Deanship of Graduation Studies

Al-Quds University

Developing a Secondary Mobile Network in the Palestinian GSM Band Using Cognitive Radio

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M.Sc. Thesis

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Jerusalem – Palestine

1438/2017

Dedication

I dedicate this work to my:

Parents, wife Heba, son Belal and all of my family and friends.

Declaration:

I Certify that this thesis submitted for the Degree of Master is the result of my own research, except where otherwise acknowledged, and that this thesis (or any part of the same) has not been submitted for a higher degree to any other university or institution.

Signed: ....

Osama Ayed Eid Najajri

Date:13/5/2017

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Abstract

The traffic on cellular data networks is growing rapidly in the world, leading to high demand for mobile communication spectrum. Thus, the traditional static spectrum regulation policies caused spectrum scarcity problem in wireless communication systems. Dynamic spectrum access (DSA) has been motivated as a solution for this problem. DSA utilizes the licensed radio bandwidth by dynamic spectrum sharing among multiple systems. Cognitive radio (CR) is a potential enabling technology for DSA that allows secondary system (SS) to operate in the existing licensed spectrum without harmful interference. CR technology shares the spectrum between the so-called primary user (PU) and secondary user (SU) in various paradigms. Indeed, there are three main platforms of primary/secondary spectrum sharing: interweave, underlay and overlay modes. In interweave CR, which is the origin of CR, the SU utilizes the unused primary system (PS) spectrum, which is called holes or white spaces. This requires spectrum sensing techniques in order to avoid SU degrading the performance of PU. Several spectrum sensing schemes have been proposed to efficiently find PS holes to be used for CR communications at the SU. In underlay CR, the SU transmits simultaneously with the PU in the same frequency band under power constraints. In that case, the interference should not be passed a predefined threshold value. In overlay CR, some *apriori* information of the PU at the SU transmitter is required to mitigate the interferences at the primary receiver.

Although global system for mobile communication (GSM), which is the European standard for second mobile generation (2G), has now become old technology and the research community is rather focusing on fifth generation (5G), this thesis addresses a real problem in some countries that could not cope with technological advances due to multiple social, political, and economical reasons. More precisely, the spectrum assigned to Palestine is very limited due to the restrictions imposed by Israel through Oslo agreement[1]. The mobile operators in Palestine are still based on GSM.

In this thesis, we propose to investigate the relevance of applying overlay CR to expand the spectrum of GSM. Particularly, a fourth generation (4G) mobile system based on orthogonal frequency division multiplexing (OFDM) is suggested for the SS whereas a 2G GSM mobile

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[1] Oslo agreement: Protocol on Israeli-Palestinian cooperation in economic and development programs, signed in 1993.

system based on Gaussian minimum shift keying (GMSK) is considered for the PS. The OFDM based 4G technology, which is widely used in the standard systems, is considered as a potential candidate for spectrum overlay technology for spectrum sharing. The interference expression due to the SS at the PS receiver and the interference expression due to the PS at the SS receiver are firstly derived. Then, to eliminate these interferences, a precoding technique based on zero forcing beamforming (ZFBF) is inserted at the SS transmitter, while a postcoding is introduced at the SS receiver. In addition, zero forcing (ZF) and minimum mean square error (MMSE) equalizers are employed to equalize the frequency selective fading channel at the GSM receiver. The comparative simulation study we carried out with existing CR based on OFDM system for both the PS and SS illustrates the performance efficiency of the proposed CR system.

Keywords— Spectrum scarcity, overlay CR, GSM, OFDM, interference cancellation, precoding and postcoding.

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Chapter 1

Introduction

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1.1. Overview

In this chapter, we present several generations of the mobile communication system. Also, we explain the fundamental of cognitive radio (CR) as a solution for spectrum scarcity problem in wireless systems. Particularly, we propose various solutions based on CR platforms for spectrum scarcity in Palestine cellular network. In addition, we address the contribution and the outlines of the thesis.

