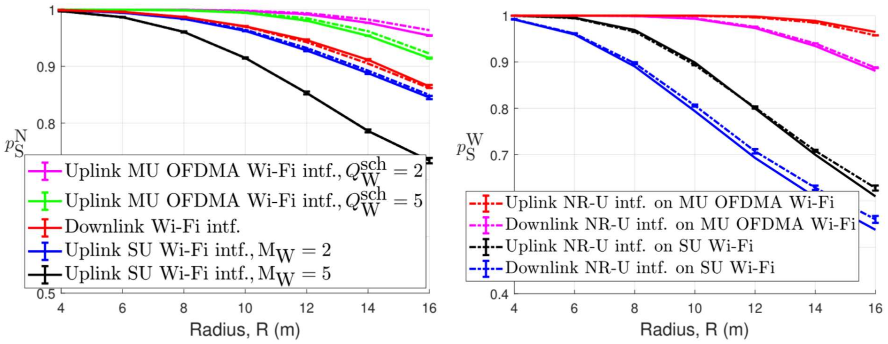


Figure 3.20: Impact of Wi-Fi interference on NR-U DL for the same number of potential interferers (left). Impact of NR-U UL and DL transmissions on Wi-Fi UL, considering the same number of active users in the UL of the two RATs (right): MU OFDMA vs legacy contention (SU mode) Wi-Fi [50].
p_S^N = probability that a NR-U transmission is successful; p_S^W = probability that a Wi-Fi transmission is successful.
Q_W^{sch} = number of scheduled Wi-Fi UL users; M_W = number of Wi-Fi SU STAs;

In UL transmissions, the maximum number of interferers is equal to the number of scheduled devices. In this case, for interference to occur, the AP/gNB must be hidden (thus falsely detecting the channel as idle) as well as the scheduled STAs. The number of interferers is equal to the number of hidden stations. Instead, when Wi-Fi uses the legacy CSMA/CA contention method, STAs do not need to be scheduled by the AP to transmit. As a result, in the UL, any hidden STA can initiate a transmission and act as a potential interferer. Figure 3.20 (left) shows the effect of Wi-Fi interference on the NR-U DL. The pink and green lines represent the performance of NR-U when MU-OFDMA Wi-Fi is transmitting in the UL, with 2 and 5 scheduled devices, respectively. The red line shows the NR-U performance in the presence of DL Wi-Fi transmissions. The blue and black lines show the effect of interference from UL Wi-Fi transmissions using the legacy CSMA/CA contention protocol, with a network of 2 and 5 SU STAs respectively. Compared to the UL SU STAs, the UL MU STAs have a significantly lower impact on the NR-U performance for the same number of potential interferers. This is because Wi-Fi 6E requires channel sensing at both the AP and the STAs, reducing the probability of the channel being incorrectly detected as idle. Figure 3.20 (right) illustrates the impact of NR-U interference on Wi-Fi UL transmissions. The red and pink lines represent the performance of MU-OFDMA Wi-Fi in the presence of UL and DL NR-U transmissions, respectively. While the black and blue lines show the effect of the same UL and DL NR-U transmissions on the performance of SU Wi-Fi. This graph reveals that MU-OFDMA exhibits a higher success probability. This positive effect is observed when the AP schedules more than one station, thereby increasing the number of active transmitters sensing the channel. Consequently, the likelihood that at least one uplink Wi-Fi transmitter falls within the sensing range of NR-U devices rises, leading to a decrease in the probability of Wi-Fi devices being hidden from NR-U devices. Thus, a greater number of scheduled users proves advantageous in enhancing the success probability of UL transmissions.

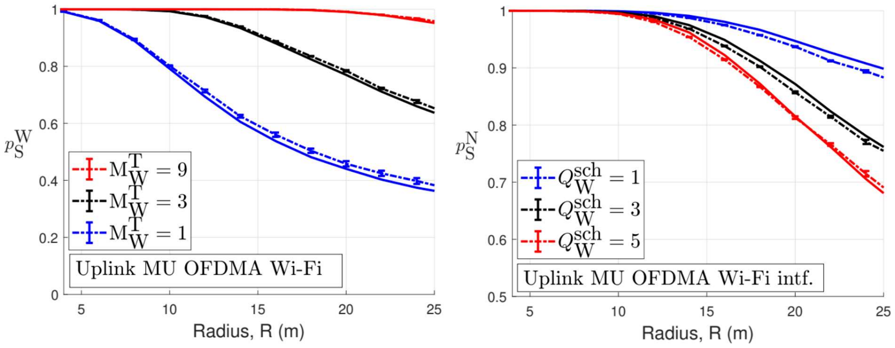


Figure 3.21: Impact of the number of active UL Wi-Fi devices, in the presence of DL NR-U interference (left). Impact of the number of Wi-Fi scheduled devices interfering with DL NR-U transmissions (right) [50].
p_S^N = probability that a NR-U transmission is successful; p_S^W = probability that a Wi-Fi transmission is successful.
Q_W^{sch} = number of Wi-Fi scheduled UL interferers; M_W^T = number of active Wi-Fi transmitters.

