Università degli Studi di Padova

UNIVERSITÀ DEGLI STUDI DI PADOVA

DIPARTIMENTO DI DIRITTO PUBBLICO, INTERNAZIONALE E COMUNITARIO

CORSO DI LAUREA IN DIRITTO E TECNOLOGIA

The evolution of Wi-Fi Networks: A Comprehensive Study of the IEEE 802.11 Standards with a Focus on the Upcoming IEEE 802.11be Version

Relatrice
Francesca Meneghello

Laureanda
Angela Ambrosin

Anno Accademico
2023–2024

A chi da lassù, più di chiunque altro, in questo giorno è orgoglioso di me.
Vorrei essere qui con voi, ma so che il vostro amore mi guida e mi protegge in ogni scelta.
Non vi vedo, ma sono certa che siete qui con me a dirmi “ce l’hai fatta.”
Un pezzettino del mio cuoricino è vostro.

A me stessa
per essere arrivata fino a qui nonostante l’ansia e le mille insicurezze.
Forse un pochino più in me stessa ci credo ora!
Alla me del futuro che penserà di non farcela ancora una volta, dirò di voltarsi indietro e convincerla che può farcela di nuovo proprio come ora.

Abstract

This thesis provides a comprehensive analysis of the evolution of Wi-Fi networks, analyzing the main characteristics of the different versions of the IEEE 802.11 standard. The Wi-Fi technology has become an essential part of our daily lives, and the ongoing development of this wireless technology is crucial to meeting the growing demands for faster speeds, lower latency, and better user experiences in a variety of environments. The first chapter discusses the development of the six major Wi-Fi generations, from the first IEEE 802.11 standard release to the upcoming IEEE 802.11be amendment, describing its key features and advancements. The operations to be performed at both PHY and MAC layers are defined through these standards, evolving ever more to address the future communication challenges and achieving the goal of connecting everyone and everything, everywhere. The second chapter examines the new specifications introduced in the IEEE 802.11be version, also known as Extremely High Throughput (EHT). These enhancements aim to improve device interoperability and connectivity, increase data transmission speeds, reduce latency and maintaining backward compatibility with existing IEEE 802.11 devices. These advancements have a significant impact across both consumer and industrial sectors. Next, the study examines the importance of standard developments and certification process, which help achieve technical excellence, security and fosters innovation. It first focuses on the description of the IEEE standardization process, ensuing its integrity through well-defined principles and procedure follows at each step. Certifications, on the other hand, guarantee the interoperability and security of products and services, allowing the choice of the best certification paths depending on the needs. Finally, the explanation of the benefits of Wi-Fi certified equipments for various stakeholders concludes the thesis.

Contents

Listing of acronyms

A

ACK Acknowledgment

AP Access Point

AR/VR augmented reality/virtual reality

ATL Autorized Test Laboratory

B

BSS Basic Service Set

C

CCK Complementary code Keying

CF end Contention-free end

CRG Comment Resolution Group

CSI channel state information

CSMA/CA Carrier-sense Multiple Access with collision avoidance

CSMA/CD Carrier Sense Multiple Access/Collision Detection

CTS Clear to send

D

DCF Distributed Coordination Function

DIFS DCF Interframe space

DSSS Direct Sequence Spread Spectrum

E

EHT Extremely High Throughput

ESS Extended Service Set

F

FCC Federal Communications Commission

FHSS Frequency Hopping Spread Spectrum

H

HT high throughput

I

IEEE SA IEEE Standards Association

IEEE SASB IEEE Standards Board

IFS Inter-frame space

IoT Internet of Things

ISM Industrial,Scientific and Medical bands

L

LAN Local Area Network

M

MAC Medium Access Control

MCS modulation and coding scheme

MIMO Multiple-input, multiple-output

MLD multi-link device

MLO Multi-Link Operation

mmWave millimetre wave

MPDU MAC protocol data unit

MU PPDU Multi-User Physical Protocol Data Unit

MU-MIMO multi-user downlink

MU-RTS Multi-User Request to Send

N

NAV Network Allocation Vector

NesCom New Standards Committeee

NSPE national security and emergency preparedness

O

OFDM Orthogonal Frequency-Division Multiplexing

P

PAR Project Authorization Request

PC Point Coordinator

PCF Point Coordination Function

PHY Physical Layer

PIFS PCF Interframe Space

PN Pseudorandom Number

Q

QAM Quadrature Amplitude Modulation

QoS Quality of Service

R

RevCom Review Committee

RTS Request to send

RTWT Restricted Target Wake Time

RU Resource Unit

S

SAP single MAC data service access point

SC Standards Committee

SNR Signal-to-noise ratio

SS spatial streams

STA station

STC Space-time coding

STR simultaneous transmit-receive

SU PPDU Single-User Physical Protocol Data Unit

T

TWT target wake time

U

UWB ultra-wideband

W

WG Working group

WLAN Wireless Local Area Network

1
Introduction

Wireless Local Area Networks (WLANs) are a crucial technology that has revolutionized the way we connect to the internet and communicate within localized areas such as homes, offices, colleges and many other places. Access to the global network has become one of the most essential part of our daily lives. The main characteristic of WLAN is that enables to connect devices without the need of physical cables, providing unmatched convenience and flexibility. As a result, the demand for it is increasing everywhere. In modern environments where mobility and connectivity are essential, this technology has become indispensable and is an ever developing field.

1.1 Characteristics of WLANs

The primary difference between wired Local Area Networks (LANs) and WLANs lies in the transmission medium. Wired LANs use cables to connect devices, ensuring stable and direct communication pathways. In contrast, WLANs rely on air as the medium, with signal generally broadcast over the airwaves. This allows users to move freely, within the network's range, using services provided and without losing connectivity.
The main features that characterize WLANs networks are detailed in the following:

- Attenuation: the strength of electromagnetic signals decreases rapidly as they disperse in all directions. Only a small portion of the signal reaches the receiver. This reduction in signal strength can significantly impact the quality and reliability of the connection

- Interference: a receiver may pick up signal not only from the intended sender, but also from unintended sources that are using the same frequency band. This can cause signal degradation and negatively affect network performance, leading to potential disruptions in the communication.

- Multipath Propagation: electromagnetic waves can be reflected back from obstacles such as walls, the ground or objects. As a result, a receiver may collect multiple signals from the same sender, each traveling along different paths and arriving at different times. This phenomenon can make the signal less recognizable and harder to interpret, leading to issues like signal fading and echo.

- Error: due to the characteristics of wireless networks, errors and error detection are critical issues. The Signal-to-noise ratio (SNR) plays a significant role in data integrity. A high SNR indicates a strong signal relative to noise (unwanted signal), making it easier to convert the signal to actual data. Otherwise, when SNR is low, it means that the signal is more affected by noise, causing potential data corruption. Therefore, efficient mechanisms for error detection, correction and retransmission are essential to ensure reliable communication over wireless networks.

- Security: it represents a critical concern, sharing nearly all the security issues of traditional wired networks, along with additional vulnerabilities inherent to their wireless nature. While physical security can be more easily managed in wired networks, wireless networks are inherently vulnerable to unauthorized access due to the broadcast nature of their signals. This makes them less secure and more susceptible to attacks. Since packets often pass through multiple nodes to reach their destination, they can be illicitly copied or redirected during this process. Effective access control mechanisms are essential to mitigate these risks, ensuring secure management of how devices share the wireless medium and addressing issues like hidden nodes and signal fading.

- Easy to install: thanks to the absence of wiring requirement, installation is easier and excel in providing a full mobility and flexibility. It is particularly advantageous in areas where traditional wired networks are difficult or costly to implement. It allows users to connect to the internet from anywhere, within the coverage area.

- Cost-Effectiveness: wireless networks are more economical than laying down extensive wiring required for a traditional wired network. With the use of specialized antennas, signals can be transmitted over several miles, enabling low-cost connections between distant locations. Once wireless access is provided, through an access point for the first user, adding additional users to the network doesn't increase the cost. In places, where the number of users can increase rapidly, it is beneficial. [1].

1.2 Wi-Fi technology

The most well-known and used wireless communications technology is Wi-Fi, acronym for Wireless Fidelity.
It allows electronic devices to seamlessly connect to a network via radio frequencies. Wi-Fi technology is based on the IEEE wireless communication standard 802.11 and has been continually

improved with each generation. In the modern world, access to the wireless connectivity is considered almost as crucial as basic physiological needs. The importance of Wi-Fi in modern life is undeniable: individuals, families, governments and global organizations rely on it every day. In 1943, psychologist Abraham Maslow published a study on the hierarchy of human needs, proposing that before individuals can fully utilize their talents and interests, they must first satisfy four fundamental needs. His theory is commonly represented as a pyramid, with the foundational levels comprising physiological needs, safety, belonging and esteem. In today's context, one might provocatively suggest adding another foundational layer to Maslow's pyramid: Wi-Fi. Figure 1.1 represents the hierarchy of human needs: physiological needs, safety, belonging and esteem. Beyond essential resources like food, shelter, clean water, and electricity, access to wireless connectivity has become fundamental. [2].

Figure 1.1: Maslow's hierarchy of human needs with an additional layer referring to Wi-Fi [3]

Wi-Fi can provide high data rates and reliable indoor connection at a low cost, for this reason it is considered the primary choice for connecting to the internet. Another option is cellular networks, typically considered as a second choice. Researches in next generations of cellular industry predict that as the cellular data rates improve and cellular costs goes down, there may be a shift towards cellular networks due to their ubiquitous availability. However, at present, Wi-Fi remains the fastest and most cost-effective way of wireless technology. Beyond smartphones, numerous others devices, such as home entertainment systems, environmental monitoring sensors and security systems, rely on Wi-Fi for internet connectivity and not necessarily through cellular networks. Wi-Fi is the primary medium for global internet traffic with 21.1 billion of devices in use worldwide and 4.1 billion of annual device shipments. [3].