1.2. Evolution of Cellular Systems

The development of mobile systems generations are started with the wide spread success of cellular idea. The first generation (1G) of mobile system is based on analog technology where frequency modulation (FM) and frequency division multiple access (FDMA) techniques are used. It was introduced in 1980s for voice communication and started with advanced mobile phone system (AMPS). AMPS use 30 KHz channel bandwidth occupying the band from 824-894 MHz [1-3].

The second generation (2G) mobile system was introduced in the late of 1980s. It provides high speed data communication as well as voice transmission since it is based on digital transmission. The multiple access technique used in 2G is the time division multiple access (TDMA) and code division multiple access (CDMA) [2][4]. A very widely used standard for this generation is the global system for mobile communication (GSM)[1]. The GSM standardized by European telecommunications standards institute (ETSI) in 1990. Although originally designed for operation in the 900 MHz band, it is adapted for 1800 MHz with 25 MHz band in each direction of communication (uplink and downlink). The GSM supports 8 time slots for every 200 KHz radio channels. Another standard of 2G is the interim standard 95 (IS-95). IS-95 is popular in North America and uses CDMA [3][4].

The second generation networks provide very low data-transfer rates. The 2.5G and 2.75G are evolved from 2G standards such as GSM and IS-95. The GSM standard is upgraded with two technologies, General Packet Radio Service (GPRS) and Enhanced Data rate for GSM Evolution (EDGE). They provide much higher data rates compared with the 2G systems [1][3].

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[1] GSM is considered in this thesis; more details are presented in the next chapter.

The third generation (3G) mobile system provides backward compatibility for 2G and 2.5G and it is implemented in 2001. The 3G standard is categorized under two projects. The first one is the 3G partnership project for wideband CDMA standard (3GPP) compatible with GSM and the other is the 3G partnership project for CDMA-2000 standard (3GPP-2) compatible with IS-95. 3GPP standard involves wideband code division multiple access (WCDMA)[2]. The channel bandwidth in this standard is 5MHz with data rate up to 2Mbps. 3G provides enhancements over previous networks such as enhanced audio and video streaming; higher data speed; video-conferencing support; wireless application protocol (WAP) browsing at higher speeds and TV through the internet support [3-5].

The fourth generation (4G) mobile communication system is released in 2010 without backward compatible with previous generations. 4G provides high quality audio/video streaming over end to end Internet Protocol (IP) at a very rapid speed which is known as mobile ultra-broadband internet access [5][6]. Indeed, 4G uses the orthogonal frequency division multiplexing (OFDM)[3] as multiple access technique. The OFDM technology uses orthogonal subcarriers to reduce the interference caused by frequency selective fading channel. In addition of interference mitigation, OFDM increases the data rate in 4G. The second technology used in 4G standard is multiple input multiple output (MIMO) where multiple antennas are used at the transmitter and the receiver to improve the performance of the bit error rate (BER) and the data rate. The 4G standards mobile system provides data rates greater than 200 Mbps [6].

In the next section, we present the information about existing cellular network generation in Palestine. In addition, we show the challenges that are faced.

1.3. Palestine Cellular Mobile System- Jawwal Case Study

Jawwal is the leading mobile operator in Palestinian territories (West Bank and Gaza sector). It is based on GSM-900 generation and has only 5 MHz band [7]. According to GSM-900 standard, it offers 25 MHz bandwidth for each of the uplink and the downlink. Each bandwidth is divided into 200 KHz radio channels yielding 124 physical channels and one channel is reserved for synchronization. The 124 physical

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[2] WCDMA is also called universal mobile telecommunication system (UMTS).

[3] OFDM is considered in this thesis; more details are presented in the next chapter.

channels are usually numbered from 1 to 124 and are called absolute radio frequency channel number (ARFCN). Thus, Jawwal has 24 ARFCNs which are the last 24 channels in the GSM-900 band, i.e., from 101 to 124. These 24 ARFCNs are divided into traffic channels (TCH) and broadcast control channels (BCCH). Therefore, high channels reuse factor to accommodate the high population density. In [8], an evaluation and enhancement study for Jawwal frequency plan in 2011 in Jenin city, which is located in the north of West Bank. According to this study, the BCCH reuse plan for Jawwal cells in Jenin is shown in Fig. 1.1. It is noted that 8 BCCH are reused between 57 Jawwal GSM cells of Jenien city. This results in very often frequency reuse for a given BCCH. Therefore, high level of interference on the BCCH carrier which results in poor quality of service (QoS) and high drop rate for those cells. To avoid this problem, one can increase the number of BCCH. However, this comes at the cost of reducing TCH due to the limited number of channels available to Jawwal.

