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List of Acronyms:

1xRTT	Single-Carrier Radio Transmission Technology
3GPP	The 3rd Generation Partnership Project
AI	Artificial Intelligence
AMPS	Advance Mobile Phone Service
AR	Augmented Reality
Argmin	Minimum argument
ASIC	Application Specific Integrated Circuit
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BS	Base Station
BW	BandWidth
CDMA	Code Division Multiple Access
CP-OFDM	Cyclic Prefix OFDM
CR	Cognitive Radio
CRBS	Cognitive Radio Base Station
CRN	Cognitive Radio Network
CRU	Cognitive Radio User
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
D2D	Device-to-device communication
DL	Downlink
dB	Decibel
DC	Direct Current
DFT-S-OFDM	Direct Fourier Transform spread OFDM.
DSA	Dynamic Spectrum Access

DVB	Digital Video Broadcasting
E	Energy
ECG	Electrocardiogram
ED	Energy Detection
EDGE	Enhanced Data rates for GSM Evolution
EM	Electromagnetic
eMBB	Enhanced Mobile Broadband service
EMR	Exchange Message Record
EVDO	Evolution Data Optimized
FC	Fusion Center
FCC	Federal Communications Commission
FDMA	Frequency Division Multiple Access
FFT	Fast Fourier Transform
FPGA	Field programmable gate array
GPRS	General Packet Radio Service
GSM	Global System for Mobile
ICT	Information and communications technology
IDFT	Inverse Discrete Fourier Transform
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IoT	Internet of Things
IP	Internet Protocol
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication
LANs	Local Area Networks
LDPC	Low-Density Parity Check Codes

LTE	Long Term Evolution
LTE-A	Long Term Evolution-Architecture
M2M	Machine-to-Machine
MAC	Medium Access Control
MANs	Metropolitan Area Networks
MATLAB	MATrix LABoratory
MF	Matched Filter
MIMO	Multiple-Input Multiple-Output
mIOT	Massive Internet of Things
MMS	Multimedia Messaging Service
mMTC	Massive Machine Type Communications
Nit	Number of iterations
NOMA	Non-Orthogonal Multiple Access
NR	New Radio
OFDMA	Orthogonal Frequency Division Multiple Access
PACKET N/W	Network Packet
Pd	Probability of Detection
Pf	Probability of False Alarm
Pm	Probability of Missing
PSD	Power Spectral Density
PSK	Phase Shift Keying
PSTN	Public Switched Telephone Network
PU	Primary User
QAM	Quadrature Amplitude Modulation
QC-LDPC	Quasi-Cyclic (QC) LDPC
QoS	Quality of Service

QPSK	Quadrature Phase-Shift keying
RF	Radio Frequency
SA	Spectrum Agent
SDR	Software Defined Radio
SFC	Service Function Chaining
SMS	Short Message Service
SNR	Signal-to-Noise Ratio
SU	Secondary User
T	Time interval
Tbps	Terabits per second
TDMA	Time Division Multiple Access
TER	Total Error Rate
THR	Threshold
UE	User Equipment
UHD	Ultra-high-definition
UL	Uplink
UMTS	Universal Mobile Telecommunications System
UN	United Nations
uRLLC	Ultra-reliable and low-latency communications
UWB	Ultra-Wide-Band
VNFs	Virtual Network Functions
VR	Virtual Reality
WG	Working Group
WIFI	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
W-CDMA	Wideband Code Division Multiple Access

الملخص

يُعتقد أن إتصالات الجيل الخامس (5G) من معايير الاتصالات اللاسلكية والراديو المعرفي (CR) هو الحل لتطبيقات البيانات المكثفة في الوقت الحاضر. من المتوقع أن توفر الشبكات اللاسلكية (5G) معدلات نقل بيانات أعلى وزمن انتقال منخفض للغاية وقدرة هائلة. توفر شبكة الراديو المعرفي (CRN) مشاركة ديناميكية للطيف لتحقيق كفاءات طيف أعلى، كما هو مطلوب في هندسة الجيل الخامس. في هذا العمل قدمنا نتائج الطبقة الفيزيائية (5G) وتم عرض التقنيات المختلفة لتقنيات استشعار الطيف من خلال المحاكاة.

الكلمات المفتاحية :إتصالات الجيل الخامس(5G)، شبكات المحمول الراديو المعرفي (CR) ،الكشف عن الطيف التعاوني.

Résumé

On pense que la cinquième génération (5G) de normes de communication sans fil et de radio cognitive (CR) est la solution pour les applications actuelles à forte intensité de données. Les réseaux sans fil (5G) devraient fournir des taux de transfert de données plus élevés, une latence ultra-faible et une capacité massive. Le réseau radio cognitive (CRN) offre un partage dynamique du spectre pour atteindre une efficacité spectrale plus élevée, comme l'exige l'architecture (5G). Dans ce travail, nous avons présenté les résultats de la couche physique de (5G) et les différentes techniques de techniques de détection de spectre sont présentées à travers des simulations.

Mots clés : La cinquième génération (5G), Les réseaux mobiles, la radio cognitive (CR), détection de spectre coopérative.

Abstract

The fifth Generation (5G) of wireless communication standards and Cognitive radio (CR) are believed to be the solution for present day data intensive applications. The (5G) wireless networks are expected to provide higher data transfer rates, ultra-low latency and massive capacity. Cognitive radio network (CRN) offers dynamic spectrum sharing to achieve higher spectrum efficiencies as required in (5G) architecture. In this work, we presented the results of the physical layer of (5G) and the various techniques of spectrum sensing techniques are shown through simulations.

Key words : The fifth generation (5G), Mobile Networks, Cognitive radio (CR), Cooperative Spectrum sensing.

General introduction

Telecommunication systems look for providing the best quality of communication between all points in this world, there are several forms to do this, the most used and frequent one is the wireless communication, this latter has known a succession of generations that evolve to give better quality, this succession started with the 1G that refers to the first generation of wireless mobile communication technology, it appeared in 1979 where the radio signals used by the networks 1G are analog. Unlike those of its replacer, 2G or GSM that appeared in 1990, it relies on digital transmission with data security (encryption), the latter had itself experienced changes (2.5G (GPRS) and 2.75G (EDGE)). The GSM was pursued by 3G (UMTS) in the year 2000, its main objective was to offer users high throughput (data rate) and more services than 2G, one of its first applications was internet access. The 3G has also known some evolutions such as 3.5G, 3.75G and 3.95G. Soon afterwards the 4G or so-called LTE comes, it significantly incorporates very high data transmission rates and better performance, its first deployment was in 2009, like all other generations, 4G evolved into 4.5G which initially uses the 2 techniques “LTE advanced pro” and “MIMO”; however, all these generations mentioned previously have their own disadvantages such as the high latency and low data rate for the 2G and 3G, let alone the energy consumption and the crowded frequency range. The 5G is coming to solve all these problems and come up with some new technologies to give the best performance.

The idea of 5G appeared in the time when 4G was available approximately everywhere, Huawei started to develop its own 5G technology as early as in 2009. In December 2016, Huawei and DOCOMO (a Japanese mobile network) teamed up to conduct the world's first 5G large-scale field trials. The 5G, known as the new revolution in telecommunications, has begun to be widely deployed in 2019, its first launch was on august, 2019 in the USA.

5G is on the cutting edge of all the wireless communication generations, it is believed to be smarter, faster and more efficient than its predecessors. It promises mobile data speeds that far outpace the fastest home broadband network currently available to consumers. With speeds of up to 100 gigabits per second, 5G is set to be as much as 100 times faster than 4G**,** each new generation of wireless networks is much faster and more efficient than the previous one, its birth has greatly benefited from the large-scale growth of the mobile Internet and the Internet of Things (IoT), and the application of 5G lies mainly in the development of these two networks, where each physical object will be connected to the

internet, and by that, we mean everything, cars, surgical robots, even cameras on the road. 5G represents another step forward.

Nevertheless, The limitation of the radio spectrum and the rapid growth of communication applications and the poor exploitation of the frequency bands leads to a shortage of spectrum, Cognitive Radio (CR) appeared as a solution to remedy this problem. It is a wireless communication system in which a user is able to intelligently determine which communication channels are in use and which are not, and can move from one unused channel to another, these operations are possible when this system uses the CR functions, and mainly the spectrum sensing with its both cooperative and/or non-cooperative technologies.

In this thesis, there are three chapters organized according to the following plan:

Chapter I: Describes the fifth-generation network, from standardization to technologies used in this network, also, its physical layer and what protocols it uses.

Chapter II: Discovers the cognitive radio technology and the methods that are mostly used in it.

Chapter III: Presents of the system model and illustrate simulation results of the 5G new radio transmission chain as well as the CR cooperative and non-cooperative techniques.

Chapter I

Presentation of the 5G networks

1) Introduction

The most recent generation of mobile phone is the fifth generation (5G), its birth was a real technological breakthrough, by offering increased data rate and decreased latency to support growing demands of customers. Communications will be covered by a new frequency bandwidth located between 6 GHZ and 300 GHZ, part of this slice will be licensed, but a large part of it will be free.

In this chapter, we will go through the history of all the technologies that preceded 5G.Then, we will see the technologies on which 5G is based , as well as the standardization of this latter, then we will take a look on the frequency ranges in which 5G works, in addition to that, we will see the composition of the physical layer and the link layer, and the chapter is ended with a conclusion.

2) Evolution of wireless technologies

The wireless communication has been developing over the time where it has known a sequence of technologies that evolve to give a better performance, this sequence is ordered as follows:

2.1) First generation systems

The first generation (1G), was pioneered for voice service in early 1980's, where almost all of them were analog systems using the frequency division multiple access (FDMA) modulation with channel capacity of 30KHz and frequency band was 824-894 MHz, which was based on a technology known as Advance Mobile Phone Service (AMPS) [1].

2.2) Second generation systems

The second generation (2G), was accomplished in later 1990's. The 2G mobile communication system is a digital system; this system is still mostly used in different parts of the world. This generation mainly used for voice communication also offered additional services such as SMS and e-mail. In this generation two multiple access technique are used; one is Time Division Multiple Access (TDMA) and the second is the frequency division multiple access (FDMA) modulation, and the frequency bandwidth is 850-1900 MHz (uplink) and 935-960 MHz (downlink).

In 2G, GSM technology uses eight channels per carrier with a gross data rate of 22.8 Kbps (a net rate of 13 Kbps) in the full rate channel and a frame of 4.6 milliseconds (ms) duration. The family of this generation consists of 2G, 2.5G and 2.75G [1].

2.3) Third generation systems

Third generation (3G) services combine high speed mobile access with Internet Protocol (IP)-based services. The main features of 3G technology include wireless web base access, multimedia services, email, and video conferencing. The 3G W-CDMA air interface standard had been designed for always-on packet-based wireless service, so that computer, entertainment devices and telephones may all share the same wireless network and be connected to internet at anytime, anywhere. 3G systems offer high data rates up to 2 Mbps, over 5 MHz channel carrier width, depending on mobility/velocity, and high spectrum efficiency. The throughput supported by 3G networks depends also on the environment the call is being made in; 144 kbps in satellite and rural outdoor, 384 kbps in urban outdoor and 2Mbps in indoor and low range outdoor. The frequency band is 1.8 - 2.5 GHz [1].

2.4) Fourth generation systems

4G usually refers to the successor of the 3G and 2G standards. In fact, the 3GPP is recently standardizing LTE Advanced as future 4G standard. A 4G system may upgrade existing communication networks and is expected to provide a comprehensive and secure IP based solution where facilities such as voice, streamed multimedia and data will be provided to users on an "Anytime, anywhere" basis and at much higher throughput compared to previous generations. One common characteristic of the new services to be provided by 4G is their demanding requirements in terms of QoS. Applications such as wireless broadband access, Multimedia Messaging Service (MMS), video chat, mobile TV, HDTV content and Digital Video Broadcasting (DVB) are being developed to use a 4G network [1].

2.5) LTE advanced

LTE release 10, also referred to as LTE-Advanced, is claimed to be the true 4G evolution step. Earlier releases of LTE are included as integrated parts of LTE release 10, providing a more straightforward backwards compatibility, for example, support of legacy terminals. The main requirement specification for LTE advanced as approved in are:

- Peak downlink data rate: 1 Gbps, Peak uplink data rate: 500 Mbps.

- Transmission bandwidth: Wider than approximately 70 MHz in DL and 40 MHz in UL.

- Spectrum efficiency 3 times higher than that in LTE; Peak spectrum efficiency downlink: 30 bps/Hz; Uplink: 15 bps/Hz [1].

2.6) Fifth generation systems

5G Wireless Communication System is not deployed entirely yet. The big challenge for the design and deployment of 5G wireless system can be faced easily as proposed features and architecture that will increase system capacity and quality within the limited available frequency spectrum, whose frequency band and data bandwidth will be 3-300GHz and throughput of 1Gbps and higher (as demand) respectively. The remarkable issue, does not have any limitation in 5G as respect to user demands in the next 200 years. The 5G also implies the whole wireless world interconnection (WISDOM-Wireless Innovative System for Dynamic Operating Mega communications concept), together with very high data rates of the Quality of Service (QoS) applications [1].

There are several advantages of 5G technology, some of the advantages are [2]:

- High resolution and bi-directional large bandwidth shaping.
- Technology to gather all networks on one platform.
- More effective and efficient.
- Technology to facilitate subscriber supervision tools for the quick action.

Table I.1: Comparison of all generations of mobile technologies [3].

Technology / Features	1G	2G	3G	4G	5G
Start/ Deployment	1970 - 1980	1990 - 2004	2004 - 2010	Now	Soon (probably 2020)
Data rate	2kbps	64kbps	2Mbps	1 Gbps	Higher than 1Gbps
Technology	Analog Cellular Technology	Digital Cellular Technology	CDMA 2000 (1xRTT, EVDO) UMTS, EDGE	WiMax LTE Wi-Fi	MIMO, small cells, millimeter waves
Service	Mobile Telephony (Voice)	Digital voice, SMS, Higher capacity packetize data	Integrated high-quality audio, video and data	Dynamic Information access, Wearable devices	Dynamic Information access, Wearable devices with AI Capabilities
Multiple access	FDMA	TDMA, FDMA	W-CDMA	OFDMA	OFDMA, NOMA
Switching	Circuit	Circuit, Packet	Packet	All Packet	All Packet
Core Network	PSTN	PLMN	Packet (N/W) IMS	Internet	Internet

3) Services of 5G

There are three potential services for the 5th generation defined by the ITU-R organization, the uses are the following [4]:

- **Enhanced Mobile Broadband service (eMBB):** 5G will not only make our smartphones better, but it will used in new immersive experiences too, like the Augmented reality (AR) and Virtual reality (VR), with faster, more uniform data rates, lower latency, and cost-per-bit.

- **Ultra-reliable and low-latency communications (uRLLC):** is a new service category in 5G to accommodate emerging services and applications having stringent latency and reliability requirements.
- **Massive Machine Type Communications (mMTC):** also known as the massive Internet of Things (mIoT), that heads to create more sophisticated mobile traffic by connecting a massive number of embedded sensors in virtually everything through the ability to scale down in data rates, power and mobility to provide extremely lean/low-cost solutions.

Only eMBB is deployed in 2019, while uRLLC and mMTC are several years away in most locations of where 5G is deployed.

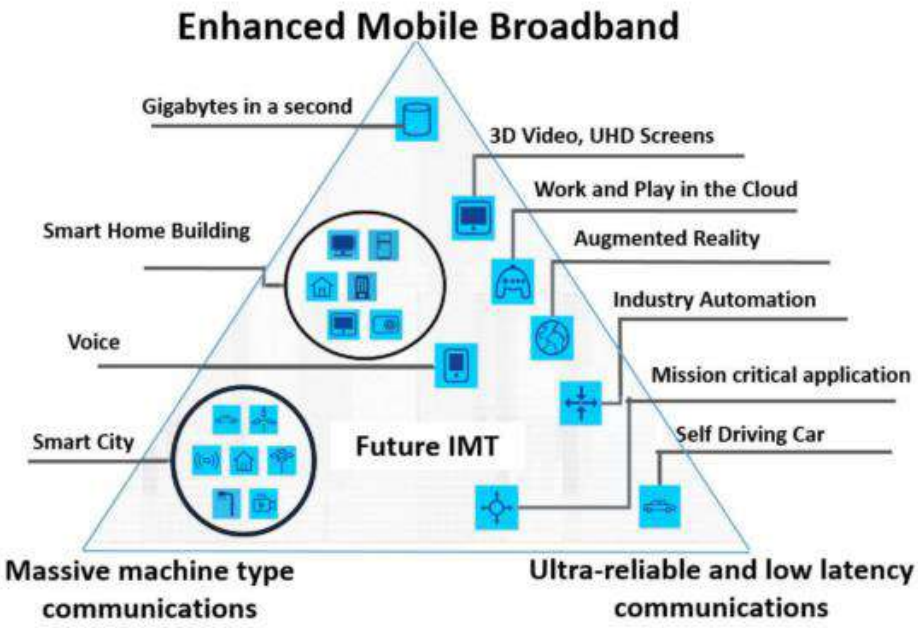


Figure I.1: Three main uses of 5G services [5].

Figure I.1 shows what the requirements mentioned previously can be used for, as an example for that, we see that the eMBB includes Gigabytes per seconds, as well as 3D videos or UHD videos, VR and AR, mMTC includes services like smart homes and smart cities, and that is the same for the uRLLC that includes also self-driving car, mission critical application like health, industry automation .

4) The reasons for the 5G standardizing

The 5th generation of the mobile communication standards needs to be standardized for the following reasons [6]:

- User and application trends.
- Very low latency and high reliability: Communication centered on people and on the machine.
- High density of use: The size of the cells will be reduced (for example, a few tens of meters).
- High quality with high mobility (UHD).
- Improved multimedia services.
- Internet of things (IoT).
- Ultra-accurate positioning applications.
- Global operation and economies of scale.

4.1) 5G Standards Organizations

With no firm, 5G technology standard is truly in place at this time, the market is still figuring out the essential 5G features and functionalities. The primary 5G standard organizations involved in these processes are the International Telecommunication Union (ITU), the 3rd Generation Partnership Project (3GPP), the Internet Engineering Task Force (IETF) and the Institute of Electrical and Electronics Engineers (IEEE) [7].

4.1.1) IMT-2020

This standard was published by the ITU, that is a specialized agency of the United Nations (UN), it takes charge of the ICT matters, where it coordinates the global use of the radio spectrum and assists in the development of global ICT(Information and communications technology) technical standards in all matters relating to broadband internet, wireless technology, latest generation wire, Internet access, data, voice, broadcasting, next generation networks, …etc.

In 2015, the ITU identified three spectrum bands that will be used for 5G, after a year from that (in 2016), it redefined the criteria for the selection of 5G radio interface technologies.

In late 2016, a special ITU focus group concluded a preliminary study into the standards necessary to meet 5G's performance targets, including concentrations on network architecture, fixed wireless convergence, network management requirements, and network management framework.

This standardization is not official, the official one is expected to be published in the next few months of 2020, but the ITU-R has published a sum of requirements for the 5G networks [7].