1.3 The value of Wi-Fi

Wi-Fi is one of the greatest achievements of the technology era, significantly contributing to social and economic growth. The global economic value of Wi-Fi is estimated at more than $3.5 trillion USD, according to a study commissioned by Wi-Fi Alliance. By 2025 that value is expected to grow to nearly $5 trillion [3]. This highlights its role in fostering digital resilience, driving innovation and serving as a key component in global efforts bridging the digital divide. Its flexibility and efficiency have made it indispensable part of modern technological infrastructure, supporting both personal and professional needs. It is continuously evolving to meet growing customer demands and facilitating the use of innovative technologies in different areas such as education, healthcare and industry. The latest advancements, the upcoming generation based on the IEEE 802.11be Extremely High Throughput (EHT) standard, aim to deliver higher data rates, lower latency and enhanced reliability. The Federal Communications Commission (FCC) has recently allocated new spectrum in the 6 GHz band for unlicensed use, which will further extend the capabilities and reach of Wi-Fi networks. This new spectrum is expected to alleviate congestion in existing Wi-Fi bands and provide additional capacity for advanced applications. These developments are set in particular to support the growth of emerging applications such as augmented reality/virtual reality (AR/VR), and the Internet of Things (IoT).

In light of these developments, it's evident that it presents a key technology for addressing future challenges in communication, access to information and brings benefits in multiple dimensions, maintaining quality connections wherever users go.

2

IEEE 802.11 standards

2.1 Introduction

Nowdays, a large number of devices such as laptops, printers, cellular phones take advantage of wireless communication, that has become an essential element of daily life. Those that implement the IEEE 802.11 standard are certified by the Wi-Fi alliance.[1]

The IEEE 802.11 standard represents a pivotal development in the evolution of wireless and it is the leading standard for WLAN.

It defines two types of services that form the building blocks for a WLAN: Basic Service Set (BSS) and the Extended Service Set (ESS).

The BSS consists of stationary or mobile stations and an optional Access Point (AP) that represents the central base station. Can be defined two types of BSSs based on the presence or absence of an AP: ad hoc architecture that is without AP and can't communicate with others BSSs, it is a stand-alone network but they can be located one another and agree to be part of BSS. Instead of, if an AP is present, it is called infrastructure architecture. The ESS consists of two or more BSSs with APs connected through a distribution system which can be wired or wireless network. It use mobile station that are inside a BSS and stationary station that forms part of a wired LAN. Stations within range of each other can communicate directly when BSSs are connected without the need of an AP while to send data between a station in BSS and the outside BSS it is required. The success of this standard is largely attributed to its ability to provide high data rates, adaptability, cost-effectiveness and greater flexibility than cabled network [1].

This makes it an ideal solution for a wide range of applications with an ever-increasing demand.

[1]Wi-Fi Alliance® is a global non-profit association formed in 1999 to promote the adoption and evolution of Wi-Fi technology through leadership, spectrum advocacy and industry collaboration. The aim is to ensure interoperability, security and reliability to users. The association continue to explore the possibilities of emerging technologies delivering a great user experience that is fundamental for the success and the value of Wi-Fi [4].

The broad implementation of the 802.11 standard has led to several amendments to the original specification, required as a consequence of emerging technologies and aimed at addressing technological challenges, integrating functionalities to support future applications: some adjustments have been developed and others are currently under development.

2.2 Protocol layers

The IEEE 802 standards form the foundation of networking technologies and are structured around two key layers: Physical Layer (PHY) and the Medium Access Control (MAC)

2.2.1 The physical layer (PHY)

The PHY is responsible for the actual transmission of data over a communication medium, such as air in wireless networks. It defines the physical characteristics of the medium, including signal types, frequencies and the physical interface. Several transmission methods have been explored for WLANs:

- Frequency Hopping Spread Spectrum (FHSS): this technique transmits signals by rapidly switching ("hopping") the carrier frequency among multiple frequency channels. This method was initially implemented in the unlicensed 2.4 GHz band: the first unlicensed band released by the FCC [2]. Anyone can transmit radio signals in this band without needing to obtain authorization or pay for a license. Instead of transmitting a single signal across the spectrum, the system splits that band into many different possible broadcast frequencies and then transmits data over each of these at regular intervals. In practice, the system "hops" from one frequency to another according to a predetermined sequence. Each frequency is only used for a short and specific period of time before the signal shifts to another one to continue the transmission. This skipping process is controlled by a predefined code, known as the "hopping pattern", shared by both the transmitter and receiver, which dictates the order of the jumps in a pseudo-random manner. [3]. This pseudorandom hopping is determined by a Pseudorandom Number (PN) generator, which produces a sequence of frequencies for the system to use. The FHSS method ensures that the only way to intercept the transmission is to have an identical code that knows the frequency sequence. It is used to enhance security and minimize the impact of interference. Constantly changing frequencies, makes it more difficult for unintended receivers to interact with or jam the communication, as they cannot

[2] The Federal Communications Commission (FCC) is an independent U.S. government agency responsible for regulating interstate and international communications by radio, television, wire, satellite and cable across all U.S. states and territories. Overseen by Congress, it is the United States' primary authority form communications law, regulation and technological innovation. The agency capitalizes on its competencies in for example promoting competition, innovation, investment in communication infrastructure and an efficient use of the radio spectrum for commercial use[5]

[3] These codes are known as "pseudo-random": They are "pseudo" because there is an underlying, but secret pattern. Both the transmitting and receiving radios know the pre-defined code sequence in order to code and decode the information at both ends of the transmission. However, to radios without the code, the signals appear to only be radio frequency noise[6]

easily predict which frequency will be used next just because only sender and receiver know the frequency hopping sequence.
FHSS is used by various devices, including Wi-Fi routers, cordless phones and microwaves, and was fundamental for the implementation and the diffusion of wireless networks. Figure 2.1 represents a frequency hopping sequence across a band ranging from 2.402 GHz to 2.480 GHz, with transmissions occurring during defined intervals labeled ”dwell time” and ”hop time.”

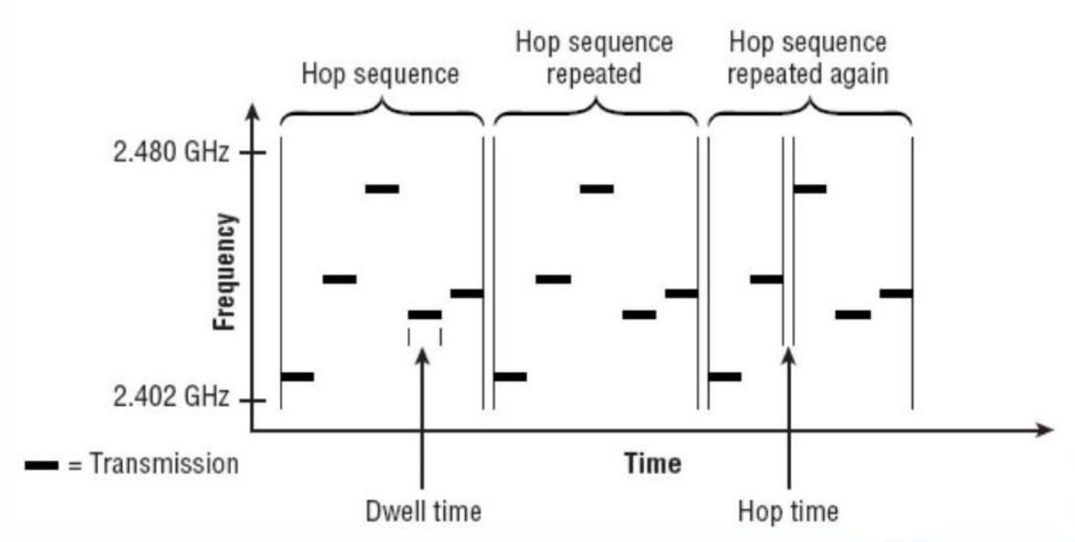

Figure 2.1: FHSS technique [7]

- Direct Sequence Spread Spectrum (DSSS): This is a successful code modulation approach for interference mitigation used in wireless communications, operating in the 2.4 GHz frequency band. The main idea is to spread the energy of the transmitted signal across a wider range of bandwidth. With this method, signal become indiscernible to noise, reducing the possibility of eavesdropping. The original data signal is multiplied with a higher-rate bit sequence known as “chipping sequence” or “PN sequence” which consists of a series of pseudo-random bits. This sequence must be known by the receiver to reinstate the original signal and extract the original data through a correlation process known as “despreading”. The PN code acts like a secret key to encode and decode the data ensuring a secure communication and signal’s clarity. Without this key, the message remains hidden within the noise. DSSS was one of the primary physical layer options and it was favored in many implementations due to its effectiveness in dealing with interference in the crowded 2.4 GHz band, making it suitable for environments with many overlapping networks or devices. This technique is still used in systems such as GPS and vehicles that are radio controlled [8].

- Infrared PHY: Infrared signals can be used as a medium for high-speed, short-range communication in an enclosed area through line of sight propagation. Infrared radiation having high frequencies cannot penetrate through walls or other obstacles so that signal is confines to the room in which it originates, so only in indoor environments. This brings an advantage: no radio frequency interference from nearby systems and improve the security of the communication channel. Looking from another point of view, this characteristic presents a significant drawback because it determines the limitation of the range and flexibility of infrared-based communication. It is not suitable for long-range communication and additionally is vulnerable to environmental factors. It can be affected by ambient light conditions such as sunlight, which can cause noise or disrupt the signal.