However, the entity responsible for scheduling uplink transmissions in both technologies must ensure accurate channel sensing. Incorrectly detecting the channel as idle can compromise the performance of one technology to the benefit of the other. Figure 3.21 (left) shows how the number of active UL Wi-Fi transmitters impacts MU-OFDMA Wi-Fi performance, in the presence of DL NR-U interference. In this case, Wi-Fi is the first RAT to gain access to the channel. As the number of scheduled transmitters increases, the success probability of each transmission increases. Figure 3.21 (right) shows the effect of the number of scheduled Wi-Fi devices when they are interfering with DL NR-U transmissions. These observations also apply to UL NR-U transmissions. As the hidden AP schedules more UL STAs, the resulting impact on DL NR-U worsens.

4

Conclusion and Future Works

4.0.1 Conclusions

The radio spectrum is a fundamental resource for current and future wireless communication systems. The spectrum can be considered a renewable resource, as frequency bands can be reassigned to new technologies by removing obsolete applications. Today, it is also considered a scarce resource because the services and applications that require spectrum allocation greatly outnumber the bands available for radio communications. Therefore, regulators allocate spectrum according to the spectrum-sharing paradigm. In this case, the usability of the spectrum is limited by the fact that more devices in the same or adjacent frequency bands can interfere with each other and affect the functioning of communication systems. This thesis analyses some regulatory and technical instruments used to achieve technological coexistence. Spectrum management has two main pillars: regulation and standardisation. To mitigate harmful interference between services and applications, and to allow fair use of the spectrum resource, proper spectrum management is essential.

In the first chapter, this thesis outlined the spectrum management process in its main steps and the regulatory and standardisation bodies involved in the different phases of this process. Regulators can be broadly categorised at three geographical levels: international, regional and national. In managing the spectrum, they face many trade-offs between social benefits, economic development, innovation and the protection of existing rights. It has been highlighted how international and regional bodies have the main objective of coordinating and facilitating the use of spectrum over larger areas compared to national territories. National authorities may join these organisations, usually by ratifying international treaties. Meanwhile, standardisation bodies support regulation by developing technical specifications that ensure the achievement of policy objectives. This work explained what SRDs are and how they are regulated by the ITU, CEPT and EU in Europe and by the FCCin the US. These devices are exempt from individual licensing and operate on a non-protected, non-interference basis. The regulation of SRDs is important for understanding unlicensed spectrum operations, particularly because SRDs include WAS/RLANs such as Wi-Fi and the more recent LTE-LAA and 5G NR-U, which are the technologies covered in this thesis. Typically, RLAN devices have operated in the 2.4 and 5 GHz bands. However, the current and expected growth in the popularity of this technology, combined with the need for high-throughput, high-reliability and low-latency connectivity capable of supporting QoS-sensitive applications, has led regulators to open up unlicensed operations in the 6 GHz band. The main measures taken by the FCC in the USA and the CEPT and EU in Europe to open up the 6 GHz band are reviewed and compared. This band is already used by other licensed incumbents and is expected to be used by various unlicensed technologies. In order to avoid harmful interference to incumbents and to allow coexistence between different RATs, spectrum-sharing techniques should be implemented. The main issues addressed by regulators relate to the coexistence of WAS/RLANs devices with existing licensed operators through the imposition of technical requirements, such as limiting operation to a certain EIRP or confining devices to indoor environments. Some requirements, such as the implementation of a contention-based protocol, are designed to reduce the channel occupation time of each device, thus allowing fair spectrum access. This is not only to better protect licensees but also to preserve the spectrum resource for unlicensed use. The FCC opened the entire 6 GHz band (5.925-7.125 GHz) in the US, while Europe only opened the lower 5925-6425 GHz band. The reasons behind Europe's choice can be deduced from the decisions taken at the recent ITU WRC-2023, which approved the introduction of IMT-2030 systems in the upper 6 GHz band (6425-7125 GHz) in Region 1, some countries in Region 3 (Cambodia, Lao P.D.R. and the Maldives) and Region 2 (Brazil and Mexico). This IMT allocation is considered fundamental to developing the 3GPP 6G standard. The critical issues associated with this global spectrum fragmentation have been highlighted.