4.1.2) 5G Standard of 3GPP

This international body is a communications-focused organization made up of seven telecommunications standard development organizations called "organizational partners." It is composed of supporting-member companies like the aforementioned company. The organization is charged with formulating the 5G technical specifications, which ultimately become standards.

In mid-2017, the 3GPP Technical Specifications Groups agreed on a detailed work plan for the first release of 5G specifications. The work plan included a set of tasks and checkpoints to guide ongoing 5G studies of next-generation architecture and the 5G New Radio (NR), focusing on eMBB, uRLLC, frequency ranges, and the importance of forward compatibility in radio and protocol design [7].

4.1.3) 5G Standard of IETF

The IETF is the standards body coming up with the key specifications for virtualization functions evolving IP protocols to support network virtualization. For example, IETF is pioneering Service Function Chaining (SFC), which will link the virtualized components of the 5G architecture such as the base station, serving gateway, and packet data gateway into a single path. This will permit the dynamic creation and linkage of Virtual Network Functions (VNFs).

Other new technology under development by IETF includes routing-related testing, including protocols for distributed networking, segment routing, and path computation to meet the constraints of the 5G NR. IETF works synergistically with 3GPP on the development of 5G, covering not only new technology under IETF development but also new uses of existing technologies [7].

4.1.4) 5G Standard of IEEE

5G will redefine a wide range of industries: immersive entertainment and experiences, safer, more autonomous transportation, reliable access to remote health care, improved public safety and security, smarter agriculture, more efficient use of energy/utilities, more autonomous manufacturing, sustainable cities and infrastructure, digitized logistics and retail. The list is organized by the relevant Working Group (WG) below [7]:

- The IEEE 802.1 WG addresses architecture, internet working, security, network management, time-sensitive networking, and protocol layers above Layer 2.
- The IEEE 802.3 WG develops standards for Ethernet, which underpins most of the world's wired packet networks. Numerous standards and projects in the WG address environments such as data centers, campuses, wide-area networks, and automobiles.
- The IEEE 802.11 WG develops standards for wireless LANs, many of which are certified as Wi-Fi. of particular interest for 5G are IEEE 802.11ad.
- The IEEE 802.15 WG develops standards for a variety of wireless specialty networks. The P802.15.3d project targets 100 G bit/s throughput in the THz spectrum for switched point-to-point links supporting applications such as data centers and intra-device communication.
- IEEE 802.15.8 Task Group develops a standard optimized for peer-to-peer communications with fully distributed coordination. Some features include fast discovery without association, group communications with simultaneous membership in multiple groups. It offers the potential of great improvement in the delivery and monitoring of ever-growing data service ranging from social networking, gaming, advertisement, emergency communications, it also offers to offload traffic from cellular networks.
- The IEEE 802.16 WG develops standards for wireless MANs. IEEE 802.16 and 802.16.1 are currently recommended by ITU for use in international 3G and 4G applications per the IMT-2000, IMT-Advanced standards.
- The IEEE 802.21 WG is developing the P802.21.1 project to address media independent services, such as handover, home energy management system, software-defined radio access networks, radio resource management, and device-to-device communication.

5)Technologies to meet the requirement of 5G

5.1) Massive MIMO

Massive MIMO (Multiple-input multiple-output) is one of the foundations of 5G technology. While the traditional telecommunication technologies use the standard MIMO, where the base stations use somewhere between two to a dozen antennas, the Massive MIMO technology uses a huge number of antennas, which can be a few dozens and, in some cases, even a couple hundred. This exponential increase in the number of antennas can help support many devices in a small area. As Huawei puts in their report, 5G could provide up to a million connections per square kilometers. This is nowhere near possible with the existing standard MIMO; hence the Massive MIMO comes with its own disadvantage. Deploying over a hundred antennas in a single place could cause a serious interference issue. Also, the MIMO systems need to pack a lot more antennas in a small area, so they require a use of higher frequency (shorter wavelength) of signals. This is where the technologies of Beam-forming and Millimeter waves come in [8].

5.2) Beam-forming

Beam-forming, basically, boils down to the principal of adapting the transmission of EMR to a particular surrounding. The traditional antennas broadcast the radiation in every direction which might cause a serious interference issue. Beam-forming works in such a way that if you are in the middle of a cluster of buildings, the signal from your phone is bouncing all over the place and interfering with signals from other phones in that area. This causes the signal to be fragmented into smaller pieces. So, the massive MIMO station keeps track of all these small pieces and their timings of arrival. Then they use their signal processing algorithms to give you a clear, uninterfered signal. This would allow the Massive MIMO station to send a focused data stream to your phone. This is way more efficient than the existing technology [8].

5.3) Millimeter Waves

The wireless technology we use today uses the frequency of less than 6 GHz. However, with more and more devices coming online, we may see some significant decrements in performance. The millimeter waves use a higher frequency i.e. lower wavelength signals (wavelength may vary from 1 to 10 millimeter). Scientists are testing the frequencies of up to 300GHz, which is going to create more room for the devices that are going to be added in the future. But this technology comes with a major drawback. The signals cannot easily travel through concrete, and they are likely to be absorbed by obstacles(trees and rain). Hence, a small cell network is used [8].

5.4) Small cell network

Small cell network is nothing but a concept of getting around an obstacle rather than facing it. As said earlier, the millimeter waves have a hard time traveling through obstacles, foliage, and rain. So, small cell network allows the signal to run past the obstacle. Huge massive MIMO stations broadcast the signals over long distances. Yet, adding thousands of small low powered sub-stations all around the city would solve the problem of signals being blocked by infrastructures. What this basically does is that when a lot of sub-stations are available, the phone can automatically switch to another, closer substation when it experiences any kind of barrier [8].

5.5) Full duplex

In one of the reports by IEEE Spectrum, they have explained full duplex in the most understandable way possible: Picture two people talking at the same time but still able to understand one another, which means their conversation could take half as long and their next discussion could start sooner. The base stations we use today transfer signals one way at a time. This is due to a principle called reciprocity which means that the signals move forward and backward in the same frequency. So, one has to wait until the signal has fully traveled to the receiver until they send back another set of signals. Until now, the transmission relied on waiting until the signal was fully transmitted or using a different frequency, which is not efficient at all due to the time it took to exchange signals resulting in more power consumption. However, researchers have been able to create a workaround for this problem. They have

created high-speed switches so that the signals can reroute themselves while being able to walk past each other [8].

✓ These five techniques are illustrated in the following figure:

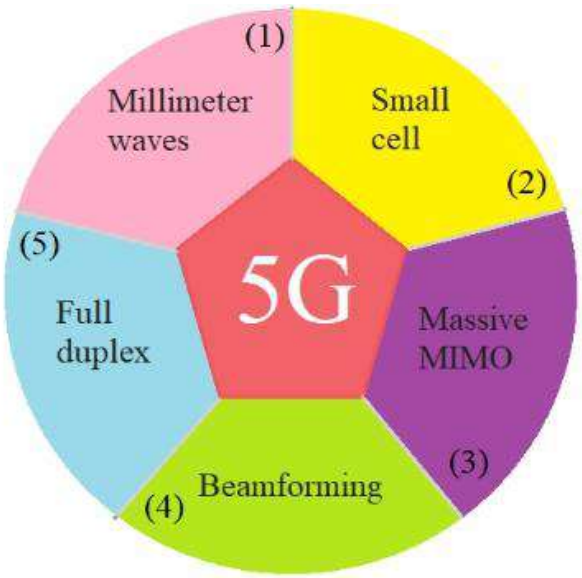


Figure I.2: The technologies used in 5G.

5.6) Device-to-Device communication

In device-to-device communication (D2D), nearby devices are allowed to establish local links with each other so that traffic flow between them rather than routing traffic through the base station, this reduces power consumption, latency as well as increases the peak data rates. D2D communication is particularly useful in a situation where the area is crowded [9].

6) Key features of 5G

The features of 5G communication systems shall enable a wireless infrastructure for human-centric communications and upcoming industrial requirements at data rates as high as 1Tbps (Terabits per second). The important 5G expectations catering to these requirements are summarized here [10]:

- Huge network capacity is expected to serve the exponential growth of traffic volume. More than 100-fold increase of area capacity from 0.1Mbits/s/m^2 to 10-100 Mbits/s/m^2 is being targeted as compared to the existing LTE-A architectures of 4G.

- Ultrahigh reliability and availability with extremely low loss rate is expected from 5G network. Network availability of 99.999% is expected particularly in critical control services, traffic safety, automated industrial applications and medical services.
- Ultra-low latency is envisioned for 5G networks for real-time applications, such as internet, traffic control, industrial processes and other vital.
- infrastructures. 5G is expected to provide latency of 1ms or less and nearly "zero latency" in case of cloud-based applications.
- Ubiquitous connectivity is required to cater expected ten to hundred-fold increment in the number of connected users resulting in connection density to rise from 105 devices/km^2 to 106 -107 devices/km^2.
- High data rate of 1 Gbps (Gigabits per second) throughput everywhere, including sparsely populated rural areas is expected. The peak data rate more than 10 Gbps is expected for indoor and dense outdoor environments.
- Energy efficiency is more compelling for future communication technologies with millions additional base stations (BS) and billions of connected user equipment (UE).
- A 100-fold increase in bits/Joule along with 10-times prolonged battery life of devices is being targeted for 5G network.

7) Physical layer of 5G

7.1) Modulation

7.1.1) Phase Shift Keying (PSK)

A simple two-state use of Phase Shift Keying (PSK) is called Binary Phase Shift Keying (BPSK). (Figure I.3) shows two distinct points, corresponding to the two phases. Each point indicates either the bit "0" or "1". The two dots indicate where the tip of the vector would land for note that the amplitude of both points is the same, and the carrier only changes its phase. With only two phases in use, they are normally chosen to be 180 degrees for maximum variation [11].

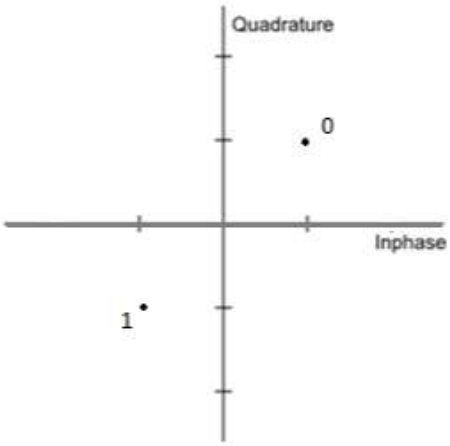


Figure I.3: Binary Phase Shift Keying (BPSK) modulation [11].

7.1.2) Quadrature phase-shift keying (QPSK)

Quadrature phase-shift keying **(**QPSK) uses four different phases of the carrier to represent four different binary sequences of two bits (Figure I.4). Improving system efficiency. Again, the amplitude of the carrier remains constant and only the phase changes [11].

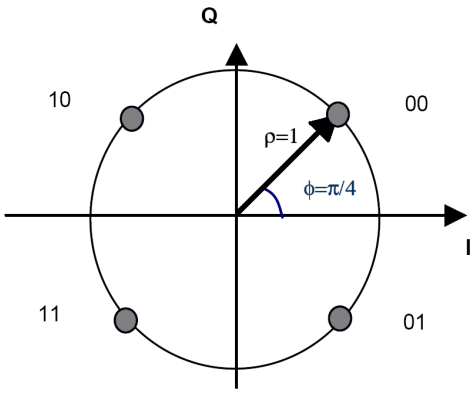


Figure I. 4: Quadrature phase-shift keying (QPSK) [12].

7.1.3) Quadrature Amplitude Modulation (QAM)

QAM uses both amplitude and phase modulation to determine the modulation state. For example, 16 QAM (Figure I.5), provides 16 different binary sequences of 16 bits with unique amplitude and phase values. Now we see why the term constellation diagram is used, because the binary sequences look like a pattern of stars in the sky. This method can encode 4 bits of

data for each binary sequences. For simplicity, these logic values are not shown in the figure, but they would sequence through 0000, 0001, 0010, up to 1111.

- ✓ Higher-order QAM systems are used, including 64-QAM and 256-QAM. Increasing the number of amplitude/phase states increases the number of bits that can be encoded which dramatically increases the system efficiency of the modulation system. The trade-off is a degradation in noise performance: the more unique states that are encoded, the closer they are together in amplitude and phase. Any noise present in the system is more likely to introduce a demodulation error [11].

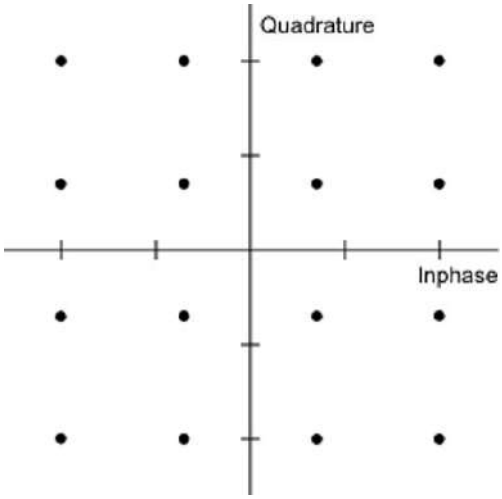


Figure I.5: 16-QAM Modulation [11].

7.2) Channel coding

The channel coding techniques for 5G NR have changed from Turbo codes into 4G to polar codes for the control channels and LDPC (low-density parity check codes) for the data channels [13].

7.2.1) LDPC Coding

LDPC is the error-correcting code.Namely delivering the correct information to the correct processing elements at the correct time. The expertise is particularly timely, because 3GPP New Radio has adopted the most flexible and most capable LDPC code ever standardized. This flexibility allows New Radio to meet the requirements of the diverse 5G use cases, but makes the implementation of flexible LDPC decoders with high throughput, low latency and high hardware efficiency more challenging than ever [14].

- **LDPC-Codes Generation:** LDPC codes use parity check matrix having uniform weight in rows and column. Parity-check matrix has M rows and A column as M x A parity check matrix so LDPC definition of LDPC in terms of parity matrix given below. Code rate of (A, K) LDPC matrix R=K/A, where K= (A-M). The regular parity-check matrix, H_1 is shown below [14]:

$$H_1 = \begin{bmatrix} 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 1 \\ 1 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 1 & 1 & 1 & 0 \end{bmatrix} \quad (1)$$

5G LDPC codes are QC-LDPC codes which belong to a family of protograph codes.Design of a permutation matrix, as well as design of the protograph, are important aspects for protograph code design [14].

In the 5G specification, a protograph is officially called a base graph, and there are two types of base graphs whose usage is determined by code rate or a size of information bits. A parity check matrix of protograph codes can be constructed from the base graph by replacing each zero-valued entry with a Z × Z all-zero matrix and each non-zero-valued entry with a Z × Z permutation matrix. QC-LDPC codes can be considered as protograph codes whose permutation is only allowed to be a circular shift. In other words, a permutation matrix of QC-LDPC codes is a circularly-shifted identity matrix. One of the main benefits of having a circularly-shifted identity matrix as a permutation matrix is that each permutation is represented by a single number. This greatly reduces the memory requirement for implementation while also facilitating the use of a simple switch network for encoding and decoding [14].

7.2.2) Polar coding

Compared with turbo and LDPC codes, polar codes are far less mature and a conventional approach too, their implementation has not yet emerged. The encoder and decoder of a polar code have regular but intricate structures. During polar decoding, the information bits are decoded one at a time, with each successive bit informing the decoding of the next. However, the complexity associated with decoding each successive bit varies considerably, depending on its position in the block and the design of the corresponding polar encoder. This makes it difficult to implement, flexible, high performance polar decoders [14].

7.3) 5G waveform

7.3.1) Cyclic Prefix OFDM

The specific version of OFDM used in 5G NR downlink is cyclic prefix OFDM (CP-OFDM), and it is the same waveform LTE has adopted for the downlink signal.

Within CP-OFDM the last part of data of OFDM frame is appended at the beginning of the OFDM frame and length of cyclic prefix is chosen to be greater than channel delay spread. This overcomes the inter-symbol interference that can result from delays and reflections. In addition to this, the channel delay spread is frequency dependent with the cyclic prefix length chosen to be long enough to account for both interferences. For this reason, the CP length is adaptive according to the link conditions.

The 5G NR uplink has used a different format to 4G LTE. CP-OFDM and DFT-S-OFDM-based waveforms are used in the uplink. Additionally, 5G NR provides for the use of flexible sub carrier spacing. LTE sub carriers normally had a 15KHz spacing, but 5G NR allows the sub-carriers to be spaced at 15KHz x 2s with a maximum spacing of 240 KHz. The integral's carrier spacing rather than fractional carrier spacing is required to preserve the orthogonality of the carriers [15].

The flexible carrier spacing is used to properly support the diverse spectrum bands/types and deployment models that 5G NR will need to accommodate. For example, 5G NR must be able to operate in mm wave bands that have wider channel widths of up to 400 MHz 3GPP 5G NR Release-15 specification details the scalable OFDM numerology with 2s scaling of sub-carrier spacing that can scale with the channel's width, so the FFT size scales so that processing

complexity does not increase unnecessarily for wider bandwidths. The flexible carrier spacing also gives additional resilience to the effects of phase noise within the system.

The use of OFDM waveforms offers a lower implementation complexity compared to that which would be needed if some of the other waveforms considered for 5G had been implemented. In addition to this, OFDM is well understood as it has been used for 4G and many other wireless systems [15].

7.2.3) DFT-S-OFDM

Direct Fourier Transform spread OFDM, commonly abbreviated to DFT-S-OFDM, is an SC or single carrier-like transmission scheme that can be combined with OFDM that gives significant flexibility for a mobile communications system like 5G. It is more commonly known as SC-FDMA.

The transmission processing of SC-FDMA is very similar to that of OFDMA. For each user, the sequence of bits transmitted is mapped to a complex constellation of symbols (BPSK, QPSK or M-Quadrature amplitude modulation). Then different transmitters (users) are assigned different Fourier coefficients. This assignment is carried out in the mapping and damping blocks. The receiver side includes one de-mapping block, one IDFT block, and one detection block for each user signal to be received. Just like in OFDM, guard intervals (called cyclic prefixes) with cyclic repetition are introduced between blocks of symbols in view to efficiently eliminate inter-symbol interference from time spreading (caused by multi-path propagation) among the blocks [15].

8) 5G frequency bands

The radio spectrum includes frequencies between 3 gigahertz (GHz) and 300 gigahertz (GHz). 4G LTE technology operated at additional frequency bands and spectrum around 600 MHz, 700 MHz, 1.7/2.1 GHz, 2.3 GHz and 2.5 GHz. Verizon's 5G UWB network operates at considerably higher radio frequencies than its early mobile counterparts.

5G, the newest generation of cellular network technology, is going to be the fastest of these networks. This new technology will be a huge leap forward in terms of reduced latency as well as speed. This speed will rely heavily on the fact that 5G uses higher radio frequencies. The anticipated peak speed of 5G is 20 Gbps, which is 20 times faster than existing 4G networks top speeds, and that is thanks to the added frequencies and spectrum bands.