2.2.2 The Medium Access Control (MAC)

The MAC layer controls how data is transmitted across the network and performs function related to medium access. It mainly focuses on two sublayers: Distributed Coordination Function (DCF) and Point Coordination Function (PCF).

- DCF sublayer makes use of Carrier-sense Multiple Access with collision avoidance (CSMA/CA), an access method that was invented for wireless networks. It enables the collision avoidance through three mechanisms: inter-frame space, contention window and acknowledgments.
  Inter-frame space (IFS) is a time interval used to avoid collisions. Even when the channel is idle, the station waits for the transmission, it isn't immediate. A distant station may have already started transmission, but not yet detected. This ensure that any signals from remote stations reach the local station. After the IFS period, if the channel remains idle, the station can transmit but it must also has to consider the contention window to determine the exact time to send data.
  The contention window is a period of time divided into slots, used to manage transmission attempts. A station, when is ready to send, selects a random number of slots that represent the time to wait before transmitting. The number of slots increase exponentially if the station can't detect an idle channel repeatedly after the IFS time. After each time slot, the channel is sensed and if it is busy, the timer is stopped and the process restarts when the channel becomes idle.
  Despite all these precautions, data could be destroyed because of a collision or corrupted during the transmission, acknowledgment is used to guarantee the correct receipt of the frames.
  The DCF technique follows a specific procedure:before transmitting a frame, the station listens to the medium to verify if it's idle. The channel uses a strategy based on a back off interval: a short random period of time to wait that the current transmission is complete before sending new data. The collision detection function is not included in the DCF, so it provides a method based on a set of delays to ensure the proper functioning of this algorithm. Due to the wide range of signals on the medium, for a station can be difficult to distinguish an incoming weak signal from noise. For this reason, the station wait for the DCF Inter-frame space (DIFS) and then it sends a control frame called the Request to send (RTS) to

obtain permission to send data. If the device is ready to receive it responds with a Clear to send (CTS) frame. The destination station, after waiting an amount of time equal to the inter-frame space send acknowledgments to communicate that has been received data. This confirmation is required because the station doesn't have the means to check the correct arrival of data. DCF provides also the Network Allocation Vector (NAV). The station, with the transmission of the RTS, specifies also how much time it needs to occupy the channel. NAV is like a timer that indicates the amount of time that must pass before other stations can check the channel to verify the inactivity. [1]

- PCF: It is an optional access method implemented on top of the DCF and is typically used for time-sensitive transmission. It is based on a central entity called Point Coordinator (PC), which corresponds to the Access Point. The AP makes polling [4] for stations that are capable of being polled: the access point asks each device, one by one, if they have data to send. When a device is "polled", it send its data to the AP. In order to give priority to PCF over DCF, it was created PCF Interframe Space (PIFS), a shorter waiting time than DIFS. As a result, if a station using DCF and an AP using PCF both want to send data at the same time, the second one will go first. Because of the priority of DCF, stations that use only DCF may not gain access to the medium. A solution to balance this can be a repetition interval which repeats continuously and starts with a beacon frame (special control frame). When stations hear the beacon frame, they set their timers NAV for the duration of the PCF period. During the repetition interval, the PC can carry out various tasks like receiving data from a station or sending an Acknowledgment (ACK). When the PCF period ends, the PCsend a Contention-free end (CF end) frame to inform others stations that now are free to use the medium.

2.3 Evolution of WLAN

We can separate the origins and evolution of WLANs into three eras: before 1985, when the first revolutionary technologies for WLANs were developed, the period from 1985 to 1997, when the IEEE 802.11 standard was established and the last from 1997 to the present with the introduction and improvement of new technologies.

2.3.1 Before 1985

In the 1980s, IBM's laboratory in Zurich began research on developing WLANs thanks to infrared technology, particularly for spaces where the implementation was more difficult due to the need for wires. The WLAN technology has established itself as a viable alternative to the wired technologies that were widely used at that time. In the same period, the laboratory HP of Palo Alto reported a

[4] polling works with topologies in which one device is designated as a primary station and the other devices are secondary stations. All data exchanges must be made through the primary device, even when the ultimate destination is a secondary device. The primary device controls the link; the secondary devices follow its instructions. It is up to the primary device to determine which device is allowed to use the channel at a given time. The primary device, therefore, is always the initiator of a session.[1]

prototype WLAN based on the DSSS approach, also with the aim of resolving wiring issues. Before all this, Norman Abramson [5] at University of Hawaii has designed ALOHA, the first academic experiment in wireless network. Early WLAN technologies required indoor antennas, whereas ALOHA's system was based on packet data networks using an antenna deployed outdoors. To make early WLANs marketable, it was necessary to overcome interferences and discover a wide-band spectrum with a low cost. In the 1985, Michael Marcus released the unlicensed Industrial,Scientific and Medical bands (ISM) bands. These bands had restrictions due to the use of spread spectrum [6] technology for interference control. The ISM band and spread spectrum technology have been fundamental in addressing issues of early technologies like overcome the challenges of indoor RF propagation and making WLANs feasible for commercial use.

2.3.2 Between 1985-1997

The release of the ISM bands by the FCC has captured the attention of some companies focused on developing WLANs using spread spectrum and infrared technologies. Although most of the companies were located in North America, there were others crucial agencies elsewhere. A small group in Netherlands developed the first DSSS technology to achieve 2 Mbps, others companies made use of FHSS method and additional ones resorted to an IR solution for WLANs. These three groups laid the foundation for the first legacy IEEE 802.11 standards series finalized in 1997. Academic research during this period were focused on multi-path radio propagation, in particular in indoor areas, with the aim to achieve data rates beyond 2 Mbps. Additionally efforts to integrate voice and data transmission in WLANs. At the beginning, it was considered to adapt existing standards for wired networks such as IEEE 802.3 (Ethernet), as first candidate, and then 802.4. However, shortly after turned out that the radio medium differs significantly from wired connections. Radio waves are strongly attenuated ever over short distances and so signal collisions cannot be detected as in cables. Consequently, while Ethernet uses the Carrier Sense Multiple Access/Collision Detection (CSMA/CD) method, which allow detecting collisions and delays data transmission, this approach is not applicable in wireless networks. The next standard considered was the 802.4 based on the token bus concept. Initially appeared more suitable than the 802.3 in fact the group for WLAN standardization was first formed as IEEE 802.4L in 1988. This group was part of the larger IEEE 802.4 group, which was originally dedicated to Token bus-based LANs used in manufacturing environments. In particular in this method a token controls access to the physical medium and the station that holds it has a momentary control over the medium. The

[5] Norman Abramson, University of Hawai i at Mānoa professor emeritus of electrical engineering and one of the founders of the pioneering ALOHAnet system, died December 1, 2020, at the age of 88. Abramson came to UH Mānoa's College of Engineering as a faculty member in 1966, and served as a professor of electrical engineering and professor and chair of the Information and Computer Sciences Department, until his retirement in 1996. Prior to joining UH, Abramson earned degrees from Harvard UCLA and Stanford, and served a faculty member at Stanford and as a visiting professor at Harvard, UC Berkeley and MIT. [9]

[6] "Spread spectrum is a means of transmission in which the signal occupies a bandwidth in excess of the minimum necessary to send the information; the band spread is accomplished by means of a code which is independent of the data, and a synchronized reception with the code at the receiver is used for dispreading and subsequent data recovery"[10]

token is passed from station to station forming a logical ring. The main operation consists of data transfer phase and token transfer phase. All the stations in the network deal with ring initialization, token recovery and general maintenance. The idea of introducing WLANs in this group was based on the idea of leverage an existing structure. New IEEE standards usually start with a closely related standard and after passing the set-up procedure, they can form their own group and series of standards. In 1991 was formed the IEEE 802.11 group specifically focused on WLANs networks with the purpose of finding the correct direction for the future technologies among the many available solutions. We can therefore say that during this period the WLAN industry was in process of discovering different technologies including examine spread spectrum, infrared (IR) and methods to mitigate multipath effects to achieve higher data rates. Among these, only the spread spectrum and infrared technologies survived in the market. [2]