The traffic reuse plan for Jawwal network is shown in Fig. 1.2. It shows the heavily reuse factor. It should be noted that, the interference in control channel is more critical compared to interference in traffic channel. The GSM specification states that carrier to interference (C/I) ratio must be larger than 9 dB. However, Ericsson recommends using C/I >12 dB as a planning criterion [8].

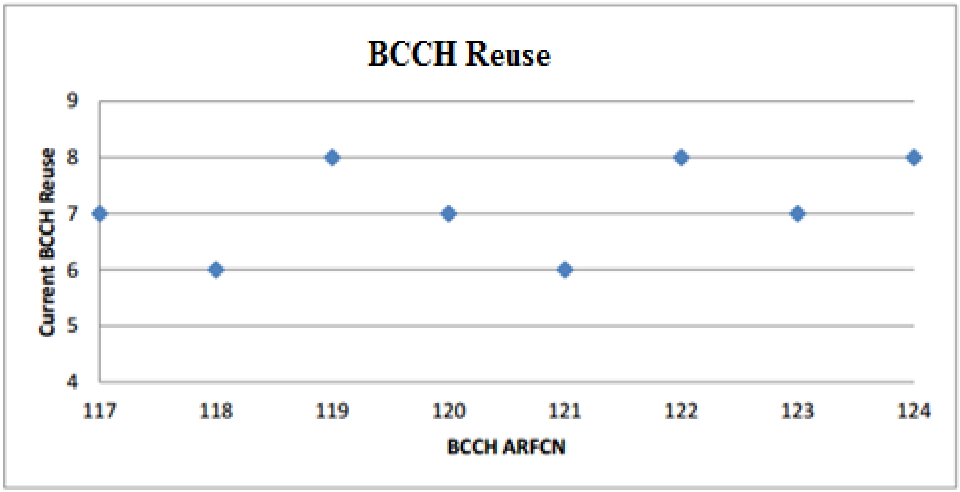

Figure 1.1: BCCH reuse plan for Jawwal GSM cells in Jenien city [8].

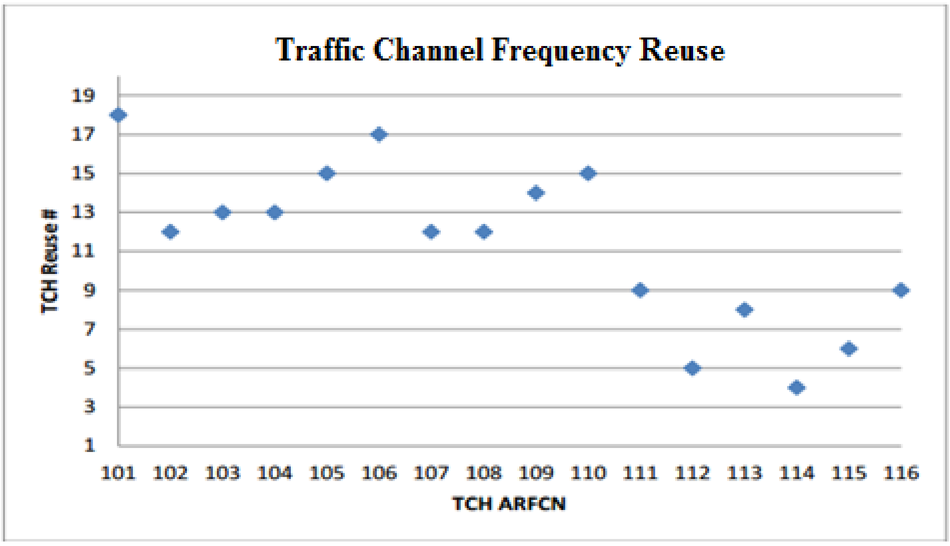

Figure 1.2: TCH reuse plan for Jawwal GSM cells in Jenien city [8].