High-band spectrum is sometimes called millimeter wavelength (mm Wave) in the cellular industry, and it enables about 28 GHz of frequency. This is considerably faster than 4G networks, which use about 700 MHz-2500 MHz frequency to transfer information.

Recently deployed, Verizon's 5G UWB network uses 28 and 39 GHz mm Wave spectrum bands having 40x bandwidth of 4G LTE 700MHz network. This will aid the network in latency, speed and capacity, as a higher number of devices will be able to operate on that high-band frequency spectrum. To give you an idea, 4G latency is around 20-30 milliseconds, which means it takes that amount of time for information to travel between origin and receiver.

5G latency, though, is expected to someday reach below 10 milliseconds. Verizon will also deploy 5G technology on lower frequency bands including 700 MHz-2500 MHz frequency range to cover wide area. This means devices that are further away from the antenna should be able to access the network [16].

9) Network densification:

The 5G architecture is going to be ultra-dense multi-tier network with the co-existence of many different classes of BSs including small cells, macro-cells, and low power nodes like relays and remote radio heads; along with the provision for device-to-device (D2D) or machine-to-machine (M2M) communication. This kind of heterogeneous network will provide flexible coverage, improved spectral efficiency, capacity and power consumption. However, robust mechanisms for the inter-tier and intra-tier interferences avoidance must be provided. The interferences related challenges associated with network densification can be addressed by cognitive radio, as discussed in next section [10].

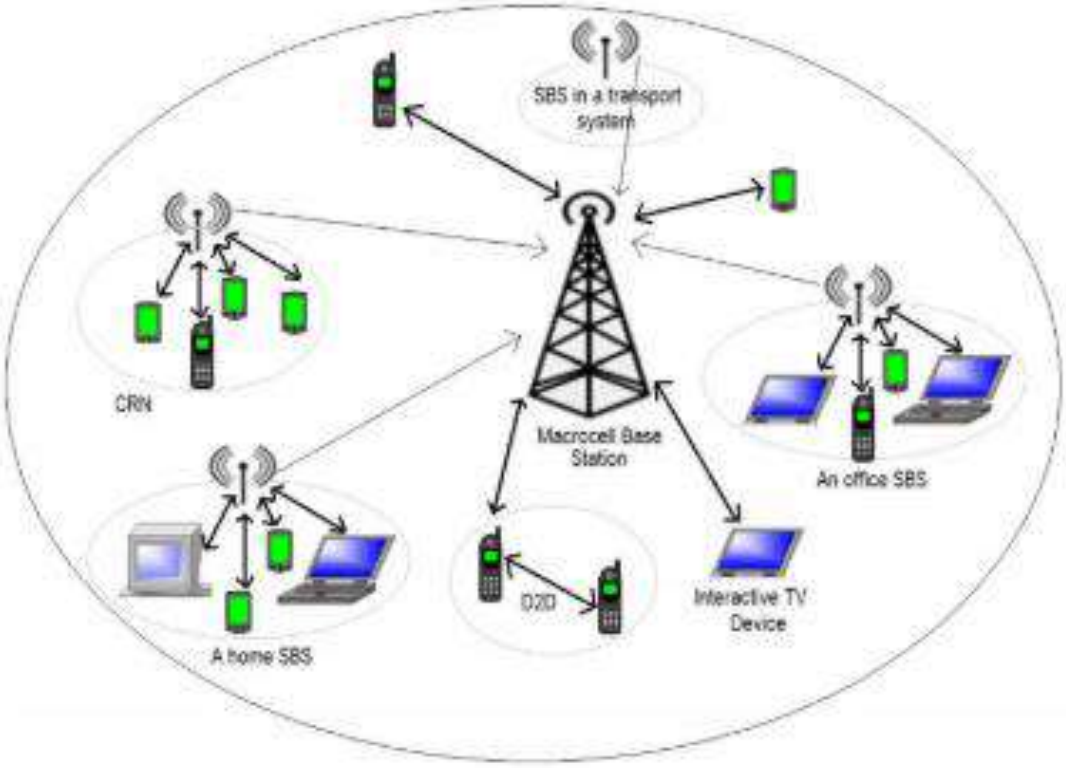


Figure.I.6: Heterogeneous multi-tier networks [10].

10) Conclusion

The fifth-generation standard for mobile network, is the new version of all the mobile technologies whose deployment will have to start, in Europe, United States and Asia in particular, in the course of 2020. It is a set of algorithms and methods of transmitting information that must offer both speed and extremely low latency, it will allow to develop new services and improvements to existing systems, 5G is going to be a new revolution in wireless systems markets, taking the lead to one of the biggest technological transformation of our lifetime providing a faster data delivery to costumers.

Chapter II:

Cognitive radio technology

1) Introduction

Conventional cellular networks built on expensive licensed bands have introduced a paradoxical situation, where on one side, there is scarcity of spectrum due to increasing demand and on other side there is spectrum underutilization. In 5G paradigms, the Cognitive Radio (CR) technology is being proposed to facilitate dynamic spectrum sharing between 5G network entities.

Cognitive Radio (CR) is one critical enabling technology for future communications and networking that can utilize the limited network resources in a more efficient and flexible way which intelligently detects a particular segment of the radio spectrum currently in use and selects unused spectrum quickly without interfering the transmission of authorized users.

In this chapter, we will know what cognitive radio is and what is the role of it in the 5G, we will also talk about its functionalities and for what it is used, and what technologies are mostly used for it.

2) Role of cognitive radio in the 5G

Apart from the humongous increase in the mobile traffic, the nature of traffic is not only random but also diverse. The diverse variation in traffic in terms of periods of time poses difficulties in the planning of network infrastructure. The networks are unable to handle huge loads during peak traffic and become underutilized when traffic is less. Further, the services offered are also diverse such as browsing, multimedia and gaming and hence the Quality of Service (QoS) requirements are different for various services. The existing cellular network are ineffective to handle high volume multimedia downloads. The major challenge is to look into aspects to make the futuristic technology of 5G real. Utilization of spectrum, consumption of energy and efficiency of cost are three major performance measures that should be majorly looked into in the development of a 5G system. In spite of the many advantages, 5G gravely experience difficult performance issues. Interference-tolerant CR networks can achieve enhanced spectrum utilization and better energy efficiency by opportunistically sharing the radio spectrum resources with licensed users. Cognitive Radio is essentially developed for Dynamic Spectrum Allocation (DSA) which makes the radio smart. Recently, dense deployment of small cells over rich portions of low radio frequency is being investigated as a potential approach for spectrum sharing and to address the energy efficiency in 5G architecture. The network densification results in partial channel sharing and co-channel deployment, with macro cells as primary licensed users and small cell tiers as cognitive or secondary users. Deployment of such a varied environment with co-existence of several

classes of cells, power nodes and user equipment create a heterogeneous network (HetNet) scenario, which has opened up enormous possibilities in addressing 5G requirements [10] [18].

3) What is cognitive radio

A Software Defined Radio (SDR) is a transmitter in which operating parameters, including transmission frequency, modulation type, and maximum radiated or conducted output power can be altered without making any hardware changes [19].

The concept of CR emerged as an extension of SDR technology. Definitions vary, but most experts agree that a CR device should have the following characteristics [19]:

- Aware of its environment.
- Capable of altering its physical behavior to adapt to its current environment.
- Learns from previous experiences.
- Deals with unknown situations at the time of the radio's design.

The CR term was initially presented as a promising technology to fully exploit the under-utilized spectrum by Joseph Mitola III in 1998 and later published on article in 1999 by him and Gerald Q. Maguire [19]. They present the idea for wireless technologies that the related networks are sufficiently computationally intelligent about, radio resources and related computer-to-computer communications to detect user communications need as a function of use context and to provide radio resources and wireless services most appropriate to those needs.

Cognitive Radio is a radio for wireless communications in which either a network or a wireless node changes its transmission or reception parameters based on the interaction with the environment to communicate efficiently without interfering with licensed users. This changing of parameters is based on the active monitoring of external and internal radio environment such as radio frequency spectrum, user behavior trends and network state [19].

Cognitive radio can learn about current use of spectrum in their operating area, make intelligent decisions, and react to immediate changes in the use of spectrum by other authorized users. The goal of CR technology is to relieve radio spectrum overcrowding, which actually translates to a lack of access to full radio spectrum utilization. Due to this adaptive

behavior, the CR can easily avoid the interference of signals in a crowded radio frequency spectrum [19].

4) Cognitive radio applications

There are several applications for cognitive radio, among which are the following [20]:

- The application of CR networks to emergency and public safety communications by utilizing white space.
- The potential of CR networks for executing Dynamic Spectrum Access (DSA).
- Application of CR networks to military action such as chemical, biological, radiological and nuclear attack detection and investigation, command control, obtaining information of battle damage evaluations, battlefield surveillance, intelligence assistance, and targeting.
- They are also proven to be helpful in establishing medical body area networks which can be utilized in omnipresent patient monitoring that aids in immediately notifying the doctors regarding vital information of patients such as sugar level, blood pressure, blood oxygen and Electrocardiogram (ECG)…etc. This gives the additional advantage of reducing the risk of infections and also increases the patient's mobility.
- Cognitive radio is practical also to wireless sensor networks, where packet relaying can take place using primary and secondary queues to forward packets without delays and with minimum power consumption.

The 5G requirements such as higher system capacity and higher spectrum efficiencies require to use the DSA as a cognitive radio application, which is focused on in this work. Figure II.1 shows the different applications of the CR [20].

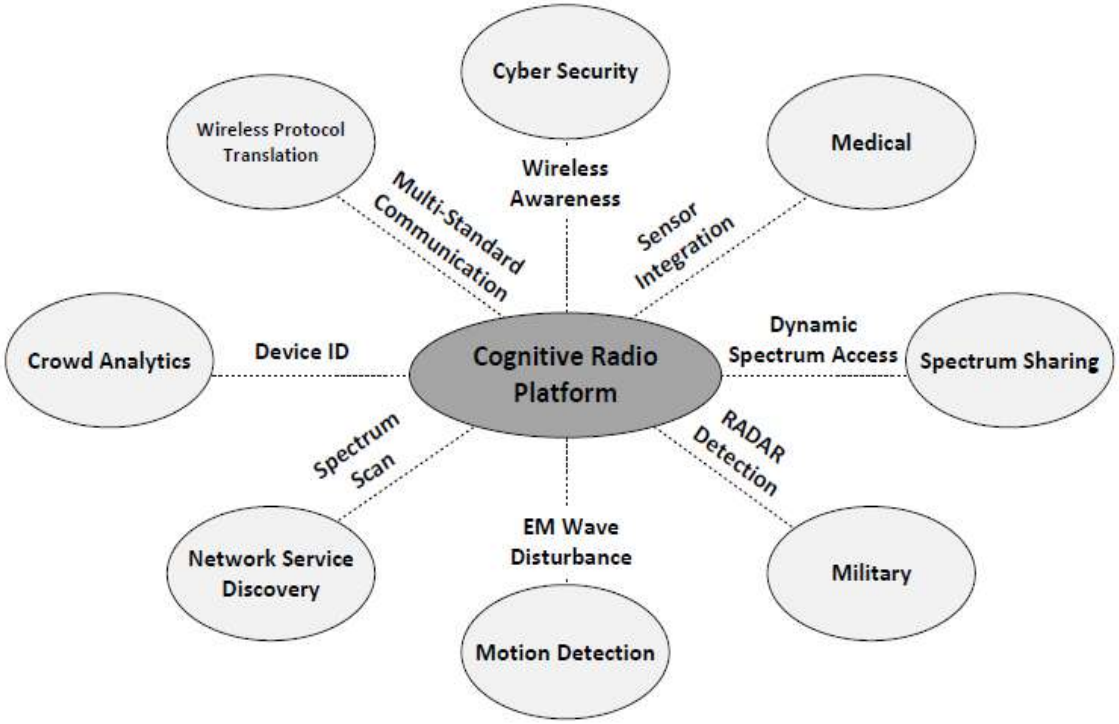


Figure II.1: cognitive radio applications [20].

5) Dynamic spectrum access technique

The aim of the CR technology is to provide the maximum efficiency of the spectrum to improve its utilization by using DSA techniques. The key to enable the maximum spectrum efficiency is to provide the capability to share the wireless channel with licensed users in an opportunistic manner. This goal might be achieved using dynamic and efficient spectrum management techniques [21].

The front end of a DSA system consists of two types of antennas, an ultra-wide-band (UWB) sensing antenna and a reconfigurable communication antenna. It has two primary objectives in mind [21]:

- Highly reliable communication whenever and wherever needed.
- Efficient utilization of the radio spectrum.

6) Cognitive radio network

Cognitive radio network (CRN) consists of three elements [22]:

- **The cognitive radio user (CRU):** The CRU does not have a band licenses, this user uses the band of the primary user opportunistically when the band is free. Sensing task is applied internally on the CR user. However, they do not make a decision on the spectrum band availability, they only report the sensing results to the Base Station (BS). The CRUs in the case of 5G network are the 5G User Equipment (UE) or Spectrum Agent (SA).

- **The CR Base Station (CRBS):** The CRBS is a fixed infrastructure in a CR network that manages and controls the spectrum. CR users report their sensing result to the CRBS in order to make a decision on the spectrum availability. Furthermore, CRBS provides synchronization in the sensing operations among the CR users. In the case of 5G network the CRBS is called the fusion center (FC).

- **Spectrum Broker:** Spectrum broker is a centralized entity that allows CR networks to share the available spectrum resources. It is not directly responsible for the sensing operation; it only manages the available spectrum resources according to the sensing information collected by each network.

The coexistence of a cognitive radio network with other existing networks can be seen in the Figure II.2 where at each time instance there are [23]:

- ✓ **Primary user (PU) with license:** A user who has higher priority or legacy rights on the usage of a specific part of the spectrum.

- ✓ **Secondary user (SU) unlicensed:** A user who has a lower priority.

- ✓ **Spectrum hole:** white space, white spectrum, idle frequency/channel/band.

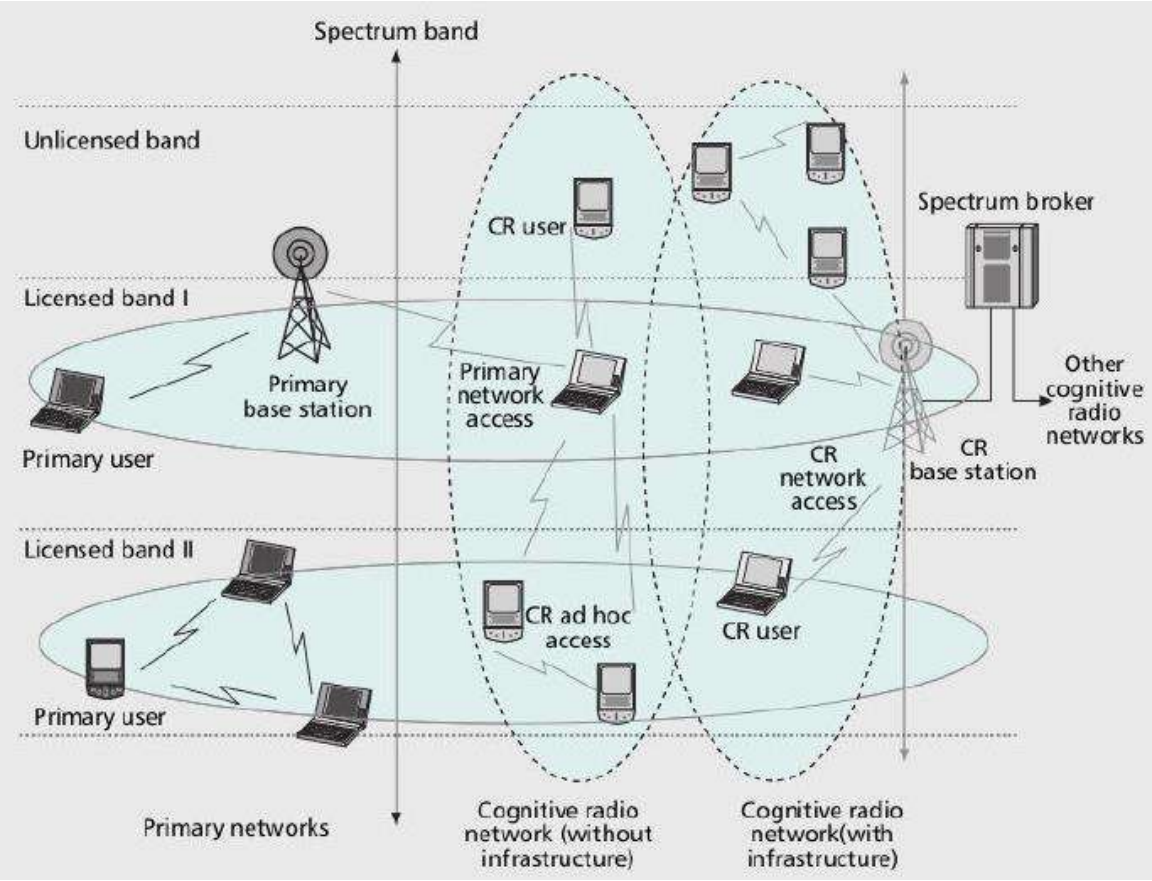


Figure II.2: Coexistence of a Cognitive Radio Network [23].

A primary network (licensed network) is an existing network for Primary Users (PU). They have permission to communicate through licensed bands. The operations of PUs are controlled by their primary network. The primary users have high priority in their bands so they should not be interfered by CRUs. CRUs have their own CRBS where the CRU accesses to their resources [23].

CRUs, then, must only communicate when PUs are not using their licensed bands. As we can see in the Figure II.2, they can also use unlicensed bands. This heterogeneous spectrum capability of CRU is an important characteristic that must be taken into account. In general, a CRN should be able to perform efficiently the spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility tasks.

The spectrum sensing consists in monitoring the spectrum and to detect spectrum holes. In the spectrum decision task, CRUs are allocated in the different available frequencies.

This function not only depends on frequency availability, but also depends on some internal or external policies [23].

Since various CRUs could try to access the same resources, we need to coordinate these accesses to prevent collisions between multiple CRUs. These actions are performed by the spectrum sharing function. Finally, if a PU would enter to a portion of spectrum that is occupied by a CRU, this CRU must be reallocated to a different frequency in order to not affect the PU communication. This is the spectrum mobility function [23].

Figure II.3 shows the different channels of wireless technology using dynamic spectrum access techniques. As we can see white space or spectrum hole can be found in time. The idea is to take this hole for the transmission of a CRU [24].