2.3.3 After 1997

The IEEE 802 standards define the MAC and PHY layer specifications for local networks, establishing the rules and technical requirements for how devices can communicate and work together correctly within the same network. The first specification for WLANs was published under 802.11 working group in 1997. At the beginning it defined only the data rate of 1 or 2 Mb/s operated at 2.4 GHz band based on FHSS, IR or DSSS. Then it has been decided to expand the standard into two groups operating at the 2.4 GHz and 5 GHz band, which are defined as 802.11b and 802.11a. Further amendments were introduced in 1999: Complementary code Keying (CCK) was implemented in 802.11b to support up to 11 Mb/s and in 802.11a was applied the Orthogonal Frequency-Division Multiplexing (OFDM) to support up to 54 Mb/s data rate.[2] The 802.11b standard operated in the ISM frequency using a DSSS technology and allowing a speed of up to 11 Megabits per second. In the early 2000s, it was expected that different systems would be used depending on applications with lower or higher data rates. However due to the high cost of radio frequency implementation, the WLAN market based on 5 GHz band was not fully exploited but the request of higher data rates with respect to 802.11b at the 2.4 GHz continued to grow.
In the 2002, as a result, the 802.11g task group, with the aim to support the data rate up to 54 Mb/s, adopted the same PHY and MAC specification of 802.11a. It has combined the 802.11b 2.4 GHz band with OFDM technologies expanding the horizon of Wi-Fi market. The next step was the 802.11n task group due to the widely use of internet browsing and multimedia. The objective was to work on a new improvement to increase the transmission rate so high throughput (HT) and overcome noise problem. The main new feature is the introduction of Multiple-input, multiple-output (MIMO) allowing multiple data streams to reach raw data rates of up to 600 Mbps in both 2.4 and 5.2 GHz bands. This significant progress in wireless communications was marked by the introduction of multi-antenna streaming that take advantage of Space-time coding (STC) and MIMO technology. The adaptive antenna arrays that can be intelligently directed to receiving devices allow to focus the transmission beam more precisely and the STC is a coding technique that enabling separation of different data streams transmitted simultaneously with coding. [2]. This standard has solved some of the interference problems and improved network coverage and

capacity. Other standards 802.11ac and 802.11ax followed the same OFDM/MIMO technology in order to achieving higher throughput. The 802.11ac has made progress in the development of MIMO technique. The study group has adopted a more advanced version called multi-user downlink (MU-MIMO) , which allows an access point to communicate with several devices simultaneously. This allowed the use of up to 160 MHz, bringing network speeds over 1 Gb/s [11]. An innovative wireless communications technology in the physical layer is the millimetre wave (mmWave) pulse transmission technology. It has been adopted by the IEEE 802.11ad group, enabling data transmission at very high speeds thanks to wide bandwidths. Operating in the 60GHz bands with ultra-wideband (UWB) transmission higher than 2 GHz, it allows to achieve data rates on the order of Gbps. This technology present limitation in indoor areas due to the difficulty of penetrating walls or other obstacles so although it has become an important feature in the cellular networking industries, standards using these technologies have not been successful in the WLAN market. [2]. We then proceed with the next major generation of wifi technology, the IEEE 802.11ax. The previous versions were mainly based on the increasing of throughput of data transmission of a station measured at an MAC data service access point, but this version has a different approach. Instead of focusing only on the maximum speed of a single device, it takes into consideration the improving the spectrum efficiency and system throughput per area, particularly in scenarios with high device density such as public spaces and public transports. It aims to improve the overall performance both indoor and outdoor deployments. The main objective of the task group was to improve the average throughput of each station by at least four times compared to previous standards. This growth must be obtained in dense deployment scenarios, and the standard needs to maintain or improve the power efficiency per station operating between 1 and 6 GHz frequency bands. Another important aspect is that IEEE 802.11ax standard must be compatible with the devices based on the previous standards and allow them to operate in the same frequency band without causing interferences. In Wi-fi networks are always present many sources of interference and due to the large number of connected devices, access point are often overloaded. The OFDM technology was present with the aim of extending the transmission range and reducing the system overhead in order to improve the network efficiency. Spatial reuse is proposed as a method to increase the system capacity and enhance medium reuse, allowing a more efficient use of the radio spectrum. The ever-growing and continuous spread of devices that use WI-FI has led to increasing the requirements of wireless data services in many areas, including homes, offices and hotspots, exceeding the capabilities of the previous standard. The emerging applications currently under development need to meet high-throughput and low-latency requirements, examples include virtual reality and gaming. Another aspect to consider is the reliability, which is becoming increasingly crucial in the digital industry. We need it to ensure the correct and timely delivery of data packets, in order to replace wired communications with wireless ones. With these requirements of high throughput, low latency and high reliability, consumers will demand further improved Wi-Fi [12]

The IEEE 802.11be standard is the candidate to meet these features required for future applications. In contrast to IEEE 802.11ax based on the improving of spectrum efficiency, this is focused on bandwidths operations, it tries to enhance the throughput and reduce latency due to the regulations that limit the bandwidth available for Wi-Fi.

3

IEEE 802.11be

Wi-Fi technology is constantly evolving to meet the ever-growing customer demands resulting from the digitalization of everything in our homes, offices and public spaces. These emerging requirements are becoming very stringent, therefore the implementation of a new standard amendment is required. As a result of the diffusion of new applications, Wi-fi networks now require capabilities that go beyond those of the IEEE 802.11ax standard, despite the significant improvements in capacity, efficiency and coverage it has led, to enable a better network performance, particularly in high-density scenarios.

The next generation Wi-Fi, based on IEEE 802.11be EHT, introduces new features and enhancements that improve device interoperability and connectivity, and enable better Wi-Fi performance across a variety of environments. With the emergence of 4k/8k video, AR/VR, gaming and industrial internet of things, the high throughput and low latency requirements have made consistent connectivity essential.

The IEEE 802.11be defines new PHY and MAC operations that will operate in 2.4 GHz, 5 GHz and 6 GHz bands, ensuring operating mode of supporting a maximum throughput of at least 30 Gb/s, backward compatibility and coexistence with pre-existing IEEE 802.11 devices [13].

Advanced features that will be introduced include: 320 MHz channel bandwidth, Multi - RU assignment, providing efficient preamble formats and puncturing mechanisms, Multi-Link Operation (MLO), MIMO enhancement and increased spatial streams, 4K Quadrature Amplitude Modulation (QAM), 512 Compressed block ack and Quality of Service (QoS) management. These advancements are described in detail in the remainder of the chapter. Key applications for IEEE 802.11be are summarized in the last part of the chapter.

3.1 PHY Enhancements for EHT

3.1.1 320 MHz channel bandwidth

The aim is providing expanded bandwidth for more than 160 MHz because, due to the limited and crowded unlicensed spectrum in 2.4 GHz and 5 GHz, the existing Wi-Fi standards with the new developed applications suffer from the low QoS. Over this unlicensed spectrum, the requirements of high-throughput and low-latency services demanded by 4k/8k video, AR/VR and online gaming, aren't satisfy.
To achieve the objective of a maximum throughput of at least 30 Gbps, EHT introduces new bandwidth modes, including: contiguous 240 MHz, non-contiguous 160+80 MHz, contiguous 320 MHz and non-contiguous 160+160 MHz. In order to enhance performance, it is necessary to improve the spectrum utilization of wideband and non-contiguos bandwidth [13].
A key component in this standard is the adoption of the 6GHz band that enables increases the available bandwidth and helps achieve the target of EHT. This band offers up to 1.2 GHz of unlicensed spectrum, more than doubling the bandwidth available in the 5GHz and delivers two times higher throughput. Superwide channels enable multigigabit Wi-Fi device speeds in countries that have opened to this band for unlicensed use [14]. This expansion can lead to new opportunities for networking approaches such as reducing the time spent on channel contention by always scheduling uplink transmissions in the 6 GHz. This allows to decrease time lost in channel access conflicts and improves the overall efficiency of the network. In addition, in cases where is needed access priority, IEEE 802.11be devices have the availability to request 802.11ax devices to free up the band, enabling more coordinated and controlled access.

3.1.2 Multi - RU assignment

A Resource Unit (RU) is a set of subcarriers designed for data transmission.
In IEEE 802.11ax, each user is only assigned to a specific RU for transmitting or receiving frames, which significantly limits the flexibility of the spectrum resource scheduling. Assigning only one RU can lead to a low spectral efficiency when there are few users and it also fails to exploit the frequency diversity, which is fundamental for the simultaneous use of multiple frequencies to improve the overall performance [15]. In order to solve this problem and consequently enhance the spectral efficiency, the initiative is to authorize multi-RU assignment to a single user. When transmitting data over multiple RUs can be applied the same or different transmission parameters, such as modulation and coding schemes (MCSs), Interleaving schemes and the number of space-time stream to combined RUs assigned to a user.
There are four different approaches to transmit data: All RUs are encoded and interleaved independently so each is treats as a distinct unit, Multiple RUs are encoded together, but each RU is interleaved independently, interleaving is applied to multiple RUs, regardless of encoding, Multiple RUs acts as one logical or continuous RU [13].
These approaches require analysis and evaluation, particularly considering the signaling overhead.

3.1.3 Providing efficient preamble formats and puncturing mechanisms

In each generation of WLAN standards have been introduced different preamble formats to improve performance, speed and resource management of wireless networks, meeting the requirements of new features. These enable functions like channel estimation, time/frequency correction and necessary signaling, including the resource allocation information. The preamble should be efficient and small but being able to support a wide range of new and existing features [16]. The EHT preamble design aims to ensure backward compatibility and coexistence with pre-existing IEEE 802.11 devices, and improve the efficiency with the introduction of new technologies. Unlike previous standard's preamble, it is recommended to reuse existing functions. This approach avoids duplication of functionality, improving compatibility with proven technologies. It includes new features like multi-RU and MIMO enhancements so the formats must support these features. In IEEE 802.11ax has been introduced a technique called "preamble puncturing" to improve the efficiency. This allows the transmission of Multi-User Physical Protocol Data Unit (MU PPDU) without devoting the entire bandwidth to the transmission of the preamble. The available band is used except for the punctured preamble part. The Single-User Physical Protocol Data Unit (SU PPDU) cannot use the preamble pucturing so must be transmitted over the entire available bandwidth. The EHT is focuses on enhancing these techniques in order to ensure that new technologies can be effectively supported [13].

3.2 MAC Enhancements for EHT

3.2.1 Multi-Link Operations

In previous Wi-Fi standards, devices communicated on one link at one frequency band at a time, despite lots of them supported operation across multiple bands. These links operate independently, without any coordination, involving a limitation of the system efficiency.
With the introduction of this innovating technique, devices are allowed to transmit and receive data over multiple frequency band or channels simultaneously. This brings advantages such as increased the overall throughput, reduced delays for time-sensitive applications and latency. Allows to effectively distributing data traffic, ensuring the transmission flexibility and success [17].