The study used two approaches to evaluate the network performance, namely key performance indicators (KPIs) and drive test. KPIs are statistical data that are processed and displayed to give us a meaningful picture about GSM cell behavior. The drive test is a professional tool preinstalled on a laptop. It is used to record a log file that contains data extracted from mobile station (MS). Based on that study at that time, the initial evaluation of the network showed that about 0.76% of the initiated connections are dropped. Also, about 7.76% of the collected samples from the drive test lie in the worst level in terms of signal quality and signal strength [8]. The authors of this study have proposed optimization solutions that manage to reduce the average TCH drop rate from 0.76% to 0.62%. In addition, the percentage of sample in the best level is increased from 65.5% to 76.8% while the percentage of samples in the worst level is decreased from 7.76% to 5.16%. Despite these efforts, the effective solution for the mobile networks in Palestine is to increase the spectrum bandwidth and upgrade the network towards high level of mobile generations.

The effective solution for the mobile networks in Palestine is to increase the spectrum bandwidth and upgrade the network towards high level of mobile generations. But this solution is not allowed at least till now. We can take the advantage of the innovative technologies that enhance the efficiency usage of the available spectrum. Millimeter-wave (mmW)[4] is a promising technology for future cellular communication systems. The wide bandwidths of mmW signals provide a solution of spectrum crowding as

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[4] Millimeter wave spectrum is defined as the band between 30 and 300 GHz.

discussed in the survey in [9]. Dynamic Spectrum Access (DSA) and the spectrum refarming are other solutions for the problem of spectrum scarcity. In [10], a novel solution is considered to provide GSM connectivity within an LTE carrier through an efficient overlay dynamic spectrum refarming. In this approach, the operators can migrate their GSM spectrum to LTE while still providing some GSM connectivity to their low data rate customers. CR is a key enabling technology for DSA that allows secondary system (SS) to operate in the existing licensed spectrum without harmful interference [11]. An overview of CR is discussed in the next section.

1.4. Cognitive Radio (CR) Overview

CR is a form of wireless communication in which a transceiver can intelligently detect which communication channels are in use and which are not. Indeed, the unlicensed /secondary users (SUs) can access licensed spectrum without cause any interference to the licensed/primary users (PUs). The concept of CR was first originated by Dr. Joseph Mitola at defence advance research products agency (DARPA) scientist, and the result of that concept is becomes a standard called IEEE 802.22 [12][13].

Frequency spectrum scarcity is currently one of the most challenges for the deployment of 4G wireless networks. CR provides a promising solution to the spectrum scarcity and system capacity problems that allow cognitive communication with minimal impact on existing users [14][15]. CR is highly intelligent radio systems; it is an evolution of software defined radio (SDR), which is a radio communication system where components implemented in software by a programmable processing device rather than hardware implementation. SDR gives CR more flexibility in choosing communications options to address these challenges. There are two features that distinguish a CR from a traditional radio: the cognition capability and the reconfigurability [14].

The CR network has three main paradigms: interweave, overlay, and underlay. **In interweave CR paradigm,** the SU can transmit only on a spectrum band where the PU is not active, and has to move onto different bands over time. Interweave platform takes advantage of temporary frequency voids, referred to as spectrum holes that are unused by the licensed primary system (PS) [16]. This requires spectrum sensing techniques in order to avoid SU degrading the performance of PU, several spectrum sensing schemes have been proposed to efficiently find PS holes to be used for CR communications at the secondary [17]. The cognition capability of a CR is defined as cycle of three components as shown in Fig. 1.3.

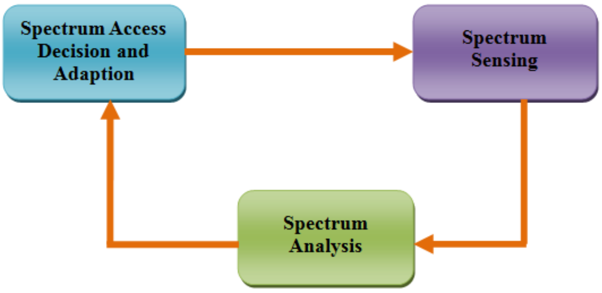

Figure 1.3: CR cycle.