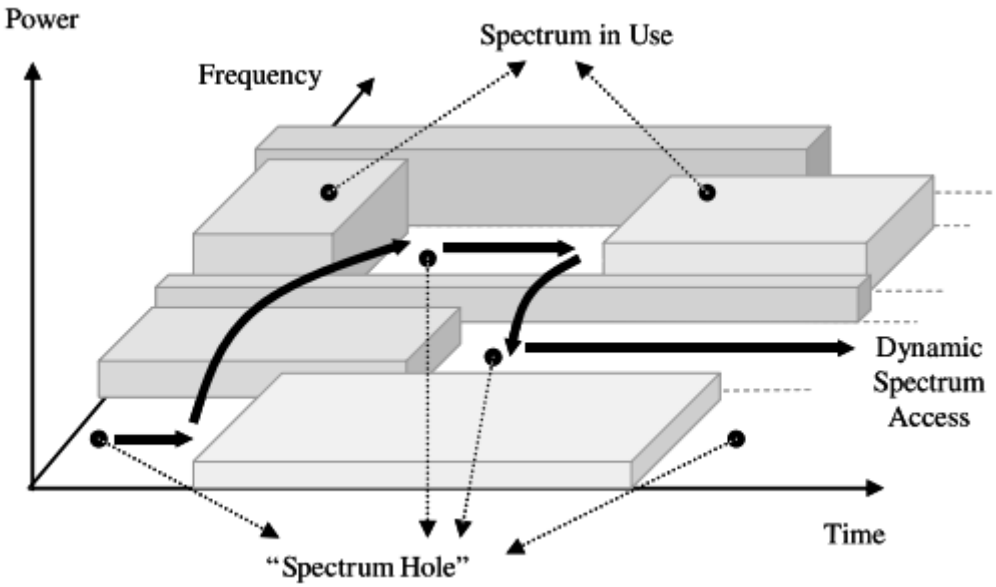


Figure II.3: The spectrum hole or white space concept [24].

7) The key enabling technologies of CR

The key enabling technologies of CR Networks (CRN) are the cognitive radio techniques that provide the capability to share the spectrum in an opportunistic manner. Formally, a CR is defined as a radio that can change its transmitter parameters based on interaction with its environment. From this definition, two main characteristics of cognitive radio can be defined [24]:

a) Re-configurability

In order to allocate the CRU into a large dynamic frequency range, the transceivers and receivers of the devices in the CRN must allow the reconfiguration of their parameters over a wide frequency range. Dynamic spectrum access is one of the major challenges in the design of a CRN.

b) Cognitive capability

This is the real-time interaction that allows the identification of the portions of the spectrum that are unused at specific time or location CR enables the usage of temporally unused spectrum, referred to as spectrum hole or white space.

8) Cognition cycle

Cognitive radio learns about the environment through the process of cognition cycle. The cognition cycle presented in the figure below summarizes the major steps involved in the cognition process [24].

Four main cognitive functionalities are performed to set up communication in a cognitive radio network. As shown in Figure II.4, these functionalities are spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility [24].

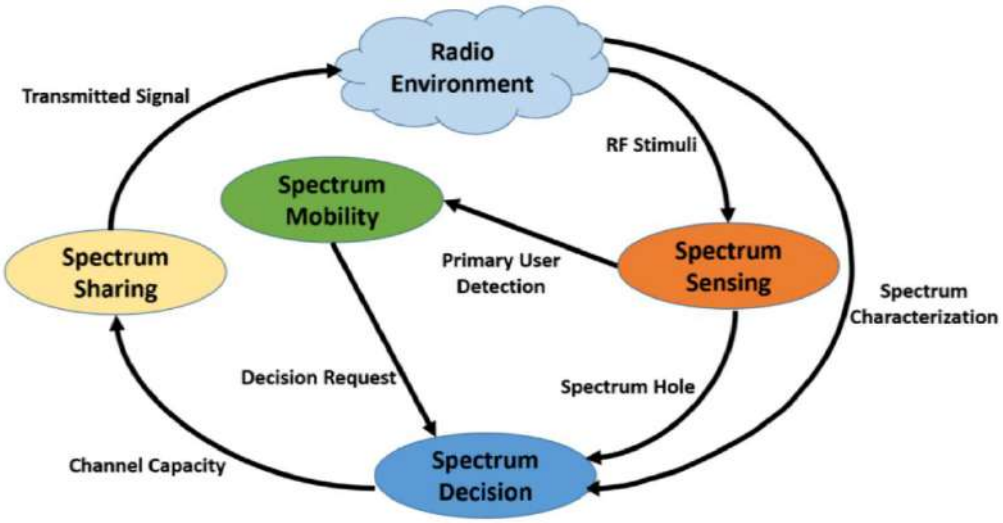


Figure II.4: Cognitive Radio Cycle [24].

Spectrum sensing is performed to exploit spectrum holes (opportunities) for unlicensed access, and spectrum decision is executed to utilize these opportunities without causing interference to the primary user. Moreover, spectrum sharing allows the secondary user to share the spectrum with the primary user and other secondary users, where the IEEE 802.22, IEEE 802.19.1 and 802.11af standards are developed to manage this functionality. Finally, spectrum mobility allows secondary users to move to another empty frequency band after vacating the current band for the primary user [24].

9) Cognitive Radio functions:

The key functions of CR, to carry efficient and intelligent dynamic spectrum access, are as follows [25]:

9.1) Spectrum analysis (decision):

The SU uses the information obtained from spectrum sensing to schedule and plan spectrum access. In this case, the transmission requirements of SUs have to optimize the transmission parameters. Main mechanisms of spectrum management are spectrum analysis and spectrum access optimization. In spectrum analysis, information from spectrum sensing is analyzed to get knowledge concerning the spectrum holes such as duration of availability, interference estimation and collision probability with a PU due to sensing error [25].

Then, a decision to access the bandwidth, frequency, transmit power, modulation mode, time duration and location of spectrum is made by optimizing the system performance

given the preferred objective i.e. maximize the throughput of the SUs (this thesis focused on these ones) and maintain the interference caused to PUs lower the target threshold [13].

9.2) Spectrum access (sharing):

Before a decision is made on spectrum access based on spectrum analysis, the unlicensed users access the spectrum holes. Spectrum access is carried out based on a cognitive medium access control (MAC) protocol, which proposes to avoid conflict with PUs and also with other SUs. The CR transmitter is also required to make compromise with the CR receiver to synchronize the transmission in order that the transmitted data is received successfully [25].

A cognitive MAC protocol either is based on a fixed allocation MAC (such as FDMA, TDMA and CDMA) or a random-access MAC (such as ALOHA and CSMA/CA) [26].

9.3) Spectrum mobility:

Spectrum mobility is a task related to the change of operating frequency band of SUs.

When a PU starts accessing a radio channel, which is currently being used by an SU, the SU switched to another idle spectrum band. This change in channel of operating frequency band is referred to as spectrum handoff. In spectrum handoff, the different layers in the protocol stacks, the protocol parameters have to be adjusted to match the new channel of operating frequency band. Spectrum handoff must attempt to make certain that the communication by the SUs can carry on in the new spectrum band. This observable fact is most appealing in this thesis [25].

9.4) Spectrum sensing:

Signal detection is a key part of spectrum sensing in cognitive radio (CR) networks. It aims to sense the unused portion of the licensed spectrum and provide opportunistic access to the secondary users in the absence of the licensed primary users. Ideally, secondary users should guarantee no harmful interference to the primary user. Therefore, detection accuracy plays a key role in determining the CR network's reliability and overall performance, when spectrum sensing occupancy is considered, the cognitive radio system must accommodate a range of considerations [25]:

- **Continuous Spectrum Sensing:** It is mandatory for the CR system to constantly sense the spectrum occupancy. Normally PU in a CR network on a non-interference basis and sensing of the spectrum when PU returns during spectrum sensing.

- **Monitor for alternative empty spectrum:** If the PU returns to the spectrum being used, then an alternative space needs to be allocated for existing SU.

10) Spectrum sensing techniques

Cognitive radio networks can operate in two modes; non-cooperative and cooperative. In the non- cooperative mode, one secondary user senses the channel and decides whether it is occupied by the primary user or not. While in the cooperative mode, multiple secondary users sense the channel and exchange their information with each other, in the case of distributed spectrum sensing, they send their information to a spectrum manager (fusion center), in the case of centralized spectrum sensing, to decide upon the status of the channel. cooperative sensing is used to achieve higher sensing accuracy by overcoming some sensing issues such as; hidden primary user problem, multipath fading, and shadowing. However, cooperative sensing can be highly affected by possible security attacks as the attacker may send false data to the fusion center and affect the final decision regarding the primary user's presence [19].

✓ The two techniques are summarized in the below diagram. (figure II.5).

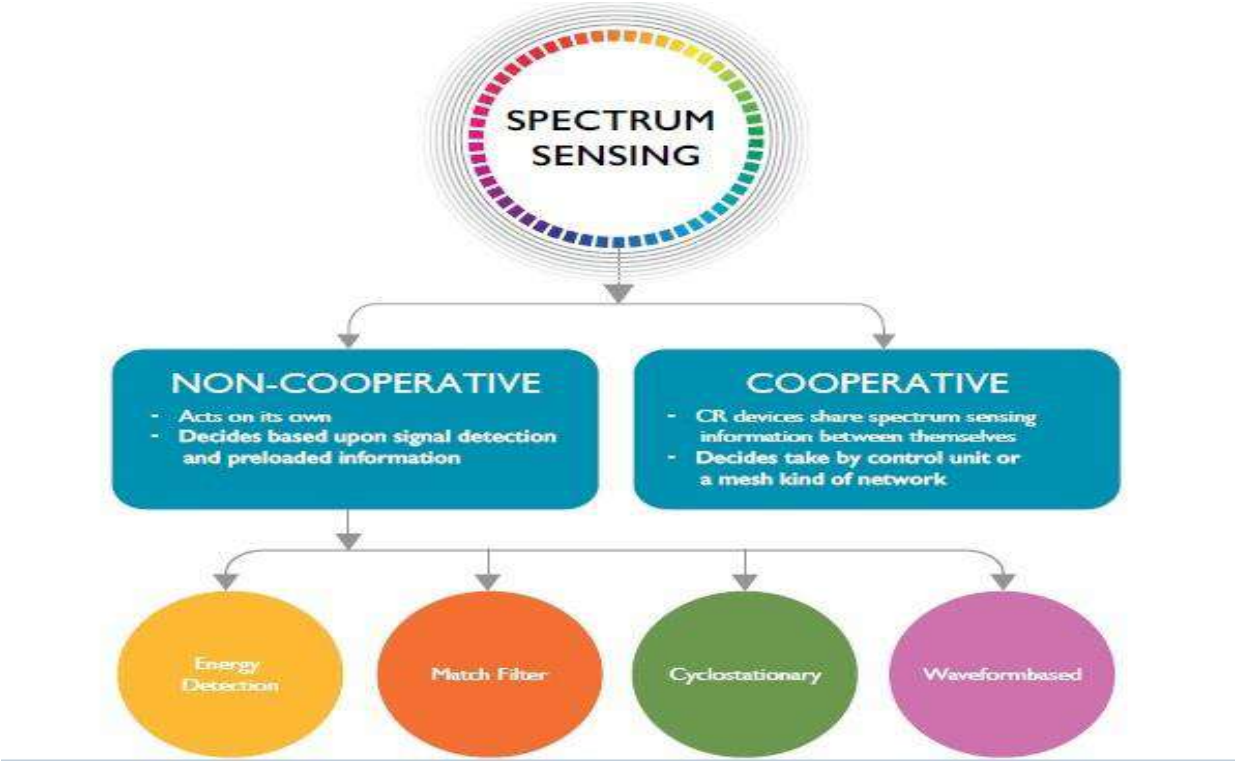


Figure II.5: Spectrum sensing techniques.

10.1) Non-Cooperative Spectrum Sensing

Each user determines the presence and absence of PUs independently. This technique is based on detecting weak signals from a primary transmitter. The primary transmitter is based on detection techniques where a cognitive user determines signal strength generated from the PU.

In non-cooperative sensing, there is no signaling between the PUs, the cognitive users and primary receivers are unaware of the cognitive user's location [25].

The transmission detection approach is based on the detection of the weak signal from a primary transmitter through the local observations of cognitive radio users. Basic hypothesis model for transmitter detection can be defined as in equation [27].

$$H_1: x(n) = s(n)h + w(n) \quad (1)$$

$$H_0: x(n) = w(n) \quad (2)$$

where x(n) is the received signal by secondary users, s(n) is the transmitted signal of the primary user, h is the channel coefficient; and w(n) is additive white Gaussian noise with variance σ_w^2 [9].

H0 and H1 are the sensing states for absence and presence of signal respectively. Another saying; H0 is the null hypothesis which indicates that primary user does not communicate and H1 is the alternative hypothesis that indicates the existence of the primary user. We can define four possible cases for the detected signal [24]:

- declaring H1 under H1 hypothesis which leads to Probability of Detection (P_d).
- declaring H0 under H1 hypothesis which leads to Probability of Missing (P_m).
- declaring H1 under H0 hypothesis which leads to Probability of False Alarm (P_f).
- declaring H0 under H0 hypothesis:

If H0 is decided under H1 hypothesis, then it leads to probability of missing (P_m) that is probability of deciding that there is no primary signal while primary signal actually exists.

If H1 is decided while H0 is observed then it refers to find the probability of false alarm (P_f) which indicates to decide primary signal exists while there is actually no primary user communicating. Thus, false alarm error leads to inefficient usage of the spectrum [24].

Literally, the aim of the signal detector is to achieve correct detection all of the time, but this can never be perfectly achieved in practice because of the statistical nature of the problem. Therefore, signal detectors are designed to operate within prescribed minimum error levels. Missed detections are the biggest issue for spectrum sensing, as it means possibly interfering with the primary system. Nevertheless, it is desirable to keep false alarm probability as low as possible, so that the system can exploit all possible transmission opportunities [24].

The non-cooperative sensing is performed by many sensing methods such as Energy detection, matched filter…etc.

10.1.1) Energy detection technique

Energy detection is a spectrum sensing method that detects the presence/absence of a signal just by measuring the received signal power. Energy Detection (ED) is the most popular sensing technique in cooperative sensing [28].

are also called Blind Signal Detection (BSD) because it ignores the structure of the signal and estimates the presence of the signal by comparing the energy received with a known threshold (THR) derived from the statistics of the noise (SNR) [28].

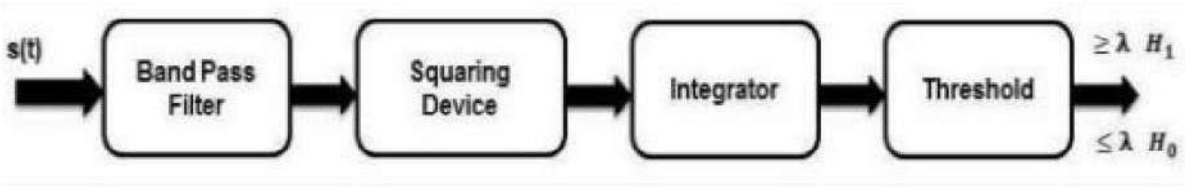


Figure II.6: Energy detection block diagram [9].

The block diagram for the energy detection technique is shown in the Figure II.6. In this method, signal is passed through band pass filter of the bandwidth BW and is squared and integrated over time interval T. The output of the integrator (decision metric) denoted by y acts as a test statistic to test the two hypotheses H_0 and H_1, y can be expressed as [9]:

$$y = \frac{2}{N_0}\int_0^T |x(t)|^2 dt \tag{3}$$

$$y = \frac{2}{N_0 W}\sum_{n=1}^{N} |x(n)|^2 \tag{4}$$

where N is the number of samples of the observation signal and N_0 is the two-sided noise power spectral density (PSD) [9].

This decision metric, y is then compared to a predefined threshold, λ. This comparison is used to detect the existence or the absence of the primary user. The threshold value can be variable based on the channel conditions [28].

a) Optimization of threshold of the energy detection technique

The optimal threshold is obtained by minimizing the total error rate, which is: $P_f + P_m$.

the average probability of false alarm, the average probability of detection, and the average probability of missed detection over AWGN channels are given respectively by [9]:

$$P_{f,i} = \frac{\Gamma\left(u, \frac{\lambda_i}{2}\right)}{\Gamma(u)} \tag{5}$$

$$P_{d,i} = Q_u\left(\sqrt{2}\gamma_i, \sqrt{\lambda_i}\right) \tag{6}$$

$$P_{m,i} = 1 - P_{d,i} \tag{7}$$

In the above equations, γ denote the instantaneous signal-to-noise ratio (SNR), $u = N/2$, $\Gamma(a, x)$ is the incomplete gamma function given by [9]:

$$\Gamma(a, x) = \int_x^{\infty} t^{a-1} e^{-t}\, dt \tag{8}$$

where $\Gamma(a)$ is the gamma function, and $Q_u(a, b)$ is the generalized Marcum Q function given by:

$$Q_u(ax) = \frac{1}{a^{u-1}} \int_x^{\infty} t^u \cdot e^{-\frac{t^2+a^2}{2}} I_{u-1}(at) dt \tag{9}$$

with $I_{u-1}(\cdot)$ being the modified Bessel function of the first kind and order $u - 1$.

There exist one and only value of λ which minimizes $\left(P_f + P_m\right)$. Thus, the optimal threshold λ^* is given by [9]:

$$\lambda^* = \text{argmin}_{\lambda}\left(P_f + P_m\right) \tag{10}$$

It can be achieved when $\frac{\partial P_f}{\partial \lambda} + \frac{\partial P_m}{\partial \lambda} = 0$.

The derivation of P_f and ∂P_m are given by [9]:

$$\frac{\partial P_f}{\partial \lambda} = -\frac{1}{(U-1)!}\frac{\lambda^{u-1}}{2^u}e^{-\frac{\lambda}{2}} \tag{11}$$

In an AWGN channel [9]:

$$\frac{\partial P_d}{\partial \lambda} = -\frac{\lambda^{\frac{u-1}{2}}}{2(2\gamma)^{\frac{u-1}{2}}}\exp\left(-\frac{\lambda+2\gamma}{2}\right)I_{u-1}\left(\sqrt{2\gamma\lambda}\right) \tag{12}$$

In a Rayleigh fading channel [9]:

$$\frac{\partial P_d}{\partial \lambda} = \frac{1}{2(1+\bar{\gamma})}\left(\frac{\Gamma\left(u-1,\frac{\lambda}{2}\right)}{(u-2)!} - P_d\right) \tag{13}$$

Using (5) and (6), the solution to $\frac{\partial P_f}{\partial \lambda} + \frac{\partial P_m}{\partial \lambda} = 0$ (for λ) can be evaluated numerically. The solution is the optimal detection threshold. The figure II.7 shows $\frac{\partial P_f}{\partial \lambda} + \frac{\partial P_m}{\partial \lambda}$ curve in term of λ for SNR of 5dB and N of 40 samples. We can observe that, the optimal threshold in this case is 43.