Multi-link framework

In the IEEE802.11be standard has been introduced the concept of multi-link device (MLD).
It is a device that has more than one station (STA) connected to it and has a single MAC data service access point (SAP) to logical link control, which includes one MAC data service [15].
There are two types of MLDs:

- AP MLD: each STA affiliated to the MLD is an AP
- NON AP-MLD: each STA affiliated to the MLD is non-AP STA

An MLD device with only a single-radio can supports multi-link operations, despite it can only transmit or receive data on one link at a time [15]

Multi-link discovery

Multi-link discovery is based on the process where a non-AP MLD discovers and requests information from the AP MLD to determine whether to associate with it based on the necessary requirements. The current discovery methods provided by IEEE 802.11 are passive and active scanning. In passive scanning, a STA listens on each channel and passively waits for beacons or unsolicited Probe Response transmitted periodically by the APs located on that channel to collect informations. In active discovery, a STA sends a Probe Request to the AP and expects a Probe Response from it.
In a multi-link network, these techniques require lots of time to repeat the scanning multiple times given that each non-AP MLD can always perform scanning in each channel separately and received the necessary informations. In order to simplify the discovery process, facilitating a non-AP MLD to find an AP and obtain informations, the IEEE 802.11be introduced several mechanisms. To avoid beacon bloating, each AP affiliated with an AP MLD includes only basic informations in the beacon and broadcast Probe Response, such as channel, operating class, to provide them to other APs that are part of the same AP MLD. Therefore, it doesn't include detailed information like capabilities or operational parameters. In the case where a non-AP MLD wants to achieve complete information of an AP MLD, it can send ML Probe Request frame, a special request frame, obtaining full information corresponding to all links that the AP MLD supports in one link. This allows to decrease the number of necessary and required scanning. [15].

Multi link set-up

The next step after the multi-link discovery is the set-up that performs association and authentication. In MLD scenarios with multiple links, EHT introduces the multi-link set up that is executed over one link, but enables capabilities exchange and setup procedures for multiple links, improving the overall performance. This enhancement was necessary because the existing process is not sufficient, it allows only setting up one link where association is done. Existing association Request and Response frames are reused for multi-link set up, managing the connection between devices and APs. New element is added containing both MLD-level information common to all STAslike the MLD MAC address and one or more STA sub-elements describing details information of a corresponding STA operating in one link. [15].

Multi-link channel access

In current Wi-Fi standards, channel access mechanism are defined only for a single link operating at 20/40/80/160 MHz channel. However, with the IEEE 802.11 enhancements, must be adapted for multi-link operations with wider channel, up to 320 MHz across 2.4 GHz, 5 GHz and 6 GHz bands. When performing MLO, we classify two categories of channel access methods: Channel access based on one primary channel that determines less flexibility in channel selection and usage

for multi-link, in particular in dense deployment scenarios. Significantly degrading system performance and increasing collisions, reducing access opportunities on the primary channel. Differently, in channel access based on multiple primary channels, a primary channel can be temporarily set on the secondary channels to increase the channel use opportunities when the primary channel is unavailable due to congestion [13].
Another aspect to take into account about the channel access schemes is the synchronous or asynchronous type of multi-link and connected to this is the division into simultaneous transmit-receive (STR) and non-STR multi-links. When STR modality is enabled, MLD can receive on one link and simultaneously transmitting on the other, however this is not possible when non-STR is active. It can receive and transmit over all links but not at the same time. The negative aspect of the STR feature is that can cause interference because of leak of energy and impacting reception on nearby links. A solution can be lowering transmission power and adjusting the spectral distance between channels. Dealing with unsynchronized multi-link transmission, is not necessary make changes on the existing mechanisms because each link has independent channel access.This enables an high spectrum utilization but may involve delays, failed reception and power leakage. Synchronized transmission doesn't present QoSissues but it has to transmit frames on multiple links with aligned transmission starting time [13].

Multi-link transmission

Multi-link transmission Implementing MLO presents new features that enhance the efficiency of wireless network. In addition to increasing network capacity, fast switching between multiple links, helps to reduce interference between neighboring nodes.The wider the transmission bandwidth, the higher the adjacent channel interference, lowering spectrum efficiency. This function, although already exists in the IEEE 802.11 specification, has been optimized by MLO allowing a more efficient implementation. It helps to have a better load balancing, improving QoS. In order to reach an high spectrum utilization, devices need to efficiently select channels. Specific categories of traffic can be directed to another idle and high quality link, enabling a successful traffic transfer. For instance, depending on the traffic types, STA can transmit high-throughput and low latency service over one link (such as 5/6 GHz) and delay-no sensitive services over another link (such as 2.4 GHz) [16].

Power saving

The transmission over multiple links increases power consumption of devices. The idea is to introduce an extremely low-power multi-link operation that can be fixed and changed dynamically, replacing the independent power-saving option. When the link is not active, the power-saving mode is deployed and MLO efficiency is maximized. AP MLD requires an enhancement of the power management. Thanks to machine and deep learning models, it can be expected user requirements and activities, and channel conditions, allowing an adjustment of the transmitted power and consumption. In the case of non-AP MLDs, in order to have a fast and efficient change of power state, has been introduced a new switch frame to enter or exit from extremely low-power mode [16].

3.2.2 MIMO enhancements and increased spatial streams

In order to meet the growing traffic demands caused by the ever-growing number of Wi-Fi devices, APs have continued to improve the spatial multiplexing capabilities and increase the number of antennas. Continuing the upgrade in the number of spatial streams (SS) can be reached an higher network capacity. The transition from 8 antennas, as in IEEE 802.11ax, allowing to simultaneously serve up to 8 user for up-link and down-link transmission, to 16 antennas in the EHT standard, theoretically doubles the transmission data rate [13].
MIMO deployment is based on the collection and analysis of channel state information (CSI) parameters that allows to properly tune and route radio waves. There are two methods used to acquire CSI parameters: Implicit sounding is based on channel reciprocity and data from the transmitting side, rather than the receiving side. Instead, explicit sounding, requires a CSI performance from the receiver and consequently feedback about the information to the transmitter, so it can direct the SS. The increasing number of spatial streams leads to a rise in the overhead of acquiring CSI. With 16 spatial terms, the use of the same channel sounding method developed on IEEE 802.11ax, is not adequate to support it, determining an huge CSI feedback overhead. To address this issue, EHT standard needs to improve current explicit and implicit schemes in order to reduce the overhead, improving the sounding channel efficiency, or develop new CSI feedback mechanisms.

3.2.3 4K QAM

4K QAM is one of the key enhancement of IEEE 802.11be, QAM is a group of digital modulation methods that allows the translation of digital data packets into an analog signal allowing wirelessly transfer data. By varying the phase and amplitude of radio waves, the spectral efficiency improves, incorporating more data into each transmission. QAM is represented as a set of constellation points arranged in a square grid with equal vertical and horizontal spacing. The number of points correspond to the number of bits per symbol, typically a power of two.
The IEEE 802.11ax allowed a maximum of 10 bits per symbol or 1024 QAM, while EHT standard can achieve 12 bits per symbol through 4096 QAM, delivering a 20% increase in data rate. This means that even more data is compressed into the limited bandwidth available. Figure 3.1 describes the evolution of QAM (Quadrature Amplitude Modulation) constellations across the different Wi-Fi standards, from Wi-Fi 4 (64-QAM) to Wi-Fi 7 (4096-QAM). [18].

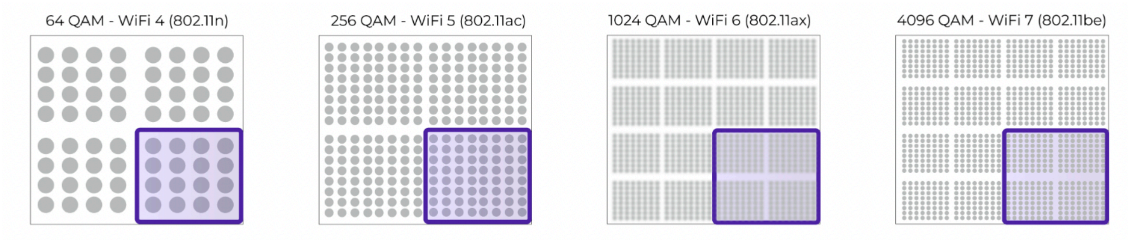

Figure 3.1: 4K QAM increase of the number of bits [19]

3.2.4 512 Compressed block ack

Whenever a unicast Wi-Fi data frame transmission occurs, an acknowledgement is required as confirmation of the data received. This reduces efficiency due to the back and forth messages exchanged between devices. This new feature introduced, based on block aggregation, enables the transmitter to consolidate as many as 512 MAC protocol data units (MPDUs) into a single frame. Single message from the receiver confirms reception of multiple transmission, improving efficiency and reducing significantly overhead. The number of MPDUs increase, the receiver can acknowledge all of these simultaneously, within a single block acknowledgment frame, improving performance at high data rates [20].