Spectrum sensing is the ability to measure the parameters related to the radio channel characteristics, availability of spectrum and transmit power, interference and noise, and user requirements and applications. It is necessary for the CR system to continuously sense the spectrum occupancy. CR system utilizes the spectrum on a non-interference basis to the PU. Spectrum analysis uses the sensed radio environment parameters to infer the existence of spectral opportunities in the surrounding radio. Based on spectrum sensing, CR analyzes the situation of several factors in the external and internal radio environment, such as radio frequency spectrum used by neighboring devices, user behavior and network state, and finding the optimal communication protocol and changing frequency or channel accordingly [11-15]. Spectrum decision is the ability of CR to decide the set of transmission actions to be taken based on the outcomes of the spectrum sensing and analysis procedures. The decision for the best available spectrum band is based on different criteria such as, probability of error, capacity, path loss, interference, PU appearance probability, etc.

The underlay paradigm allows SU to operate if the interference they cause to PU is below a given threshold in which the SU cannot significantly interfere with the communication of PU. In that case, a SU can spread its signal over a very wide bandwidth such that the interference power spectral density (PSD) is below the noise floor at any PU location [14][18].

In **overlay paradigm,** the SUs overhear the transmissions of the PUs, and then use this information along with sophisticated signal processing and coding techniques to maintain or improve the performance of PUs, while also obtaining some additional bandwidth for their own communication. The interferences to PUs are reduced or completely eliminated by using sophisticated coding interference cancelation techniques, such as zero forcing beam forming (ZFBF) [19], interference alignment (IA) [20] and dirty paper coding (DPC) [21].

Underlay CR can only be used when there is a strong primary signal, whereas overlay CR is more appropriate for weak primary signals [14]. Fig. 1.4 shows the architecture of the three different platforms of CR [12].

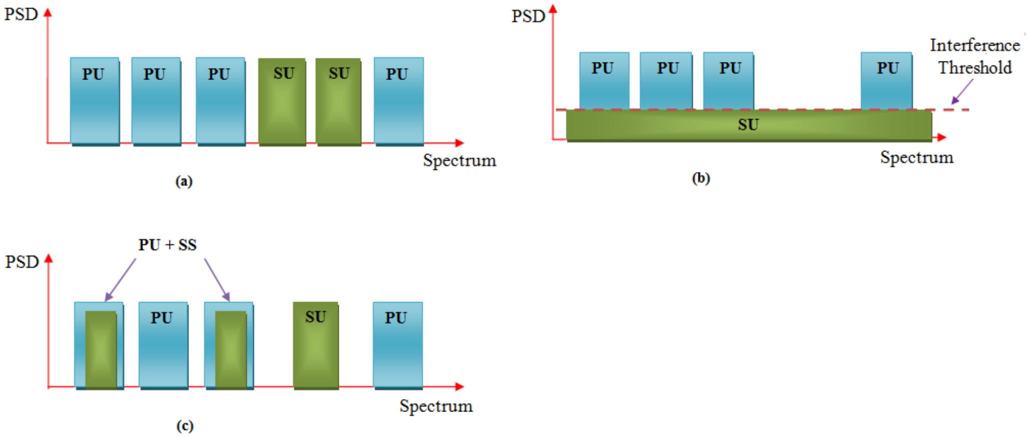

Figure 1.4: CR platforms: (a) interweave; (b) underlay; (c) overlay.

1.5. Motivation of the Thesis

The situation of the Palestinian mobile network is critical due to the following reason: The number of communication channels allowed by the regulation authorities is limited to 19% of the global bandwidth generally allocated to a country to perform GSM. In spite of the efforts of the engineers to optimize the radio planning, it is frequent that the voice communications are interrupted. These interruptions are due to the inter and intra channel interference caused by the massive reuse of the channel communications. Moreover, the high population density makes this problem worse. CR technology has emerged as a promising solution to many wireless communication problems including spectrum scarcity and underutilization. The aim of this study is to assess the feasibility of superimposing a secondary network on the primary Palestinian GSM network using the principle of CR. This would make it possible to shift part of the GSM communications to the secondary network. This way, it would be possible to limit the channel reuse, and consequently to limit the inter and intra channel interference.