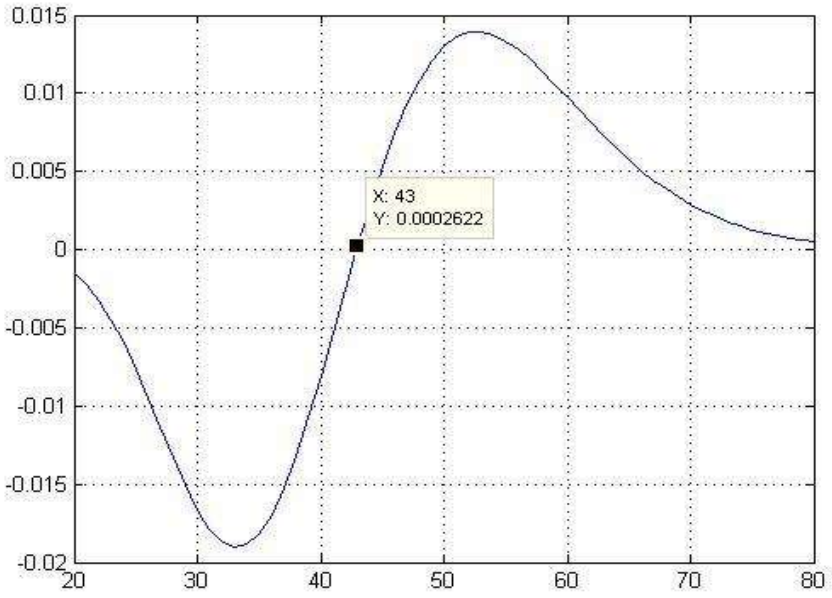


Figure II.7: Optimal non-cooperative ED Threshold.

10.1.2) Matched filter Based detection

The matched filter is the linear optimal filter used for coherent signal detection to maximize the signal-to-noise ratio (SNR) in the presence of additive stochastic noise [28].

This detection method is known as an optimal detector in stationary Gaussian noise. However, the matched filter necessitates not only a prior knowledge of the characteristics of the Primary User signal but also the synchronization between the Primary User transmitter and the Cognitive Radio user [28].

Matched filter operation is equivalent to correlation in which the unknown signal is convolved with the filter whose impulse response is the mirror and time shifted version of a reference signal. The operation of matched filter detection is expressed as [9] [28]:

$$Y[n] = \sum_{k=-\infty}^{\infty} h[n-k] \cdot s[k] \tag{14}$$

Where 's' is the unknown signal (vector) and is convolved with the 'h', the impulse response of matched filter that is matched to the reference signal for maximizing the SNR.

Detection by using matched filter is useful only in cases where the information from the primary users is known to the cognitive users.

a) Pilot detection

In mostly all current communication system, a deterministic pilot signal is transmitted for synchronization and channel acquisition. The power of the pilot tone is typically 1-10% of the total transmitted power. This makes transmitter detection based on pilot signal detection a very attractive technique. The benefit of pilot signals, if they are perfectly known to cognitive radio sensor, is that it can be processed coherently using a matched filter, hence achieve a maximal SNR as explained before. In most primary communication systems, a sine wave tone is used. However, for packet-based systems, a short preamble packet containing a high autocorrelation pseudo-noise sequence is used as a pilot. If a cognitive radio sensor knows the packet structure of the system, then it can perform coherent processing of a preamble through a set of matched filter correlations [9].

The decision metric or the test statistic of the matched filter-based sensing is given by:

$$y = \sum_{N} x(n) x_p^*(n) \tag{15}$$

Where $x_p^*(n)$ is the conjugate of the known pilot signal.

The decision on the occupancy of a band can be obtained by comparing the decision metric with a threshold λ. The optimal threshold is obtained by simulation results of the total error rate curve in term of λ, which is discussed in the next chapter.

10.1.3) Cyclostationary based detection

Another detection method used is the cyclostationary feature detection which depends on the fact that modulated signals are generally coupled with sine wave carriers, pulse trains, repeating spreading, hopping sequences or cyclic prefixes which result in periodicity and their statistics, mean and autocorrelation, exhibit periodicity in wide sense.

This periodicity trend is used for analyzing various signal processing tasks such as detection, recognition and estimation of the received signals. Despite having a drawback of high computationally complexity, cyclostationary feature detection performs satisfyingly well under low SNR regimes due to its robustness against unknown level of noise. Another saying; it is not susceptible to noise levels as energy detection [19].

- Under H0 $\boldsymbol{x(t)}$ is not cyclostationary and thus the band is considered free (null hypotheses).
- Under H1 $\boldsymbol{x(t)}$ is cyclostationary and thus the band is considered congested.

10.1.4) Waveform Based detection

As it is mentioned before; the energy detection method is very prone to false detections since its susceptible to changing noise levels. A new approach named waveform-based sensing is proposed. This method is only applicable to systems with known signal patterns. It is underlined that waveform-based sensing outperforms energy detectors in reliability and convergence time. It is also shown that the performance of the sensing algorithms increases as the length of the known signal pattern increases [29].

- The table below shows the advantages and disadvantages of each method:

TableII.1: Summary of spectrum sensing techniques.

Methodology	Advantages	Inconvients
Energy Detection	✓ Less complexity ✓ Does not require prior information about the primary user signal or its statistics	✓ Threshold level depends on the noise floor and false alarm ✓ cannot differentiate between primary signals, noise or interference
Matched Filter	✓ High accuracy ✓ It requires short time and low number of samples to achieve required level of false alarm ✓ Less time for high processing gain	✓ Complexity is high since detailed information about primary is needed ✓ requires dedicated receiver for every primary user signal class ✓ have large power consumption
Cyclostationary	✓ it can differentiate wanted signal from the noise ✓ Primary user transmissions can be detected	✓ computationally complex ✓ When noise is stationary then it performs worse than energy detection method
Waveform Based Detection	✓ Requires short measurement time	✓ Susceptible-to synchronization errors

10.2) Cooperative spectrum sensing

CR cooperative spectrum sensing occurs when a group or network of CRs distribute the sensed information they gain. This provides a better picture of the spectrum usage over the area where the CRs are located. Cooperative sensing is categorized based on how CR users cooperate and share the sensing data in the network, as centralized and distributed sensing [25].

Centralized cooperative sensing includes a central identity called Fusion Center (FC) that follows a three-step process of cooperative sensing [25].

Selecting a frequency band for sensing, that instructs all cooperating CR users to individually perform local sensing.

All cooperating CR users report their sensing results via the control channel. The FC combines the received local sensing information, determines the presence of PUs, and disseminates the decision back to cooperating CR users [25].

10.2.1) Cooperative spectrum sensing elements

Distributed cooperative sensing is a three-stage process that includes local sensing, reporting, and data fusion, which includes fundamental components of cooperative sensing [25].

The process of cooperative sensing is analyzed based on the following key elements shown in Figure.II.8 [25]:

- Techniques required for cooperation, called cooperation models.
- Various sensing techniques as shown in the previous subsection.
- Model for controlling channel and reporting.
- Data fusion model.
- Hypothesis testing.
- Selection of user.
- Knowledge base.

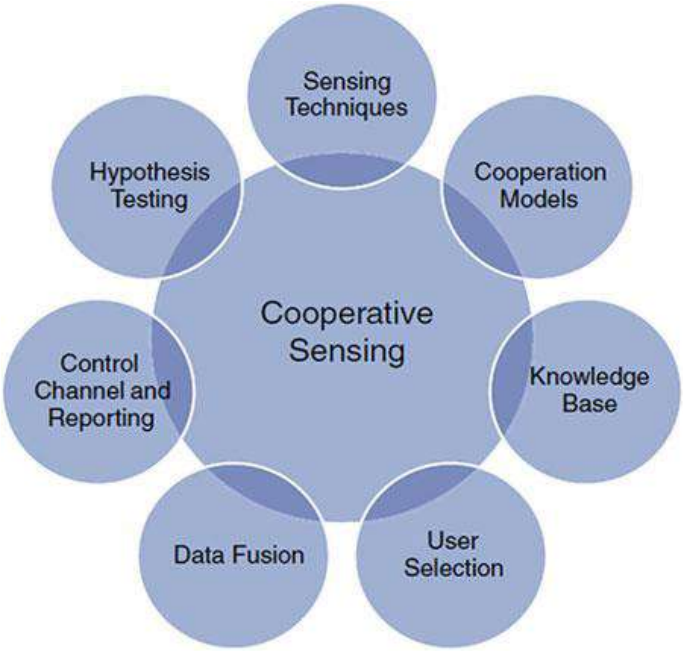


Figure II.8: The process of cooperative spectrum sensing [25].

✓ The cooperative spectrum sensing elements are as follows [25]:

Radio Frequency (RF) environment can be sensed via sensing techniques that are used for detecting the PU signal or the available spectrum, which analyzes how CR users cooperate with each other.

The presence or absence of a PU can be identified using hypothesis testing, and is a statistical test, performed individually by each cooperating user to make local decisions by the fusion center for cooperative decision.

In control channel and reporting, the sensing result obtained by cooperative data fusion is combined, and the sensing results are shared to make the cooperative decision. The signal combining techniques or decision fusion rules can be used for sensing results based on their data type shown in Figure II.8.

User selection is done to maximize the cooperative gain and minimize the cooperation overhead in order to efficiently select the cooperative CR users to find the spectrum space.

Knowledge base includes prior knowledge or accumulated information through experience and may include various details like PU and CR user locations, PU activity models, and Received Signal Strength (RSS). This facilitates the cooperative sensing process to improve detection performance. Spectrum sensing classified as: primary transmitter detection, interference-based detection [25].

10.2.2) Cooperative spectrum sensing with energy detection:

An optimization of cooperative spectrum sensing with energy detection in cognitive radio networks (CRN) was proposed. We consider a CR network composed of K SUs and a Fusion center (FC), as shown in Figure II.8 We assume that each SU performs spectrum sensing independently using energy detection and then the local decisions are sent to the FC which can fuse all available decision information to infer the absence or presence of the PU.

In the following we only consider the spectrum sensing at SU i. e the sensing method is to decide between the following two hypotheses [10]:

$$x_i(t) = \begin{cases} w_i(t), & H_0 \\ h(t)s(t) + w_i(t), & H_1 \end{cases} \quad (16)$$

where $x_i(t)$ is the received signal at the i^{th} SU in time slot t, $s(t)$ is the PU signal, $w_i(t)$ is the additive white Gaussian noise (AWGN), and h_i denotes the complex channel gain of the sensing channel between the PU and the i^{th} SU.

In cooperative spectrum sensing, each cooperative partner makes a binary decision based on its local observation and then forwards one bit of the decision D_i (1 standing for the presence of the PU, 0 for the absence of the PU) to the FC through an error-free channel. At the FC, all 1-bit decisions are fused together according to logic rule:

$$Y = \sum_{i=1}^{k} D_i \begin{cases} \geq n, & \mathrm{H}_1. \\ < \mathrm{n}, & \mathrm{H}_0. \end{cases} \quad (17)$$

where H_0 and H_1 denote the inferences drawn by the FC that the PU signal is not transmitted or transmitted, respectively. The threshold n is an integer, representing the "n-out-of-K" voting rule. It can be seen that the OR rule corresponds to the case of n = 1 and the AND rule corresponds to the case of $n = K$.

The false alarm, Q_f and the missed detection probability, Q_m of cooperative spectrum sensing are given by [9][10]:

$$Q_f = Prob\{H_1|H_0\} = \sum_{l=n}^{K} \binom{k}{l} P_f^l \left(1 - P_f\right)^{k-l} \quad (18)$$

$$Q_f = Prob\{H_1|H_0\} = 1 - \sum_{l=n}^{K} \binom{k}{l} P_d^l (1 - P_d)^{k-l} \quad (19)$$

Where P_f and P_d are obtained from equation (18) and (19), respectively.

We assume that, compared with the distance from any cognitive radio to the primary transmitter, the distance between any two cognitive radios is small, so that the received signal at each cognitive radio experiences almost identical path loss.

a) Optimal voting rule

Suppose that the threshold, λ and K are fixed, the optimal voting rule for cooperative spectrum sensing that minimizes $Q_f + Q_m$ is [9]:

$$n_{opt} = \min\left(k, \left\lceil \frac{k}{1+\alpha} \right\rceil\right) \tag{20}$$

Where $\alpha = \frac{\ln\frac{P_f}{1-P_m}}{\ln\frac{P_m}{1-P_f}}$ and $\lceil . \rceil$ denotes the ceiling function.

b) Optimal energy detection threshold

Suppose that K, n, and the SNR γ are known, the optimal threshold is obtained by minimizing the total error rate $Q_f + Q_m$. The optimal threshold is given by [9][10]:

$$\lambda^* = \text{argmin}_\lambda\left(Q_f + Q_m\right) \tag{21}$$

It can be achieved when $\frac{\partial Q_f}{\partial \lambda} + \frac{\partial Q_m}{\partial \lambda} = 0$ can be evaluated numerically. The solution is the optimal detection threshold. The figure II.9 shows $\frac{\partial Q_f}{\partial \lambda} + \frac{\partial Q_m}{\partial \lambda}$ curve in term of λ for SNR of 5dB and N of 40 samples. We can observe that, the optimal threshold in that case is 44.

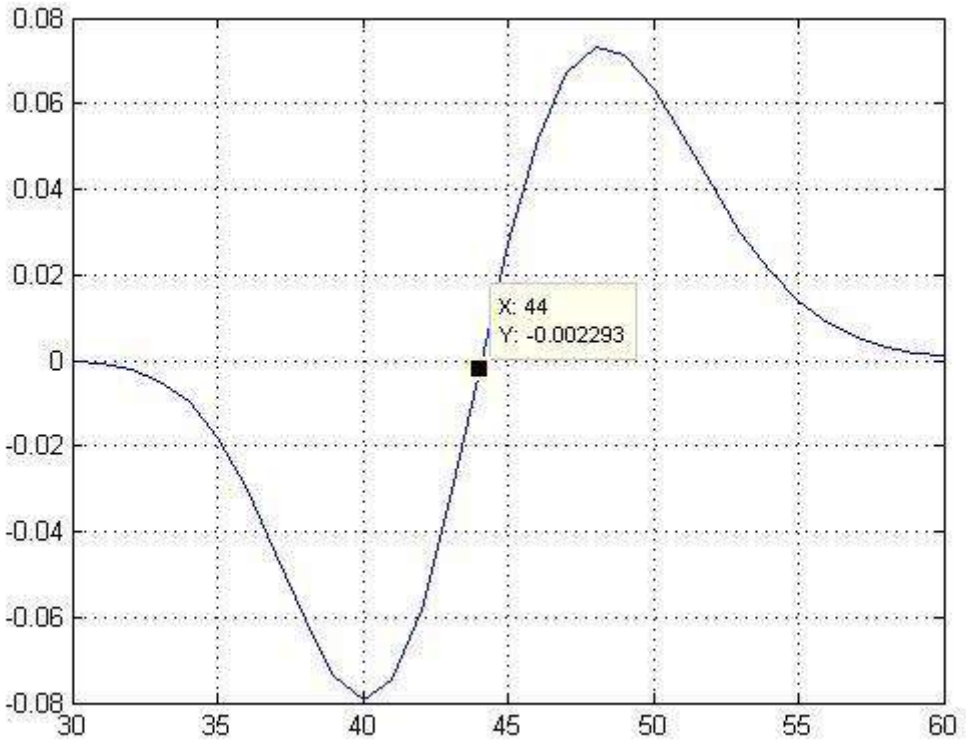


Figure II.9: Optimal cooperative ED threshold.

11) Conclusion

Cognitive Radio is a communication system that allows good spectrum management. This starts with a good detection of the holes by means of techniques which vary in robustness, complexity, calculation time. Using a combination of two techniques (cooperative and sensing technique) will give better results in detection to take advantage from the benefits of each and overcome their limitations. Furthermore, a theoretical optimization of the threshold in the non-cooperative and cooperative energy detection are presented.

chapter III:

Modeling and simulation results

1) Introduction

In this chapter, we simulated through MATLAB software the transmission and reception chain of 5G New radio (NR) physical layer. Then, we evaluated the performance of this physical layer in term of bit error rate (BER) for different values of signal to noise ratio (SNR).

In addition, we simulated various non-cooperative and cooperative spectrum sensing techniques such as: energy detection and matched filter and compared their results in term of total error rate.

2) System model of 5G New Radio transmission and reception chain

The 5G NR physical layer is composed of the LDPC coding, modulation and CP-OFDM. The transmission and reception chain of NR Physical layer is simulated in this chapter. Random input data is generated, and then passed through LDPC coding, after that through modulation then an OFDM system. The block diagram of the 5G NR transmission and reception chain is shown in Figure III.1. In this work, we assumed the additive white Gaussian noise (AWGN) Channel.

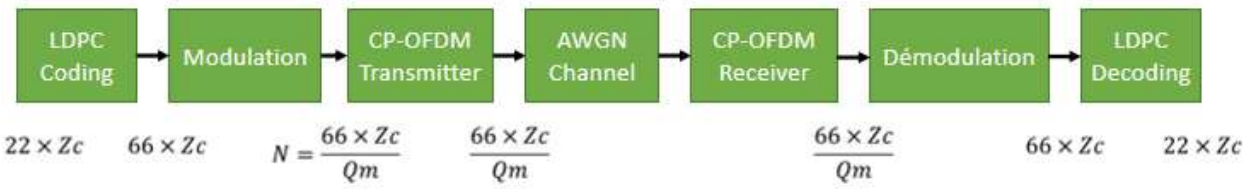


Figure III.1: Block diagram of the 5G NR transmission and reception chain.

2.1) LDPC Coding

In the case of 5G NR, the number of bits of the input data (*A*) of the LDPC coding block must be multiple of 22.i.e. A = 22×Z_C. In this work, we set Z_C to 32. The possible values of Z_C are shown in the table below:

Table III.1: The relationship between shift-value sets and lifting sizes for 5G LDPC codes [30].

Shift-value set index (i_{LS})	Set of lifting sizes (Z)
0	{2, 4, 8, 16, 32, 64, 128, 256}
1	{3, 6, 12, 24, 48, 96, 192, 384}
2	{5, 10, 20, 40, 80, 160, 320}
3	{7, 14, 28, 56, 112, 224}
4	{9, 18, 36, 72, 144, 288}
5	{11, 22, 44, 88, 176, 352}
6	{13, 26, 52, 104, 208}
7	{15, 30, 60, 120, 240}

✓ In the table III.1 The way to generate the parity check matrix (H) of the LDPC code is descried in the 3GPP standard 38.212 [31]. The size of this matrix is: $48Z_c \times 68Z_c$ which is a base graph 1 matrix. The fist $2Z_c$ is then removed after the LDPC coding as shown in Figure III.2. Therefore, the number of bits of the LDPC code output is $66Z_c$. Thus, the code rate of the LDPC coding is 1/3.

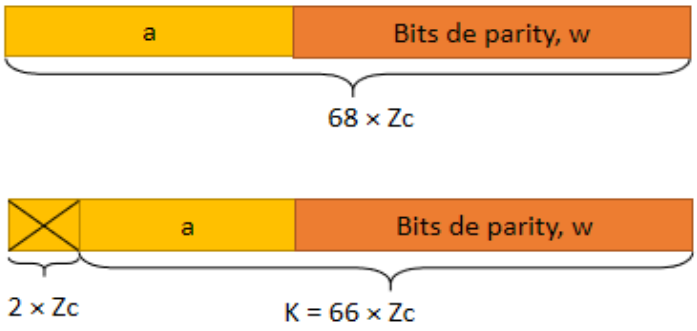


Figure III. 2: Structure of coded LDPC data.