3.2.5 QoS management

The standard presents several methods to achieve improved QoS management: provide a refined QoS model with a reliable and low-latency access category to identify traffic. Additionally,to prioritize the QoS traffic have been introduced enhanced channel access methods such as Restricted Target Wake Time (RTWT), triggered TXOP sharing and national security and emergency preparedness (NSPE) priority access. target wake time (TWT),presented in IEEE802.11ax, is a mechanism that allows to reduce the medium contention through the schedule of traffic between an APand a STA. The identification of the time periods when the STAs should be awake enables to save power and consequently reduce power consumption. The IEEE 802.11be introduces a new mode known as RTWT that offers a better medium access protection and mechanisms that allow the resource reservation. The aim is to provide more predictable latency, reduce worst case latency and higher reliability for latency-sensitive traffic. The broadcast TWT mechanism that allows an EHT AP to communicate with multiple devices, is extended to allow the scheduling communication of the RTWT service periods. To guarantee additional medium protection, any ETH non-AP STA that supports RTWT must finish its TXOP before the start of the scheduled RTWT service periods. During the quiet intervals, any non-AP STA that is not a member doesn't have the access to the transmission medium. The triggered TXOP sharing allows an AP to allocate a portion of the time (TXOP) that it has obtained to a non-AP STA. Consequently, this device can transmit one or more data packets directly to the AP or to another non-AP STA with the AP's assistance. In particular, once the AP has obtained the TXOP, it can send a Multi-User Request to Send (MU-RTS) Trigger frame to a non-AP STA and allocate time within the TXOP for the transmission. This method permits a direct peer-to-peer transmission requested for example by VR applications or the file transfers from a phone to a printer. The priority access NSPE is based on the concept of ensuring that authorized users have priority access to system resources during periods of network congestion or disaster events, thereby enabling successful communications even when the networked is overloaded. During the capability exchange in the association, the AP verify if a non-AP STA has the right to use the NSPE priority access to ensure the concept of precedence. After successful setup, the NSPE works on request [15].

3.3 Key applications

IEEE 802.11be's enhancements in terms of data rates, latency and network efficiency have a significant impact across consumer and industrial sectors. Some applications include AR/VR, high resolution video-streaming, automotive industry and industrial applications [17].

3.3.1 Augmented Reality/Virtual Reality

The advanced capabilities introduced relating to high data rated and low latency are crucial to process and transmit data in real-time and to enhance the realism allowing an immersive AR/VR experience. Enables the development of new possibilities in gaming, entertainment and education.

3.3.2 High-resolution video steaming

The growing demand for 4k/8k video streaming requires robust and high-speed wireless connections. With data rate of up to 40 Gbps and MIMO enhancements, EHT standard can supports high-resolution video streaming, ensuring smooth playback without quality degradation. It can be useful for the adoption of 4/8k video content in home entertainments and professional applications

3.3.3 Automotive Industry

This standard, through the features of low-latency and high-capacity, can contribute to improve the automotive industry, enabling faster and more reliable vehicle to vehicle and vehicle to infrastructure communication. It can support real-time data exchanged between connected vehicles, traffic management and road safety. It can also support the development of advanced driver assistance system and autonomous vehicles.

3.3.4 Industrial application

In cases where reliable and real-time data transmission are fundamental, such as in healthcare, financial services and industrial settings, the EHT standard offers an optimal solution. In health sector enables remote patient monitoring, telemedicine and robotic surgery while, in finance, can facilitate secure, efficient transaction and high speed data exchange. The real-time monitoring of equipment and processes, robotics and advanced automation are instead useful in industrial field. Additionally, can support the integration of IoT devices allowing smart factories and Industry 4.0 initiatives.

In summary, IEEE 802.11be can play a pivotal role in influencing the future of wireless connectivity offering unprecedented speed, latency and network efficiency enabling rich experience in a variety of environments. It can has a significant impact on transforming people's lives, work and communication, meeting the growing demands for connectivity in an increasingly digitalized world. The integration of this standard will depend on the collaborative efforts of network operators and regulatory bodies. [17]. The EHT standard is expected to be completed and certified by the Wi-Fi Alliance in the 2024-2025 timeframe, with rapid adoption across a broad ecosystem. More than 233 million devices are expected to enter the market in 2024, growing to 2.1 billion devices by 2028 [21].

4

Standard development and certification

4.1 Standard development

Standards form the basis of social well-being, especially in an era based on globalization and convergence across traditional technology and market boundaries. Technical standards are instruments that facilitate communication, commerce and manufacturing, providing a basis for mutual understanding to people and organization. Standardization is essential in order to provide technological innovation and enables the development of complex solutions in a more efficient way, with a better cost structure. They help to ensure the growth of global markets and open up new opportunities to their users by allowing interoperability of products, services and processes. Additionally, help protect public health and safety.
IEEE [1], as a global standards development organization, supports and advocates a set of standards development principles, executed by the IEEE Standards Association (IEEE SA), proving technical excellence and innovation for economic growth and social prosperity [23].
These principles are:

- Direct participation: there aren't intermediaries between the originators of a promising idea and the group that takes charge the standard, and any individual or organization from any location worldwide can submit a proposal.

- Due process: decisions are based on equity and fairness among all participants, transparently, ensuring that no party dominates the process.

- Broad consensus: all viewpoints are considered with a decision made by either a majority or

[1]IEEE provides hardware manufacturers, software developers, service providers, and other businesses with the time-tested platforms, rules, governance, methodologies, and facilitation services they need to transform a concept into an industry standard [22]

supermajority of participants and no individual or organization influence in an undue way the creation of the standard

- Balance: steps are taken to provide the participation of a multitude of stakeholders, ensuring that the process is not dominated by any particular party.
- Transparency: make available to participants the processes and procedure under which standard are developed, allowing to understand rules guiding engagement and decisions. Records of decisions and supporting materials shall be accessible.
- Broad openness: from the beginning of the process, appropriate notification is given to a global audience and potential stakeholders, regarding the opportunity to engage. Before the approval and the adoption of the standard are provided public comments periods.
- Coherence: IEEE coordinates with industry, governments, associations and numerous other organizations in the development of standards.
- Development dimension: Anyone in the world can participate in developing IEEE standards, the organization tries to reach individuals and entities in developing countries that for example can submit comments during a formal consensus ballot [24].

4.1.1 Standard development process

The IEEE standards development process, in order to ensure the integrity of the standard, includes a set of policies, procedures and guidelines that are followed at every step. These are established and maintained by boards, committees and professional staff. Once a new standard is finalized, IEEE SA provides a framework for the distribution and continually updating it to satisfy evolving marketplace conditions and opportunities.
IEEE Standards are developed using a time-tested, effective and trusted process that can be divided into 6 main stages: Initiating the project, mobilizing the Working group (WG), drafting the standard, balloting the standard, gaining final approval and maintaining the standard. Figure 4.1 illustrates the standards development life cycle, divided into six stages: from the stage 1 initiating the project to the stage 6 maintaining the standard after final approval.

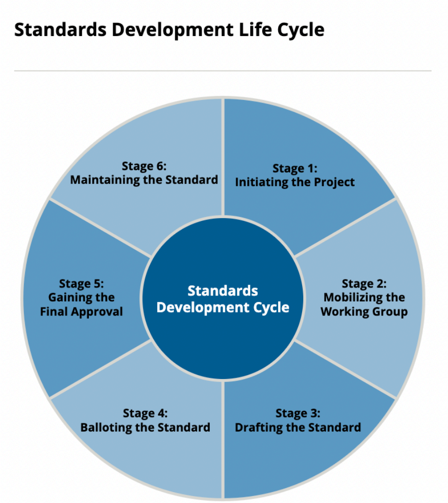

Figure 4.1: Standard development cycle [23].

- Initiating the project: The development of an IEEE standard begins with an idea or concept proposed by individuals, companies or other entities that discuss the need for a new standard among themselves. Then, if the need is confirmed, the idea is presented to a Standards Committee (SC) which will provide guidance, direction and mentorship during the entire standard development process. In order to officially begin the project, must be sent a formal request to IEEE SA by the SC responsible for that area of standard development, including the organization of the WG and its activities. A Project Authorization Request (PAR) is a structured document that includes the scope, reason for the project (the need) and its purpose. It is submitted by the SC supporting the project. Additionally, a SC may form a Study Group, if the idea for a standard is not yet fully defined. It has to examine and make recommendations for the project, to generate a PAR usually has 6 months. Also existing WGs can well develop new PARs. Upon submission, each PAR is placed on an upcoming New Standards Committeee (NesCom)agenda [2]. The committee examines Project Authorization Requests (PARs) and makes recommendations to the IEEE SA Standards Board regarding approval. NesCommembers, one month before the NesCom meeting, review the PARs and submit comments. The PAR submitter, WG Chair and SC Chair receive notification of these comments, along with instructions on how to prepare and submit responses. NesCom provides its recommendations to the IEEE SA, who approves the PARs. Once approved, a PAR should be completed in four years. In some cases, if the WG is unable to complete the project within the established time, a PARextension may be requested from NesCom. It reviews the request and evaluates whether to recommend the approval of the extensions to the IEEE Standards Board (IEEE SASB).[3]

[2]NesCom is responsible for ensuring that proposed standards projects are within the scope and purpose of IEEE, assigned to the proper Society or other organizational body, and interested parties are appropriately represented in the development of IEEE standards [25]

[3]IEEE SA Standards Board encourages and coordinates the development and revision of IEEE stan-

- Mobilizing the Working Group: Once the IEEE SASB approves the request to develop a new standard, the SC follows the rules and processes to establish a WG for the standards development activity. WGs are composed of individuals or entities like companies, organizations and government agencies, that have an interest and technical expertise in a specific area of the development and voluntarily participating on it, they are united by a shared vision of how the world will be a better place though the implementation of this standard. WGs aim to unsure a balance of interests represented, broad inclusion of all involved parties and promote global participation. There is the presence of a chair which has the task of facilitates the group discussion and managing the WG, moving the project forward. The engaged entities work collaboratively during the WG meetings to reach consensus and present the draft standard to Standard Association Ballot and, finally, IEEE SASB approval [27].