Chapter 2 discusses the technical advances implemented in the *greenfield* 6 GHz band to allow for more efficient spectrum utilisation and to overcome the challenges associated with the coexistence of Wi-Fi and cellular technologies. These technologies present many differences, the most relevant for the subject of this thesis are related to the MAC layer protocols implemented and the system architecture. At the MAC layer, Wi-Fi implements CSMA/CA, based on the LBT concept and interference is managed in a distributed manner, whereas in licensed cellular networks channel access is based on a non-sensing scheme and is centrally managed and coordinated by the BSs. In this thesis, two main approaches to technology coexistence are discussed. One approach exploits spatial diversity and is based on MIMO and transmit beamforming techniques. Two recently proposed schemes based on these techniques are analysed: mMIMO-U and CoBeam. In mMIMO-U, BSs are equipped with large antenna arrays and access the channel through an eLBT protocol based on transmit beamforming techniques. The BS estimates the channel characteristics and places reciprocal radiation nulls towards WLAN interferers. This intelligent interference suppression technique allows channel access and spectrum reuse to be increased. mMIMO-U is not exempt from challenges, which will be analysed. CoBeam is a spectrum-sharing technique designed to achieve spectrally efficient channel coexistence without modifying the protocol stack of the technologies involved. To this end, CoBeam does not require an LBT phase and operates at the lowest physical layer. This technique allows coexistence between technologies with different architectures and medium access technologies in the same frequency bands. A prototype of CoBeam for LTE and Wi-Fi coexistence in unlicensed bands proposed in [49] is discussed. The second approach is to modify cellular standards to allow them to operate in the unlicensed spectrum and coexist with Wi-Fi. The main unlicensed technologies sharing this band are Wi-Fi 6E, based on the IEEE 802.11ax standard, and 5G NR-U. NR-U is the latest unlicensed cellular technology to be developed by 3GPP, after LTE LAA, and the first to operate in this part of the spectrum. This technology relies on dense small-cell networks to provide better indoor coverage. Wi-Fi 6E is the first technology in the IEEE 802.11 family of standards to operate in the 6 GHz spectrum. With NR-U and Wi-Fi 6E, industry stakeholders have focused on techniques that use time/frequency diversity and channel sensing to achieve coexistence in the same geographic area and frequency bands. In the past, due to the dominance of Wi-Fi devices in the 5 GHz band, 3GPP unlicensed standards had to adapt to Wi-Fi standards. The unlicensed 6 GHz spectrum provided an opportunity for both Wi-Fi 6E and NR-U to implement technology-neutral channel access techniques and parameters. A significant improvement in Wi-Fi 6E compared to previous generations of Wi-Fi is the use of OFDMA, a multiple access scheme that allows frequency resources to be partitioned into orthogonal time-frequency RUs that can be allocated by the AP to multiple scheduled users. This contrasts protocols that use only CSMA/CA, where an entire channel is allocated to one device at a time. In this way, OFDMA improves the efficiency of spectrum use. NR-U and Wi-Fi 6E have converged on the use of an LBT-based protocol based on an OFDMA channel access scheme. An important advantage of this hybrid solution is the reduction of the hidden node probability, which leads to a higher transmission success of both RATs compared to a simple CSMA/CA access scheme. Furthermore, this work highlights the importance of the choice of convergent channel access parameters and mechanisms for fair coexistence between unlicensed RATs. In particular, the choice of channel occupancy detection method between ED and PD, and the energy detection threshold used to detect inter-RAT transmissions.

4.0.2 Future Works

There are many challenges and open research questions for spectrum management in the coming year. Apart from the same old major challenges for regulators, such as maximising spectrum efficiency and balancing conflicting stakeholder demands, many open questions arise from the need to improve the spectrum-sharing techniques employed. The spectrum-sharing methods currently used are based on channel sensing techniques or rely on technologies such as databases that allow interference coordination by knowing the deployments of wireless systems and coordinating interference to acceptable levels. The most recent approaches proposed are based on MIMO techniques that exploit spatial diversity. Other solutions involve the restriction of certain operations to indoor areas or geographical separation. However, these methods will not be sufficient as the number of devices continues to grow, especially those accessing bandwidth-intensive services, and as wireless networks become more heterogeneous [51]. These issues will be particularly relevant in the 6G era. The deployment of IMT-2030 systems in the 6 GHz band in Region 1, and partially in Regions 2 and 3, raises issues regarding the introduction of Wi-Fi 6E, Wi-Fi 7, NR-U and future unlicensed standards in this band, which can be addressed by using more sophisticated spectrum sharing techniques. Interference management with a large number of wireless devices whose transmission patterns vary in time and location can be computationally complex. Given this complexity, Artificial Intelligence (AI)-inspired spectrum-sharing algorithms have attracted increasing attention with advances in computing resources. Machine Learning (ML) models allow techniques based on predefined rules to be replaced by more robust and adaptive alternatives. Wireless network traffic data can be used to provide real-time analytics that can be used to train ML models. This can improve network performance by allowing dynamic management of spectrum resources. In [52], an ML-based approach is developed to enable spectrum sharing between LTE-U and Wi-Fi networks. LTE-U adapts its duty cycle depending on the number of Wi-Fi APs detected in the OFF periods. The presence of Wi-Fi APs is inferred from the collected energy level data using an ML algorithm trained on real data. Other issues are related to the time needed to achieve international-level spectrum management compared to the development of radio technology [51].

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