2.2) Modulation schemes

5G NR supports the BPSK, QPSK, 16QAM, 64QAM and 256QAM modulation formats. The modulation converts the data from binary to complex form, the number of this complex values equals to the number of input bits divided by the modulation order. The modulation order (Q_m) of BPSK, QPSK, 16QAM, 64QAM and 256QAM is: 1, 2, 4, 6 and 8, respectively. Different modulation schemes for different UE categories may also be included in the NR specification.

2.3) CP-OFDM

Figure III.3 shows how N equally-spaced sub-carriers can be combined to form an array of parallel signals. Each of the sub-carriers is modulated. These modulated sub-carriers can be used to support independent baseband signals but more typically they are combined to provide the maximum data throughput for one stream of data [32].

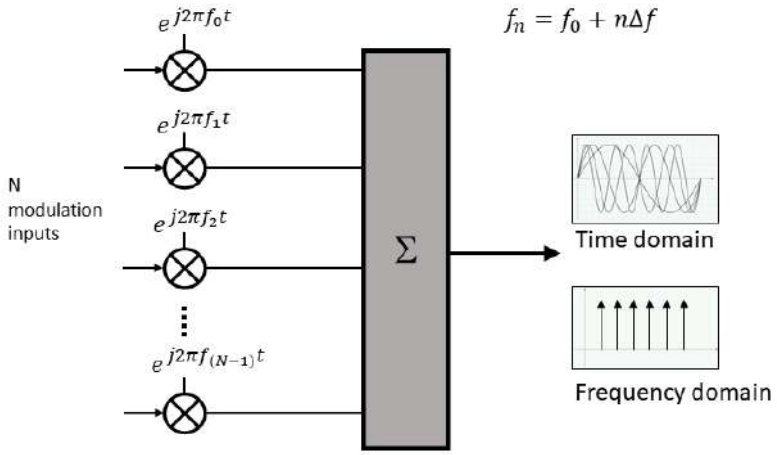


Figure III.3: An OFDM modulator sums signals of different frequencies [32].

We can represent these sub-carriers mathematically, using the complex form [32].

$$x(t) = \sum_{n=0}^{N-1} c_{n\, e^{j2\pi f_n t}} \tag{1}$$

Where:

$$f_n = f_0 + (n * \Delta f) \tag{2}$$

Δf is denoted the sub-carrier spacing, in this work, we set Δf to 60kHz, and the sample time is given by:

$$T_c = \frac{1}{\Delta f \times N} \tag{3}$$

The cyclic prefix (CP) is created so that each OFDM symbol is preceded by a copy of the end part of that same symbol as shown in Figure III.4.

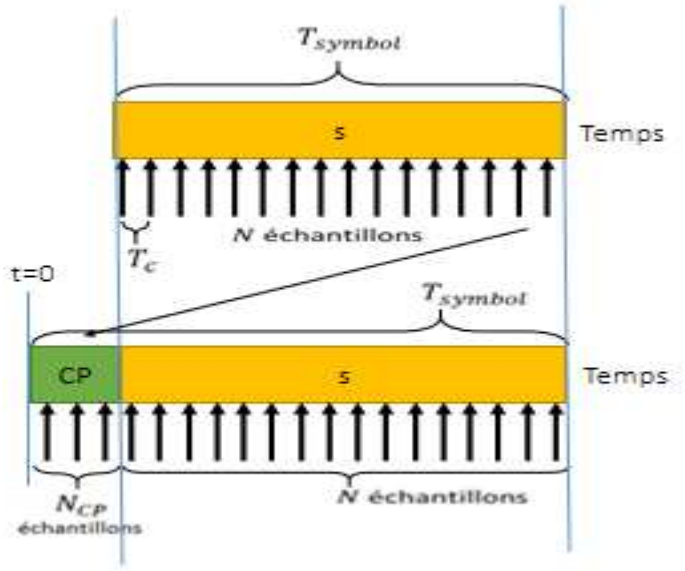


Figure III.4: OFDM cyclic prefix.

The time of a symbol CP-OFDM i.e. an OFDM symbol with prefix cyclic (PC) is defined as:

$$T_{symbol} = (N_{CP} + N)T_c \tag{4}$$

The number of samples of CP is given by:

$$N_{CP} = \text{round}\left(144 \times \frac{N}{2048}\right) \tag{5}$$

In the CP-OFDM receiver, these samples of CP are removed.

3) System model of spectrum sensing techniques

Spectrum sensing is one of the most important processes in the cycle of cognitive radio. It aims essentially to decide between two states:

- ✓ Primary user signal is absent, denoted by H0, or primary user signal is present, denoted by H1. These two states can be modeled as follows [32]:

$$H0: \ x(n) = w(n) \tag{6}$$

$$H1: \ x(n) = h\, s(n) + w(n) \tag{7}$$

where $x(n)$ denotes the received signal, $s(n)$ denotes the transmitted signal, and $w(n)$ denotes the AWGN noise affecting the transmitted signal.

- ✓ In the following, we describe the concept of various non-cooperative and cooperative spectrum sensing techniques such as Energy detection and matched filter.

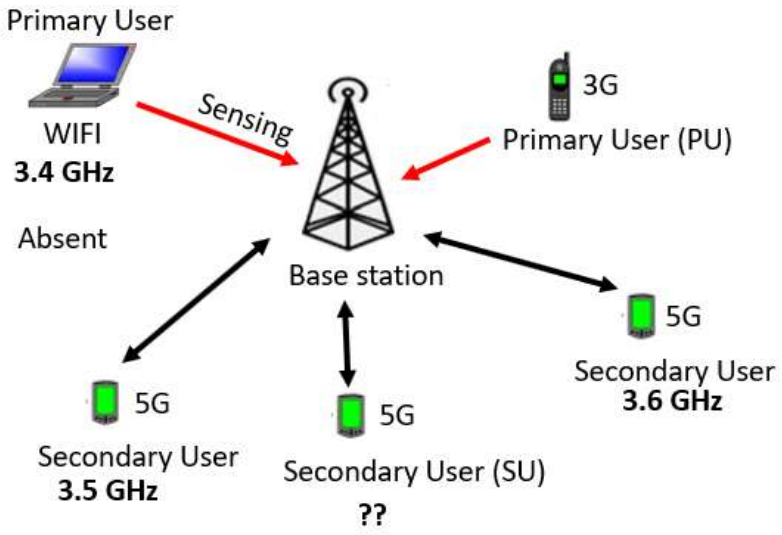


Figure III.5: Cognitive radio system.

The real-time cognition system is illustrated in the figure III.5, when the Primary User (PU) is absent (this case PU is the WIFI user), the base station senses the spectrum using either the Energy Detection method or the Matched Filter method that we focused on in this thesis, the bandwidth is automatically given to the Secondary User (5G user) after confirming that the primary user has quit from that bandwidth.

In the practical environment while sending data from transmitter (PU), there is a lot of disturbance and which corrupts the signal and also, the strength of the signal decreases or varies

at the receiver (Fusion Center) due to multipath fading. Because of this fading, the Bit Error Rate (BER) of the signal increases. In our thesis, we will be using the AWGN and the Rayleigh fading channels model.

3.1) AWGN channel

AWGN channel is a channel model in which the only impairment to communication is the addition of white noise with constant spectral power density and a Gaussian distribution of amplitudes. AWGN is usually taken as a starting point in the design of a communication system [33].

The received signal for hypothesis H_1 in that case is calculated as [33]:

$$\boldsymbol{x(n) = s(n) + w(n)} \tag{8}$$

3.2) Rayleigh fading channel

Rayleigh Channel is used in the wireless communication in which a large amount of noise is added to the transmitted signal. Rayleigh fading is a reasonable model where many objects in the environment scatter the radio signal before it arrives at the receiver. If there is no dominant component to the scatter, then such process will have zero mean and phase evenly distributed 0 and 2π radians. Calling this random variable R, it will have a probability density function [34]:

$$\boldsymbol{P_R(r) = 2\pi/\Omega e^{-r^2/\Omega} \quad ; \quad r \geq 0} \tag{9}$$

$$\text{Where} \quad \boldsymbol{\Omega = E(R^2)} \tag{10}$$

The received signal for hypothesis H1 in that case is calculated as [34]:

$$\boldsymbol{x(n) = h\, s(n) + w(n)} \tag{11}$$

Where $\boldsymbol{h}$ is a random complex Gaussian variable with zero mean and normalized variance [34].

3.3) Total Error Rate (TER)

The total error rate is the sum of the probability of false alarm with the probability of missed detection:

$$\text{TER} = \boldsymbol{P_f} + \boldsymbol{P_m} \tag{12}$$

3.4) Primary User (PU)

The primary user's signal passes by a sum of blocks in the transmission chain, as shown in the figure below, the signal passes by a Q-PSK modulator, then is transformed to a sinc form due to passing through a raised cosine filter where:

$$\boldsymbol{sinc\ x} = \frac{\boldsymbol{\sin x}}{\boldsymbol{x}} \tag{13}$$

At last, the signal goes through an Up converter that translates the frequency of the input signal to the carrier frequency. (see figure III.6).

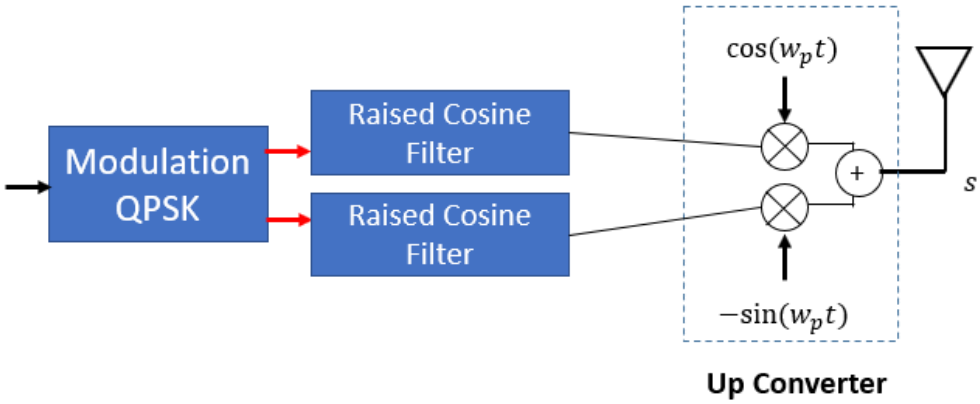


figure III.6: primary user's signal.

In this thesis, we assumed eight samples per bit of the raised cosine filter and the bandwidth of the signal is 5MHz.

3.5) Spectrum sensing techniques

The spectrum sensing techniques that we simulated in this thesis are illustrated in the figure below:

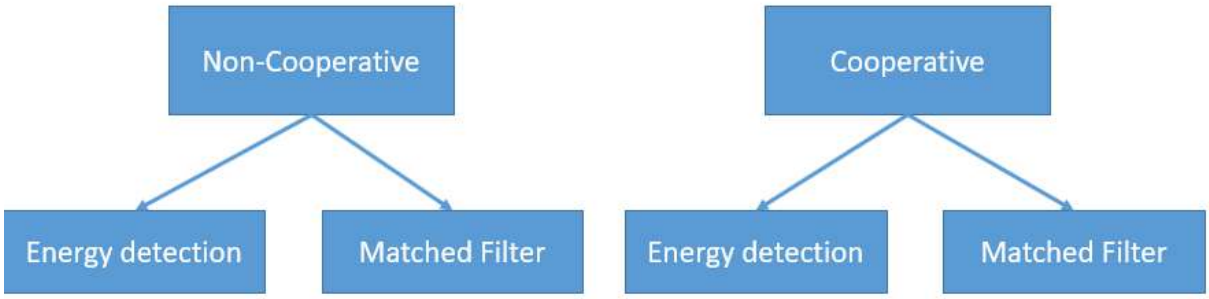


Figure III.7: Spectrum sensing techniques.

3.5.1) Non-cooperative spectrum sensing

This technique is the ideal case of the cognitive radio where there only exists one system, in this case Base Station (BS) that allow to detect the spectrum, the primary user sends the signal to the BS where on its way, it goes through some noise that can change some properties concerning the signal, the BS receives this signal and decides whether the PU is present or absent. The system model of the non-cooperative spectrum sensing is presented in the following figure:



Figure III.8: non-cooperative spectrum sensing system model.

The signal x(n) received at the reception (BS) is processed by a sum of blocks presented in the following figure:

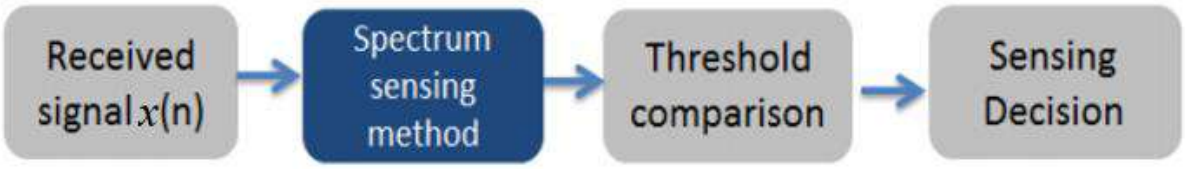


Figure III.9: block diagram of the received signal in the BS.

After reaching the BS, the signal is processed in the spectrum sensing block which consists of either the ED or MF method that we explain right after this, and then, the signal is compared to a predefined threshold for passing finally to the last step which is making a sensing decision for whether the PU is present or not. (see figure III.9).

3.5.1.1) Energy detection (ED)

At the reception, the energy of the received signal is calculated by this equation [9]:

$$\mathrm{E} = \frac{2}{\mathrm{N_0} \times \mathrm{W}} \sum_{1}^{\mathrm{N}} |\mathrm{x}|^2 \tag{14}$$

Where:

- E is the energy of the received signal.
- N_0 is the Noise spectral density.
- W is the two-sided bandwidth of the signal.
- N is the number of samples.

For a given SNR, the N_0 is calculated as follows [9]:

$$N_0 = \frac{E_s^{(N)}}{\mathrm{SNR}} \tag{15}$$

Where the energy of source signal, $E_s^{(N)}$ is calculated as [9]:

$$E_s^{(N)} = \frac{1}{W} \sum_{1}^{N} |x|^2 \tag{16}$$

The variance of the noise (complex Gaussian variable) used in the simulation is given by [9]:

$$\gamma = N_0 \times W/2 \tag{17}$$

To sense the presence of the PU for a given SNR and N we compare the energy with the threshold as follows [9]:

- If $E \geq$ Threshold: Presence of the PU.
- If $E <$ Threshold: Absence of the PU.

The optimal threshold, λ_{opt} is obtained by resolving the equation $\frac{\partial P_f}{\partial \lambda} + \frac{\partial P_m}{\partial \lambda} = 0$ with the unknown λ as descried in subsection (Table III.2). Where it is given graphically i.e. the intersection of the $\frac{\partial P_f}{\partial \lambda} + \frac{\partial P_m}{\partial \lambda}$ and the threshold axis (see Figure II.7). The optimal threshold for $N = 40$ is got in the following table:

Table III.2: non-cooperative spectrum sensing ED's optimal threshold for different SNR.

SNR (dB)	0	5	10	15	20
λ_{opt}	40.8	43	48.7	65	80

- $E_0^{(N)}$ is the received signal energy for N samples when the PU is absent, which means that the received signal is the noise only; it can be calculated by this equation [9]:

$$E_0^{(N)} = \frac{1}{N_0 \times W/2} \sum_1^N |w|^2 \tag{18}$$

- $E_1^{(N)}$ is the received signal energy for N samples when the PU is present (hypothesis H_1), it can be calculated by this equation [9]:

$$E_1^{(N)} = \frac{1}{N_0 \times W/2} \sum_1^N |x|^2 \tag{19}$$

The algorithm that calculates the total error rate (TER) is as follows:

Pd = 0
Pf = 0
for i=1: Nt
    if $E_1^{(N)}$ > optimal threshold
        Pd = Pd + 1
    end
    if $E_0^{(N)}$ > optimal threshold
        Pf = Pf + 1
    end
end
Pd = Pd/Nt
Pf = Pf/Nt
TER = Pf + (1- Pd)

3.5.1.2) Matched filter (MF):

For the MF detection, the PU sends a signal composed of the pilot which is the information that the receiver needs for the calculation of the signal's energy for a certain number of samples N. (see figure III.10).

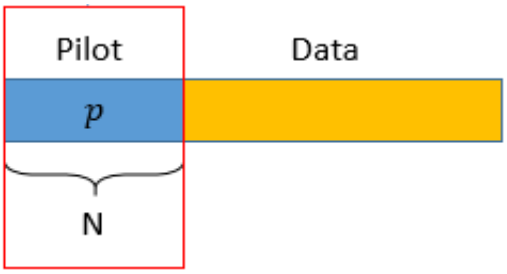


Figure III.10: Frame structure of the received signal of MF sensing.

The MF is based on the same scheme of ED as shown in (figure III.8), where there is:

- $\boldsymbol{E_0^{(N)}}$ is the received signal energy for N samples when the PU is absent, which means that the received signal is the noise only; it can be calculated by this equation [9]:

$$\boldsymbol{E_0^{(N)} = \Re\left(\sum_1^N w \times p^*\right)} \quad (20)$$

- $\boldsymbol{E_1^{(N)}}$ is the received signal energy for N samples when the PU is present, it can be calculated by this equation [9]:

$$E_1^{(N)} = \Re\left(\sum_1^N x \times p^*\right) \tag{21}$$

Where $\Re(.)$ is the real part function and p is the pilot source signal.

3.5.2) Cooperative Spectrum Sensing

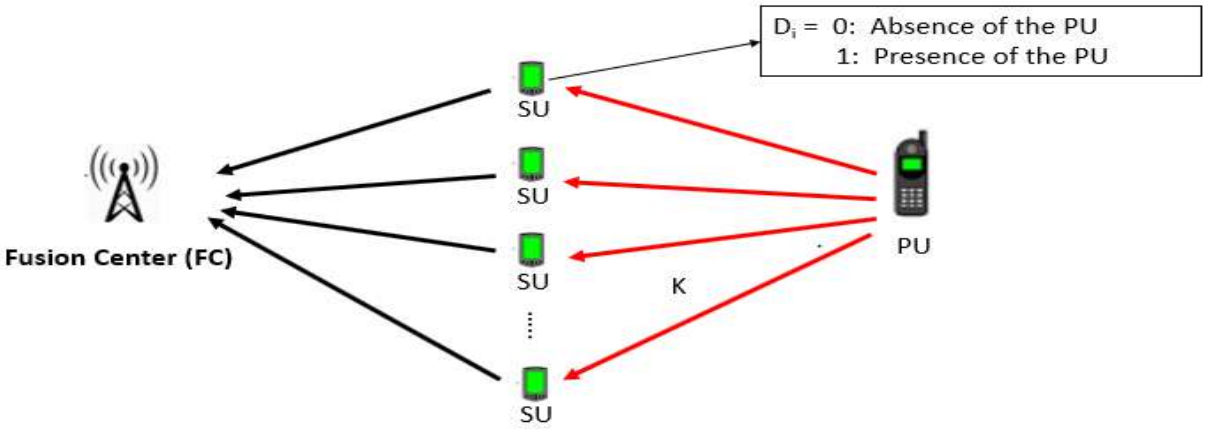


Figure III.11: Cognitive Radio Network (CRN).