- Drafting the standard: The IEEE SA provides editorial draft development support to more than 500 WGs and in a year are published more than 100 standards. WGs collaborate with editorial staff 3 times during the development project of the standard: drafting stage, balloting stage and the post-IEEE SASB approval publishing stage. IEEE staff project editors such as Program Managers, Content Production and Management, are trained in the publishing and standard development process. They are available to help in the field of editorial or figure requirements, PAR and DRAFT submittal/revision [28].

- Balloting the standard: the draft standard, before it can move forward to the IEEE SA Ballot, it must be reviewed, finalized and approved by the WG. Once approved, it is submitted to the SC for further approval. Now the consensus balloting process begin: the group is formed by individuals or entities and each balloter has one vote. Entities taking part need to have an interest in the subject, an IEEE Account, and IEEE SA membership or payment of the per-ballot fee. In order to guarantee balance, balloters must select one interest category and any of that can compromise over one-third of the balloting group. A wide variety of interested parties are invited to participate, ballot invitations are open for a minimum of 12 days. Non necessarily, the WG members are included in the balloting group. During this process, stakeholders who may not have been able to participate in the WG, can give their contribution. The aim is to achieve an high-quality standard. Initial SA Ballots are open for 30 days during which balloters can approve, disapprove or abstain. They can also express their consensus through comments, that can be general, technical or editorial, and all of them are considered. If a vote is negative, specific reasons shall be given for the vote to be counted. In order to might change a vote from disapprove to approve, can be submitted comments or changes to the draft by the Comment Resolution Group (CRG) [4] [29]. A negative vote that

dards. This includes approving the initiation of IEEE standards projects and to reviewing them for consensus, due process, openness, and balance [26].

[4] CRGconsiders all comments received during the ballot period, whether submitted by those within or outside of the balloting group. Comment responses may result in the draft being modified.Once the CRG has considered all comments, the Working Group must recirculate the ballot if new technical changes have been introduced in the document or if there are unresolved negative comments. The balloting group has the right to examine these along with any revisions to the document so that balloters can determine whether they want to maintain their vote [29]

can't be resolved, hasn't got any include on the standard's content. Simultaneously with the initial IEEE SA Ballot, can occurs the public review process. It lasts 60 days and provides an opportunity for any interested party to submit comments and obtain responses from the WG, allowing an even broader participation and input to IEEE Draft standard. The goal is to achieve the greatest consensus. The ballot can be considered valid if at least 75 percent of the group members have expressed their vote, to guarantee a proper participation, and if the 75 percent of the responses are approved votes. If 30 percent or more of the ballot are abstentions, the ballot fails. Upon successful completion of the IEEE SA Ballot process, during which an IEEE SAProgram Manager can provide assistance, the draft standard is presented to the Review Committee (RevCom). After it has been reviewed, it is submitted to the IEEE SASB for approval.

- Gaining the final approval: the IEEE SASB approves or disapproves draft standards based on the recommendation of its RevCom. It examines all the documentation and determines whether the standards development process has been followed. Concerning the technical nature of the draft, it doesn't express, it's a task of the balloting group. It's provide the right of appeal during the standardization process. Once a standard has been approved by the IEEE SASB, it receives a detailed edit from a professional IEEE Standards editor, to ensure that the standard is grammatically and syntactically correct using American English, and that meets the IEEE standards style. The WG receives a copy of the final standard to review and approve before the publication. After this, the standard is published and made available for distribution and purchase. IEEE standards are sold both as individual documents and within multiple subscriptions. IEEE standards included in the IEEE Electronic Library and in the IEEE Standards Online Subscriptions are topical collections of standards and drafts accessible online through an annual subscription. IEEE standards can be purchased directly from IEEE through the IEEE Standards Store, IEEE Xplore Digital Library or an IEEE Contact Center representative [30].

- Maintaining the standard: standards are "living documents", that based on market conditions, feedback and other factors, may undergo changes, corrections or adjustments. It can include additional documents produced by the respective WG. A standard is active for 10 years from the IEEE SASB approval year. During this period, SCs can take the following actions: revise the standard by updates, changes or additions, Submit Amendments for additional material to the standard, Submit Corrigende for correction to the standard, Withdraw the standard from active to inactive withdrawn status through a SA Ballot. If a standard has not been revised before the end of the ten year maintenance cycle, it may be administratively withdrawn by the IEEE SASB. WG can also spend the decade period creating handbooks, tutorials, and other related material, in order to help interested parties to better understand and apply the standard [31].

4.1.2 IEEE and Wi-Fi Alliance

Wi-Fi technology stands as a remarkable success story of the high-tech era. Industries, through the implementation of IEEE standards, brought Wi-Fi to the world, creating a virtuous cycle between IEEE members, Wi-Fi alliance members, and Wi-Fi users, that play an important role by voicing their preferences through their purchases. This collaboration inspired the creation of new businesses and products, solidifying Wi-Fi in our daily lives, changing how we live and work. Wi-Fi Alliance, made up of companies from the global Wi-Fi ecosystem, provides a forum where stakeholders, with commercial interests in Wi-Fi, can discuss and determine use cases, market needs, and develop standards-based solutions. As the industry evolves, the Wi-Fi Alliance attempts to meet new demands and technological advancements by driving global Wi-Fi adoption, advocating for spectrum access, guarantee that products meet essential interoperability and security requirements, and helping governments recognize the strong economic value that Wi-Fi delivers. The Wi-Fi alliance work is based on: leadership: in order to make Wi-Fi consistently more secure, efficient and user-friendly, Advocacy: advocate for spectrum rules that support Wi-Fi due to the continued growth, Collaboration: innovate ensuring high performance and great user experience The vision is: Connecting everyone and everything, everywhere, providing the best possible user experience [32].

4.2 Certification

Wi-Fi CERTIFIED™ is an internationally recognized seal of approval for products, the best way to ensure Wi-Fi devices meet user expectations. It indicates that a product met industry-agreed standards for interoperability, security, and a range of application specific protocols. In order to convalidate the highest standards for interoperability with others Wi-Fi certified equipment, that operates in the same frequency band, products undergo a series of rigorous tests in a variety of ways. Users and enterprises, with the ever-increasing number of devices, expect them to work well together, regardless of brand.
There are three possible certification paths to certify Wi-Fi products, members can choose the best option to meet their needs and find the right for testing and certification [33].

- FlexTrack: products are built from the group and allows the most flexible customization of functionality built into components. The testing process is completed at an Autorized Test Laboratory (ATL).

- QuickTrack: it is a simple and lower cost option. Allows members to build products based on trusted Qualified Solution, that have already completed full Wi-Fi functionality testing. These solutions are leveraging as a base for new end user products. It allows targeted changes to Wi-Fi functionality and the testing process can be completed at an ATL or member testing site. It provides many benefits to product developers: lowering testing costs, reducing time needed to complete testing, avoiding redundant testing Wi-Fi components and ensuring Wi-Fi CERTIFIED products continue to meet certification requirements throughout the product life cycle. This method enables companies to develop products more quickly, ensure that the testing process runs smoothly and meet industry-agreed quality Wi-Fi standard. [34].

- Derivative: copies of a Wi-Fi CERTIFIED device Source Product, there aren't changes to Wi-Fi functionality. Members may apply for certification of derivative products without additional testing requirements. For example the same chipset used for multiple laptop models.

Certification is available for a variety range of consumer, enterprise and operator-specific products such as smartphones, appliances, computers and networking infrastructure. The Wi-Fi CERTIFIED logo assurances that Wi-Fi devices and applications from different vendors work well together and deliver a good user experience in a variety of environments. Service providers and enterprise IT managers through it reduce supports cost and ensure industry-agreed requirements. To use the Wi-Fi certified logo and Wi-Fi certified certification marks, a company must be a member of Wi-Fi Alliance and have obtained the certification. Since 2000, Wi-Fi Alliance has completed more than 80,000 Wi-Fi certifications. Today, more than half of the internet traffic is carriers by Wi-Fi. The aim is maintaining interoperability between different Wi-Fi generations, continuing to work on its adoption and evolution [35].

4.2.1 Benefits of Wi-Fi CERTIFIED Equipment

Since the first Wi-Fi CERTIFIED product, announced in 2000, thousands of products have been certified and all the certification programs preserve legacy interoperability. This allows ensuring a good user experience, reduce support costs and higher sales volumes.

- Application developers: thanks to the global reach of Wi-Fi, applications that support it can be marketed worldwide, allowing an expansion of the addressable market. Through Wi-Fi Alliance certification, application developers can provide ever more advanced technologies.

- Service providers: Certifications enables interoperability for large scale deployments. Technical support and management for Wi-Fi devices is optimized, helping to keep operating costs low. High awareness of the Wi-Fi CERTIFIED brand among users enhance the confidence in certified devices. As a result, service providers can leverage this to achieve greater marketing impact when launching new products.

- Consumer users: the Wi-Fi CERTIFIED brand offers interoperability, standards-based security, and easy installation. In order to ensure compatibility with other Wi-Fi CERTIFIED equipment, a third part has tested the product in different configuration and with a diverse sampling of other devices.