The calculation of the energy of the received signal is the same as non-cooperative one.

To sense the presence of the PU, the fusion center calculates Y based on the received SUs decision (D_i) and it compares the Y with the voting rule, n as follows [9]:

$$Y = \sum_{i=1}^{k} D_i \tag{22}$$

- If $Y \geq$ voting rule: Presence of the PU.
- If $Y <$ voting rule: Absence of the PU.

In the case of ED, the optimal threshold, λ_{opt} is obtained by resolving the equation $\frac{\partial Q_f}{\partial \lambda} + \frac{\partial Q_m}{\partial \lambda} = 0$ with the unknown λ as descried in subsection (Table III.3). Where it is given graphically i.e. the intersection of the $\frac{\partial Q_f}{\partial \lambda} + \frac{\partial Q_m}{\partial \lambda}$ and the threshold axis (see figure II.11). The optimal threshold for $N = 40$, voting rule $n = 5$, and $K = 10$ is got in the following table:

Table III.3: cooperative spectrum sensing ED's optimal threshold for different SNR.

SNR (dB)	0	5	10	15	20
λ_{opt}	41.8	44	50	58.5	65

The optimal voting rule is obtained by the following expression as in ssubsection:

$$n_{opt} = \min\left(k, \left[\frac{k}{1+\alpha}\right]\right) \quad (23)$$

The optimal voting rule for $N = 40$, threshold $\lambda = 50$, and $K = 10$ is got in the following table.

Table III.4: cooperative spectrum sensing ED's optimal voting rule for different SNR.

SNR (dB)	0	5	10	15	20
n_{opt}	2	3	5	9	10

4) Simulation results

4.1) 5G NR simulation

In this subsection, we simulated and evaluated 5 types of modulation (BPSK, QPSK, 16 QAM, 64 QAM and 256 QAM) of the physical layer "new radio" of 5G depending on SNR under AWGN channel in term of Bit Error Rate (BER) by using MATLAB software.

Once, we perform enough simulations to obtain valid results at all SNRs of interest, we will plot the results. We begin by creating vectors for both axes. The X-axis vector will contain SNR values, while the Y-axis vector will contain bit error- rates.

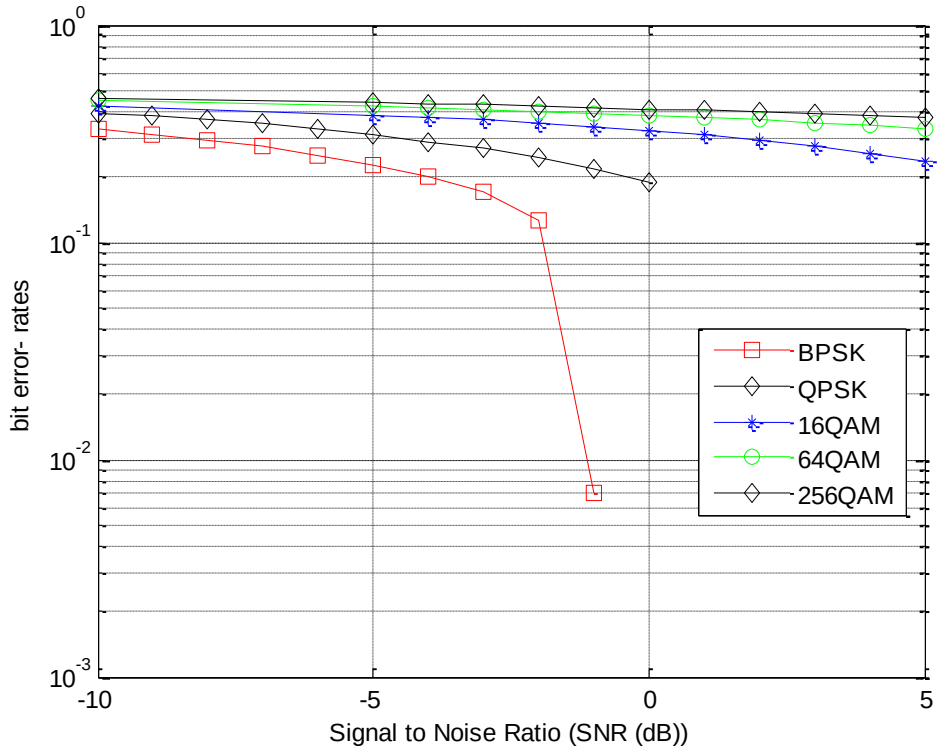


Figure III.12: BER vs. SNR of 5G new radio for (BPSK, QPSK, 16QAM, 64QAM, 256QAM).

✓ The results are presented graphically in figure III.12, which shows the performance in term of BER of 5G New radio physical layer as a function of the SNR. The modulation techniques considered are BPSK, QPSK, 16 QAM, 64 QAM and 256 QAM. The different curves of BER against SNR for various values of SNR=-10, -9, -8….,5 dB for (16QAM, 64QAM, 256QAM) where the number of iterations Nit=500 and Zc=32.

We can see that, the BPSK modulation outperforms the other modulation and the 256-QAM modulation gives the worst performance in term of BER. For example, at SNR = −1 dB the BER of BPSK improves approximately by 0.19 compared with QPSK.

4.2) Power spectral density of primary user signal

✓ Figure III.13 shows the power spectral density (PSD) before raised cosine filter of I component of the primary user signal as described in subsection 3.4 for 200 bits. We observe that, the PSD has the highest value when the frequency is 0 Hz (DC component) where it is equal to -65db/MHz We can also see that, there are the secondary lobes, and the bandwidth of the primary lobe is 5MHz.

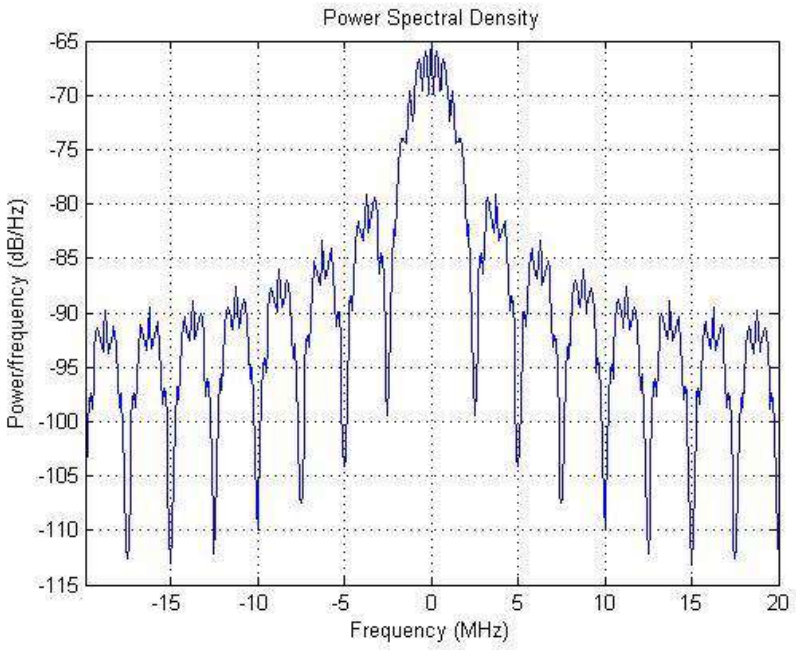


Figure III.13: Power spectral density before raised cosine filter.

✓ Figure III.14 shows the power spectral density (PSD) after raised cosine filter of I component of the primary user signal as described in subsection 3.4. For 200 bits. We observe that, the secondary lobes do not exist, due to elimination by the raised cosine filter.

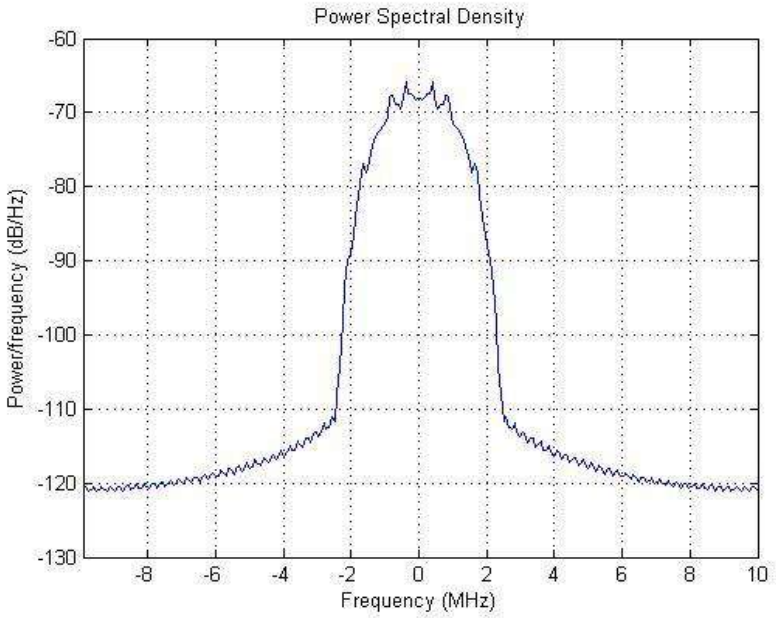
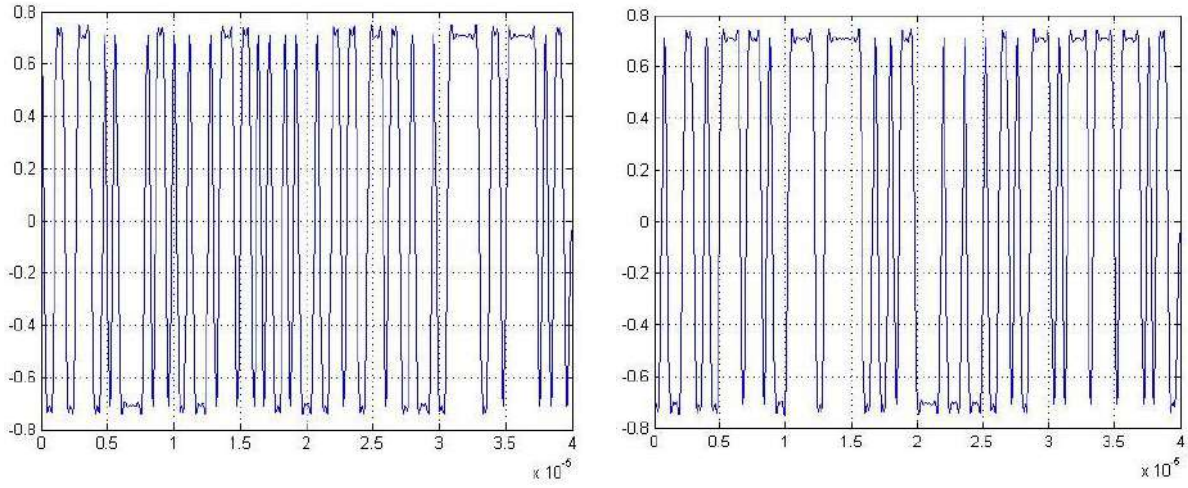


Figure III.14: power spectral density after raised cosine filter.

✓ Figures III.15 shows the time domain of I and Q of PU signal. We can observe that the waveform of the bits symbol is sinc waves.



I **Q**

Figure III.15: Time domain of I and Q of PU signal.

✓ Figure III.16 shows the PSD of the transmitted PU signal with AWGN channel for SNR=dB5. We can see that the spectrum of the PU is centred of the carrier frequency and their bandwidth is limited. The purpose of the spectrum sensing is to band-pass filter and sense the presence of this spectrum.

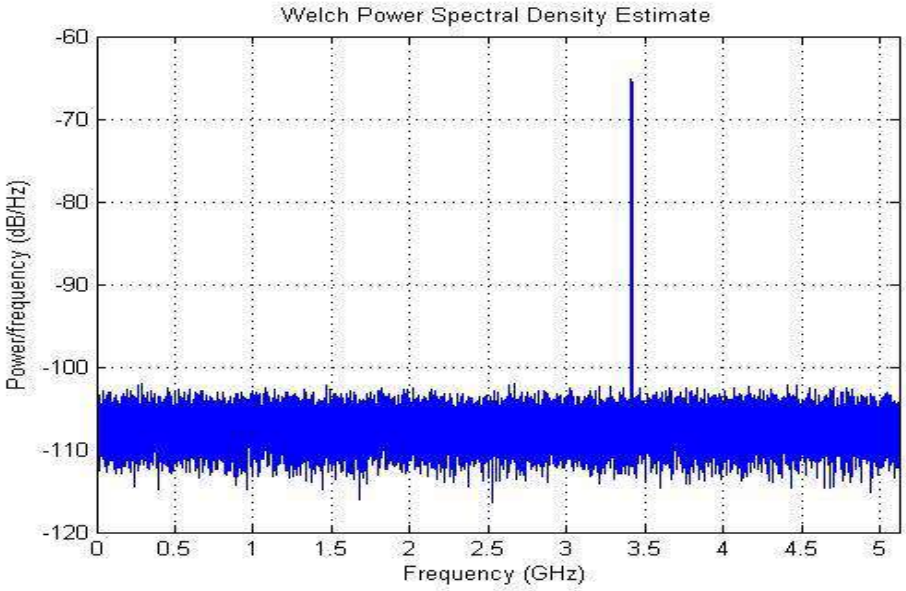
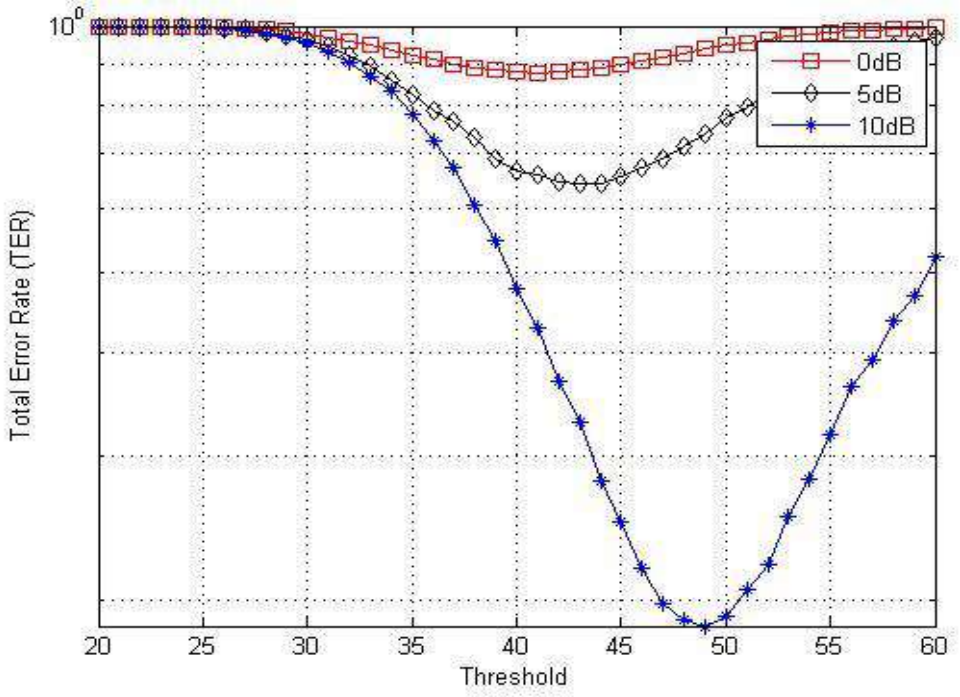


Figure III.16: power spectral density.

4.3) Simulation results of spectrum sensing

4.3.1) Non-cooperative spectrum sensing simulation results

The following figure shows the different curves of total error rate (TER) of energy detection spectrum sensing vs. threshold for various values of SNR=0 dB; 5dB; 10dB, when the number of iterations Nt=10000, the number of samples N=40, and the bandwidth BW=5MHz:



:

Figure III.17: TER vs. threshold curves of the non-cooperative ED.

We can observe that, the optimal threshold when the TER achieve the minimal value of each curve is the same as the ones that we found in the theoretical way. Hence, the optimal threshold for SNR=0 dB, 5dB and 10dB is respectively 41, 44 and 48.

4.3.2) Cooperative simulation results

The following figure shows the different curves of TER of cooperative energy detection spectrum sensing vs. threshold for various values of SNR=0 dB; 5dB; 10dB, when the number of iterations Nt=10000, the bandwidth BW=5MHz, the number of samples N=40, voting rule, n=5 and number of SUs K=10:

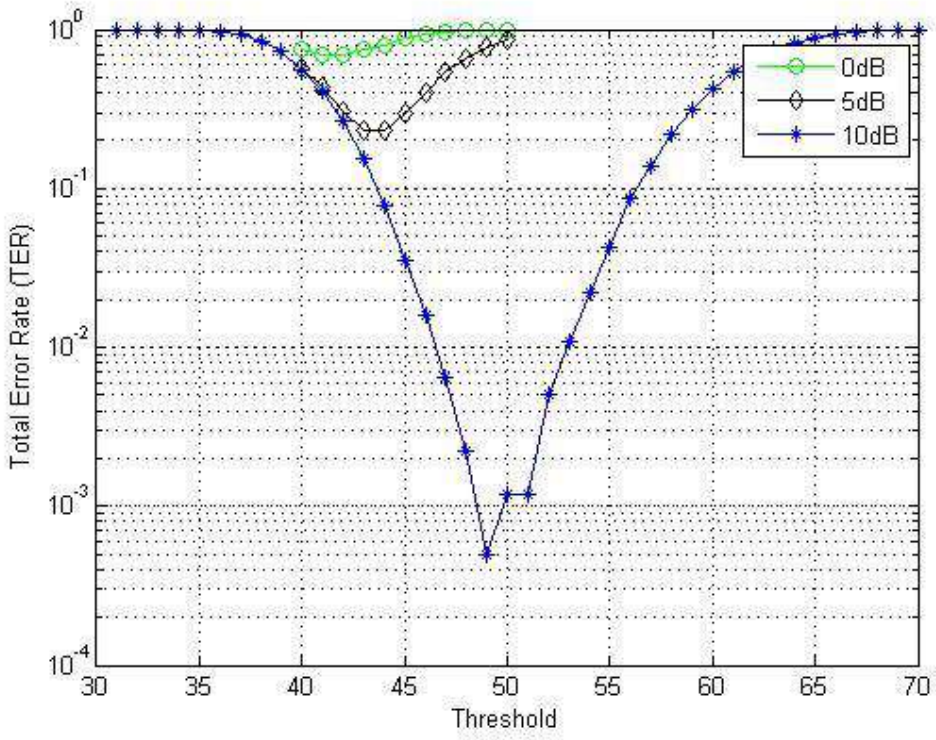


Figure III.18: TER vs. threshold curves of the cooperative ED.

We can see that the minimal values of each curve are similar to the ones that we found in the theoretical part. Where the optimal threshold for SNR=0 dB, 5dB and 10dB is respectively 41, 43, 49.

- ✓ Figure III.19 shows the different curves of TER of cooperative energy detection spectrum sensing vs. voting rule for various values of SNR=0 dB; 5dB; 10dB, when the number of iterations Nit=10000, the bandwidth BW=5MHz, the number of samples N=40, voting rule varies [1,2,3,…,10], number of SUs K=10 and the threshold, thr = 50:

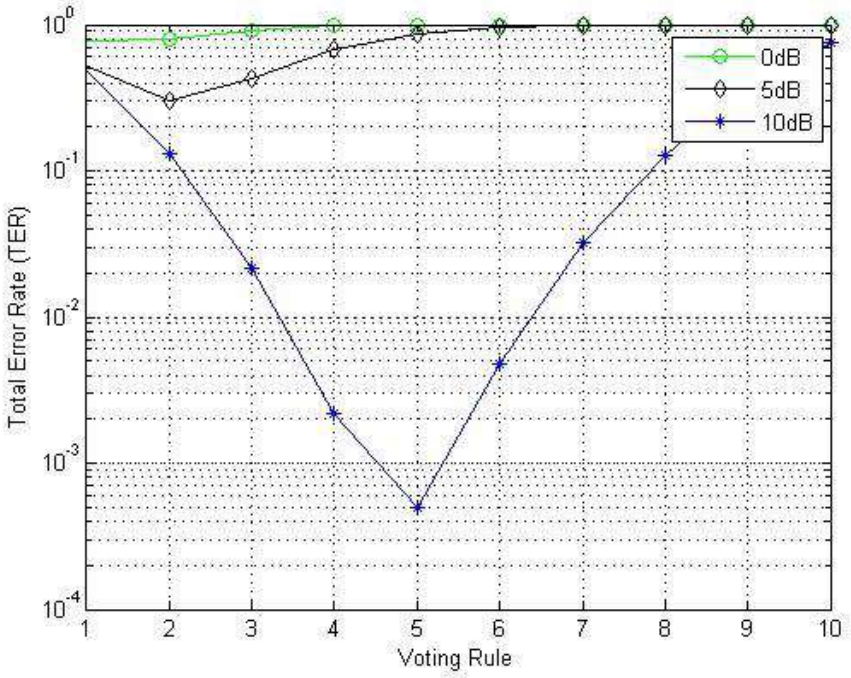


Figure III.19: TER vs. voting rule curves of the cooperative ED.

We can see that there is a similarity between the theoretical values of the optimal threshold and the practical ones that are represented in the figure as minimal values of TER where the optimal voting rule for each of SNR= 0dB, 5dB and 10dB is respectively 1, 2, 5.

4.4) Simulation results of TER vs. SNR of all the spectrum sensing techniques

The following figure shows the different curves of each spectrum sensing technique (cooperative MF/ED and non-cooperative ED/MF) depending on SNR in the AWGN channel, when the number of iterations is Nt=10000, the bandwidth BW=5MHz, and the number of samples N=40. For the cooperative technique, the voting rule n=5 and number of SUs K=10 and the optimal thresholds of ED are the ones that we have found in the theoretical one. The optimal thresholds of MF are obtained by simulation (when the TER achieves the minimum value).

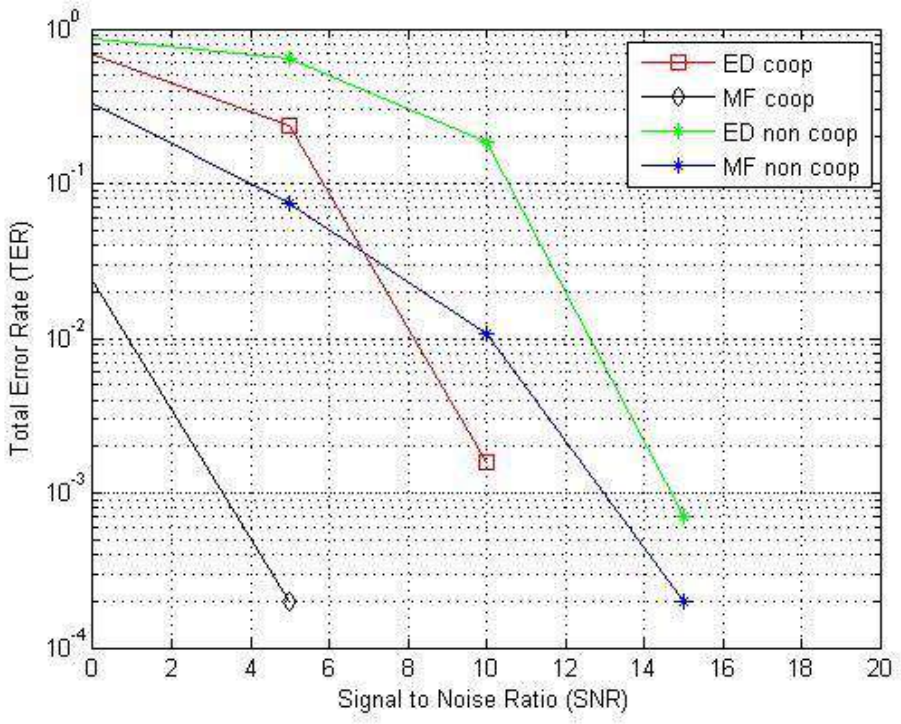


Figure III.20: TER vs. SNR of the spectrum sensing techniques in AWGN channel.

We can observe that the MF of the cooperative spectrum sensing has the best performance among all these techniques, since it has the lowest TER comparing to the others, while the highest TER is the one that belongs to the non-cooperative ED technique. The non-cooperative matched filter shows a better result than the cooperative energy detection, when SNR less than 7dB.

For example, the TER of cooperative MF, cooperative ED, non-cooperative MF and non-cooperative ED techniques for SNR=5dB is respectively 0.0002, 0.0016, 0.0002,0.0007. The TER of MF cooperative provides an improvement of 0.1 compared with MF non cooperative.

- ✓ The following figure shows the different curves of each spectrum sensing technique (cooperative MF/ED and non-cooperative ED/MF), when the number of iterations is Nt=10000, the bandwidth BW=5MHz, for the cooperative technique, the voting rule n=5 and number of SUs K=10 and the thresholds are the ones that we have found in the theoretical part for each technique when the total error rate changes in term of noise (TER vs. SNR) in the Rayleigh fading channel:

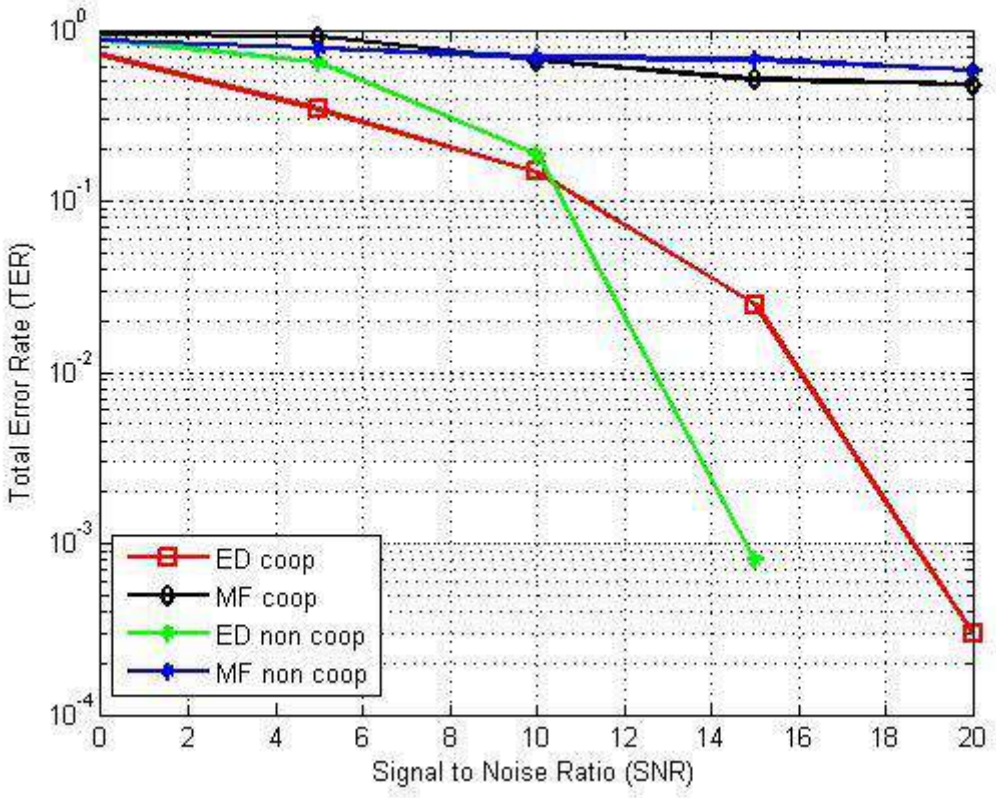


Figure III.21: TER vs. SNR of the spectrum sensing techniques in Rayleigh channel.

On one hand, we can observe that the ED of the cooperative spectrum sensing has the highest TER comparing to the other techniques for SNR less than 10dB which means that it gives the worst performance among all these techniques, on the other hand, the two MF techniques have the lowest TER in Rayleigh channel and this means that they have the best performance. The TER of non-cooperative ED, cooperative ED, cooperative MF and non-cooperative MF technique for SNR=5dB is respectively 0.0008, 0.0003, 0.4771 and 0.5778.

4) Conclusion

In this chapter, we gave a brief description of the transmission and reception chain of 5G New radio (NR) physical layer and the different techniques of spectrum sensing. First, we simulated and evaluated the performance of the physical layer of the 5G NR. Then, we simulated the various spectrum sensing methods (non-cooperative and cooperative), and we compared their performance and their corresponding results have been discussed. Among the non-cooperative spectrum sensing methods, the energy detection is simpler than the matched filter. However, the performance of the cooperative matched filter method is better than the other methods in the AWGN channel. However, in the Rayleigh fading channel, the energy detection techniques have the best performance among the above techniques.

General Conclusion

The 5G network is expected to have capabilities to overcome the limitations of previous system generations, the cellular mobile communication systems were designed to meet human being's demands, which is essential to a human-centralized communication system. However, it is desired to consider the thing-centralized communication in 5G as well, which means device-to-device (D2D) or machine-to-machine (M2M) communications that will be taken into serious consideration. The 5G systems are expected to be intelligent in nature, as well as providing a platform for operators to effectively exploit their network resources in an era where spectral resources are at a premium. The smart cities can be designed based on cognitive radio which is meant for spectrum sensing and spatial sensing. It also uses the massive MIMO and the heterogeneous network which uses small cells called Femto/ Pico cell.

The objective of this thesis was to define both the cognitive radio (CR) and the fifth generation of cellular wireless standards (5G), they are considered to be the future technologies. On one hand, CR offers the possibility to significantly increase the spectrum efficiency, by smart secondary users (CR users) using the free licensed user's spectrum holes, on the other hand, the 5G implies the whole wireless world interconnection together with very high data rates Quality of Service (QoS) applications.

This study was structured around three essential chapters, the first dedicated to the domain of 5G wireless technology, this part focused on the definition of fifth generation, as well as its different technologies and services, also, the modulation types used in it, in addition to the explanation of its functioning algorithms, where some examples were treated with MATLAB software (the performance of the physical layer 5G NR). In the second chapter, we talked about the cognitive radio technology, We started by giving a short definition of it, and presented the most important element is to detect the spectrum, we followed it by some descriptions of the various spectrum sensing techniques, at last, we simulated the non-cooperative and cooperative methods using the same software, after that we compared their performance and discussed their performance.

Finally, we conclude that the cooperative matched filter spectrum sensing method is better than the other spectrum sensing methods in the AWGN channel, but in the Rayleigh fading channel, the cooperative energy detection has the best performance among all the previous techniques.

Bibliography

[1] A. U. H. Sheikh, “3G Wireless Communication Systems,” Wirel.Commun., no. 10, pp. 643–704, 2004, doi: 10.1007/978-1-4419-9152-2_13.

[2] Dr. Anwar M. Mousa, “Prospective of Fifth Generation Mobile Communications”, International Journal of Computer Networks and Applications.

[3] MORENO, Luis Fernando Espinosa, “Network performance evaluation with real time application ensuring quality of service with ns2. International Journal of Next-Generation Networks”, 2012, vol. 4, no 3, p. 1.

[4] “Recommendation ITU-r m.2083, framework and overall objectives of the future Development of IMT for 2020 and beyond». Available: https://www.itu.int/rec/R-REC-M.2083-0-201509-I/en.

[5] D. Suhag, M. Chauhan, A. Shakeel, and S. Das, “Emerging trends in nanotheranostics”, Nano Biomedicine, no. September, pp. 335–368, 2020, doi: 10.1007/978-981-32-9898-9_14.

[6] KUMAR, Munna, MISHRA, Bimal Kumar, et PANDA, T. C. Effect of quarantine & vaccination on infectious nodes in computer network. International Journal of Computer Networks and Applications, 2015, vol. 2, no 2, p. 92-9.

[7] Wang, C., and D. Lopez-Perez, “Global Impact of 5G Network Topology**”,** October 30, 2017.

[8] P. Paudel and A. Bhattarai, “5G Telecommunication Technology: History, Overview, Requirements and Use Case Scenario in Context of Nepal,” no. May, pp. 0–5, 2018.

[9] F. F. Digham, M. S. Alouini, and M. K. Simon, “On the energy detection of unknown signals over fading channels,” IEEE Trans. Commun., vol. 55, no. 1, pp. 21–24, 2007, doi: 10.1109/TCOMM.2006.887483.

[10] S. Bhandari and S. Joshi, “Cognitive radio technology in 5G wireless

communications," 2018 2nd IEEE Int. Conf. Power Electron. Intell. Control Energy Syst. ICPEICES 2018, pp. 1115–1120, 2018, doi: 10.1109/ICPEICES.2018.8897345.

[11] PACKARD, "Hewelett. Digital Modulation in Communications Systems», An Introduction. Application Note, 1997, vol. 1298.

[12] Number ,Keysight Technologies ,2014.Available: http://literature.cdn.keysight.com/litweb/pdf/5965-7160E.pdf.

[13] Robert G.Maunder, "overview-channel-coding", September 2019.Available : https:// www.accelercomm.com/overview-channel-coding.

[14] Maunder, Robert, "A Vision for 5G Channel Coding "Archived from the original (PDF) on December 6, 2018. Retrieved January 6, 2019.

[15] A. Ramzan and M. O. Bin Saeed, "LDPC-coded OFDM-system with BPSK modulation: Performance comparison with uncoded OFDM system," 2018 3rd Int. Conf. Control Robot. Eng. ICCRE 2018, pp. 213–217, 2018, doi: 10.1109/ICCRE.2018.8376467.

[16] Ian Poole,"5g-mobile-wriless-cellular/wave forms-OFDM-modulation», Available : https://www.electronics-notes.com.

[17] JOHNSON, Matthew. An Exploration of 5G Wireless Network Attenuation Using Finite Element Analysis in COMSOL Multiphysics. 2020.

[18] D. M. Venkatesan, D. A. V. Kulkarni, and D. R. Menon, "Role of Cognitive Radio in 5G," Helix, vol. 9, no. 2, pp. 4850–4854, 2019, doi: 10.29042/2019-4850-4854

[19] B. Wang and K. J. R. Liu, "Advances in cognitive radio networks: A survey," IEEE J. Sel. Top. Signal Process., vol. 5, no. 1, pp. 5–23, 2011, doi: 10.1109/JSTSP.2010.2093210.

[20] T. Manku et al., "A 680MHz to 4GHz 4RX-1TX SoC for cognitive radio applications," IEEE MTT-S Int. Microw. Symp. Dig., pp. 586–589, 2017, doi: 10.1109/MWSYM.2017.8058634.

[21] W. Xu, Wu, Daneshmand, Liu, "A data privacy protective mechanism for WBAN,"

Wirel. Commun. Mob. Comput., no. February 2015, pp. 421–430, 2015, doi: 10.1002/wcm.

[22] Y. Xiao and F. Hu, Cognitive radio networks: CRC press, 2008.

[23] A Survey on Spectrum Management in Cognitive Radio Networks. Ian F. Akyildiz, Won-Yeol Lee, Mehmet C. Vuran, and Shantidev Mohanty, Georgia Institute of Technology. April 2008. 0163-6804/08/ , s.l. : IEEE Communications Magazine, April 2008.

[24] I. F. Akyildiz, W. Y. Lee, M. C. Vuran, and S. Mohanty, "NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey," Comput. Networks, vol. 50, no. 13, pp. 2127–2159, 2006, doi: 10.1016/j.comnet.2006.05.001.

[25] A. Haldorai and U. Kandaswamy, Intelligent Spectrum Handovers in Cognitive Radio Networks.
2019.

[26] L. Berlemann and S. Mangold, "Cognitive Radio and Dynamic Spectrum Access," Cogn. Radio Dyn. Spectr. Access, pp. 1–230, 2009, doi: 10.1002/9780470754429.

[27] H. and T. Yücek. 2007. Spectrum Sensing for Cognitive Radio Applications.
Cognitive Radio, Software Defined Radio, and Adaptive Wireless Systems
Springer 3: 263-289.

[28] T. Mehta, N. Kumar, and S. S. Saini, "Comparison of Spectrum Sensing Techniques in Cognitive Radio Networks 1," 2013.

[29] W.A., 1988 Signal Interception: A Unifying Theorotical Framework for Feature Detection IEEE Transactions on Communications 36(8): 897- 906.

[30] 3GPP:TS 38.212 NR; Multiplexing and channel coding, 2018. Available: https://www.researchgate.net/publication/337274094_A_survey_on_channel_coding_techniques_for_5G_wireless_networks.

[31] 3GPP:TS 38.212 NR; RTS/TSGR-0138212vf50.

[32] “The History of Orthogonal Frequency-Division Multiplexing”, Stephen B. Weinstein, IEEE Communications Magazine, November 2009. Available: https://ieeexplore.ieee.org/document/5307460.

[33] A. Farzamnia, N. W. Hlaing, M. Mariappan, and M. K. Haldar, “BER comparison of OFDM with M-QAM modulation scheme of AWGN and Rayleigh fading channels,” 2018 9th IEEE Control Syst. Grad. Res. Colloquium, ICSGRC 2018 - Proceeding, no. August, pp. 54–58, 2019, doi: 10.1109/ICSGRC.2018.8657503.

[34] G. Vidyadhar Reddy and N. S. Murthy, “Optimization of cooperative spectrum sensing under AWGN and rayleigh channels in cognitive radio network,” Proc. - 2013 3rd Int. Conf. Adv. Comput. Commun. ICACC 2013, pp. 126–129, 2013, doi: 10.1109/ICACC.2013.32.

[35] P. L. Butzer, P. J. S. G. Ferreira, J. R. Higgins, S. Saitoh, G. Schmeisser, and R. L. Stens, Interpolation and Sampling: E.T. Whittaker, K. Ogura and Their Followers, vol. 17, no. 2. 2011.