- Enterprise customers: Wi-Fi CERTIFIED products ensure interoperability of Wi-Fi products from multiple vendors, so it can be useful for deploying a new infrastructure or integrating new equipment into an existing infrastructure. Examples of advantages are fewer network problems and support calls [36]

5

Conclusion

This thesis has explored the evolution of WLAN, with a specific focus on the IEEE 802.11 standard. It provides an in-depth analysis of the wireless network technology, highlighting its crucial importance in modern communication.
As stated in the introduction, Wi-Fi technology has become indispensable over the years, playing an important role for individuals, families, governments and global organizations. It is a key to enabling continued social and economic growth. Wi-Fi offers features that are essential in today's connected world such as flexibility, reliability, cost-effectiveness, ease of use, support for modern applications, all of which provide significant societal benefits. Additionally, it is important to emphasize the global economic impact of these technologies. The Wi-Fi value now amounts to approximately $4.3 trillion according to a study commissioned by Wi-Fi Alliance, and it is expected to grow further [37]. Wi-Fi's value will continue to increase in the coming years, with the aim to meet the growing customer demands and maintain quality connections. The never-ending innovation, including developments towards IEEE 802.11be and the allocation of new spectrum bands, promises to address future communication challenges by providing improvements to reach the goal of connecting everyone and everything, everywhere.
As described in the first chapter, the broad implementation of the IEEE 802.11 standard, driven by the ever-increasing number of connected devices and the growing need for high-speed data transmission in various applications, has headed continuous innovation in wireless technologies. Some of these adjustments have already been developed, while others are currently under development. Over the years, solutions for both PHY and MAC layers have been defined, meeting requirements needed by the newer Wi-Fi generations. Since the adoption of the first standard in 1997, this work has produced six major generations of standardized networks, each focusing on specific technical features, and the IEEE 802.11be version currently under development. Each generation, from 802.11a/b to the most recent 802.11ax, presents several objectives: expanding frequency bands, achieving higher data rates, reducing latency, improving reliability, especially in scenarios with

high device density. The main focus of this elaborate is the upcoming IEEE 802.11be version, which aims to optimize performance in the 2.4 GHz, 5 GHz and deliver unparalleled performance on 6 GHz band. It brings advanced capabilities that enable rich experiences in a variety of environments. It facilitates innovations that require high throughput, lower latency and greater reliability for technologies such as AR/VR, industrial IoT and automotive applications. All these changes will form a basement for further Wi-Fi evolution. This standard is expected to see a rapid adoption across a broad ecosystem, by promoting worldwide product interoperability and gaining early market traction. The last chapter discusses standards development and certification processes, explaining their importance and benefits. The IEEE standards development process is based on well-defined principles, ensuring they are followed at every step. It allows achieving technical excellence and helps innovation for economic growth and social prosperity. About certification, the Wi-Fi certified seal is crucial in order to ensure interoperability and security of products and services. This validation encourages consumer confidence and improves the overall user experience. There is a choice between three certifications paths, allowing members to select the best option for their needs by testing products in a rigorous way. Furthermore, the Wi-Fi Alliance and IEEE collaborate by exchanging questions and feedback, supporting the virtuous Wi-Fi cycle in view of a shared, connected future with this technology.

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Acknowledgments

Ed eccoci qui, è arrivato anche il momento di ringraziare coloro che mi hanno supportata... o forse dovrei dire sopportata in questi tre lunghi anni. Il primo grazie va alla mia relatrice, Professoressa Meneghello Francesca, per avermi guidato in questo percorso ed essere stata di grande supporto e sempre presente per la stesura di questa tesi. Un grande grazie va poi a mamma e papà, se sono arrivata fino a qui, è anche merito vostro. Non vi siete mai stancati di sostenermi, continuando a darmi la forza di cui avevo bisogno, anche nei momenti in cui tutto mi sembrava crollare addosso. E lo so, io con il mio caratterino non sono proprio semplice da gestire. Forse dovrei chiedervi scusa per tutte quelle volte in cui, con la mia testardaggine, ho continuato per la mia strada, rendendomi conto solo dopo che avrei solo dovuto fermarmi un attimo e ascoltare i vostri consigli. A ripensarci ora forse mi viene anche un po' da ridere, pomeriggi persi a disperarmi per uno "stupido" esame mandando un po' tutti in crisi. Quindi grazie per l'eterna pazienza che spero però sia adesso ripagata da questo momento, rendendovi un po' orgogliosi di me.

Poi c'è Nico, il mio fratellino, devo essere onesta, soprattutto in questo ultimo periodo sei stato fondamentale per me. Lo sai che ti invidio tanto per la tua sicurezza e autostima, non hai mai pensato di regalarmene un po'? In tutti i modi hai provato a spronarmi e a convincermi a credere un pochino di più in me stessa. Ti sei letto tutti i capitoli della tesi e nel tuo piccolo ti sei impegnato al massimo per farmi arrivare fino a qui. Tutti i tuoi messaggi e le telefonate subito dopo l'esame per capire se fossi sopravvissuta, ricevendo però sempre la stessa risposta "non lo so vediamo, non dico niente, un po' ho fatto, dipende come valutano". Solo all'ultimo esame, per una volta, sono riuscita a dire "è andato bene!". Non ce lo diciamo tanto spesso sai, ma ti voglio tanto bene e lo so che sotto sotto, anche se a volte lo nascondi e fai finta di fregartene, pensi lo stesso pure tu! Oggi puoi dire che la tua sorellina preferita, come dici tu, ce l'ha fatta a raggiungere questo traguardo che sembrava tanto lontano.

Adesso vorrei ringraziare altre persone che so per certo che in questo momento sono ancora più felici e fiere di me: Chi da qua e chi da lassù, i miei angioletti custodi che mi guardano e mi controllano sempre, non hanno mai smesso di credere in me, convincendomi a non mollare mai nonostante le difficoltà, che ora mi rendo conto grandi difficoltà non erano. Con piccoli gesti e semplici parole, ma ogni volta perfette per tirarmi su e permettermi di raggiungere i miei obiettivi. Non potete neanche immaginare il bene che vi voglio e quanto io mi senta fortunata ad avere voi al mio fianco. In particolare un ringraziamento speciale alla nonna Maria Rosa e alla Zia Berti che rappresentano per me un punto di riferimento. Che ad ogni esame erano più preoccupate di me! Ma avete sempre provato a tranquillizzarmi e convincermi a credere in me stessa, "stai tranquilla che ce la fai, sei brava!" e alla fine avevate proprio ragione. Grazie al nonno Dino sempre pronto e sull'attenti nel chiedermi come fossero andati gli esami, convincendomi a essere più sicura di me stessa.

Grazie alla Zia Valeria per essere stata presente e disponibile a darmi consigli. Sempre orgogliosa

di me in ogni mio piccolo traguardo di questo percorso e adesso lo sarai ancora di più.

Grande grazie a Laura e Luca per essere stati sempre pronti ad aiutarmi nei momenti di crisi per gli esami e in quest'ultimo periodo per scrivere questa tesi. Tutte le sere passate, mangiando una pizza o le famose piadine di Luca, a cercare di capire quel maledetto phyton sono servite dai! Ma l'aspetto positivo era che passavamo del tempo insieme e siete sempre riusciti a farmi svagare un po' nonostante i mille pensieri che avevo in testa.

Non in secondo piano, tutti gli zii e cugini in cui so che nel momento del bisogno posso contare su di voi, conoscete il mio carattere e riuscite sempre a strapparmi un sorriso.

Un grazie a tutte le mie amiche che posso ormai dire di conoscere da una vita, siete sempre state presenti, condividiamo momenti indelebili, gioie, risate ma anche delusioni e momenti tristi. Siamo sempre riuscite a farci forza a vicenda soprattutto in questo periodo in cui possiamo dire che l'esaurimento ha colpito un po' tutte. Ora a ripensare ai nostri audio infiniti in cui a vicenda ci dicevamo le stesse identiche parole per i pomeriggi passati a studiare e per le notti insonni pre-esame mi viene da dire che un po' pazzerelle lo eravamo. Grazie per avermi sopportata a causa di tutte le mie insicurezze e per la mia pesantezza determinata dalla mia migliore amica, l'ansia. Piano piano tutte stiamo raggiungendo questo traguardo che spero ripaghi, almeno in parte, i nostri sforzi.

Non mi sono dimenticata di un'altra persona che è entrata da relativamente poco tempo nella mia vita ma che è diventata per me tanto importante. Sarò un po' timidina anche ora, come sempre! Sei riuscito a sopportarmi fino a qui, sei stato bravo!. Nei momenti in cui ho bisogno di non pensare a niente e liberare un po' la testa per fortuna ora ci sei tu. Non posso negare che a volte un po' pesantina lo sono stata, a volte so di averti un po' infastidito con le mie paranoie, ma se mi sfogavo è perché so che di te mi posso fidare. Grazie per farmi ridere anche quando non ne ho voglia e per lo sforzo che fai nel cercare di capirmi in ogni situazione. Mi hai aiutata a convincermi che ce l'avrei fatta nonostante tutto e anche in questo caso posso dirti che avevi ragione amore!.

Per concludere vorrei ringraziare le persone con cui ho avuto la fortuna di vivere un'esperienza che rimarrà per sempre parte della mia vita. In particolare Adrian, Giovanni e Matilde con cui ho trascorso sei bellissimi mesi. Ci sono stati momenti di puro divertimento, ma anche attimi in cui la malinconia ha preso un po' il sopravvento, tutto è stato però colmato dalla vostra presenza. Grazie per gli infiniti pre-serata passati insieme nonostante la mia sempre presente sonnolenza, i miei "ho sonno, sono stanca", grazie per la "vacanzella bella" che abbiamo fatto, grazie per le famose serate a fare tapas, insomma grazie per avermi fatto passare momenti che avranno per sempre un posticino nel mio cuore.