We can propose solutions for this problem from several viewpoints. The three CR paradigms, interweave, underlay and overlay, can be considered in different scenarios to improve the efficiency in the GSM-900 spectrum scarcity as follows:

1) In interweave CR; the SS determines the so-called white space or hole in the existing spectrum. A television white space (TVWS) can be discussed as a good example in this regard. TVWS is a portion of spectrum in the very high frequency (VHF)[5] and ultra high frequency (UHF)[6] bands which is not utilized based on time and location. Until relatively recently, all television broadcasting in Palestine employed analogue terrestrial transmission stations, and all household television receivers were analog based. Currently, Palestinian authority works on a plan that all broadcasters analogue system turn to digital system. The digital TV transition means extra free space in the TV band will be available due to the higher spectrum efficiency of digital TV. TVWS provides a spectrum opportunity but it introduces a number of technical challenges like spectrum sensing, requirement of new wireless physical and media access control (MAC) layer designs [22]. Recently, there has been a large amount of interest in expanding the broadband wireless network spectrum with CR technology using the new TVWS [23].
2) According to agreement between Palestinian and Israeli sides, the 3G licensing is obtained and Palestinian telecommunication companies may be started to release 3G services in the near future with another two 5 MHz bandwidth, one of them is shared with Israeli operator. The 3G cellular mobile system uses the CDMA technology as channel access method. The features of CDMA, which is a type of broadband system based on the spread spectrum technique, are suitable with the idea of underlay CR in which the power level of the transmitted signal can be reduced to become less than the power level of the background noise [18][24]. Thus, the CDMA signals are harder to interfere with the narrow band signals such as GSM system. In that case, an underlay CR model can be considered where the GSM-900 is the PS and the 3G based on CDMA is the SS.

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[5] VHF: is the range of radio frequencies that belong to the domain between 174 MHz to 216 MHz.

[6] UHF: is the range of radio frequencies that belong to the domain between 470 MHz to 862 MHz.

In this system, SUs are allowed to share the channel simultaneously with PUs under interference power constraints. The underlay CR in GSM band achieves the target of increasing the network capacity and aid in reducing the problem in Palestine. In this scheme, the power limit for secondary transmission limits the SS for short rang communication.

3) Another proposed solution with spectrum leakage in Palestine is the 4G cellular mobile, which is based on multicarrier communication as a secondary transmission system in the GSM-900 band. Therefore, an overlay CR model can be considered where the GSM-900 is the PS and the 4G based on OFDM is the SS. Overlay paradigm allows for co-existence between secondary and PUs in the same band without power limit for secondary transmission. Instead of interference power constraints, a precoding can be defined to cancel or mitigate the interferences at the PS [15]. In this thesis, we consider this solution.

1.6. Thesis Contribution

In this thesis, we propose to apply the idea of overlay CR using 4G-OFDM as SS to expand the GSM spectrum [25]. In that case, two scenarios are considered, the first one is the overlay CR using OFDM in the GSM band and the model is compared with a second scenario overlay CR where the primary and secondary systems are based on OFDM technology. Therefore, we formulate the mathematical expression of the interferences due to the SU at the PU receiver and due to the PU at the SU. Then, we study how to use ZFBF to cancel these interferences. More precisely, a precoding can be inserted at the SU transmitters to cancel the interference at PU receiver. Since we cannot change the existing system or PS, the interference from PU at SU can be cancelled by insertion a postcoding at the SU receiver. The MATLAB simulation performance of the two scenarios are measured based on BER.

1.7. Thesis Outlines

The thesis is organized as follows:

In the first chapter, we provide a review of mobile communication generations. Also, we present a study on GSM network in Palestine that illustrates the crucial challenge of available cellular spectrum. In that sense, we discuss in details the CR definition and platforms as proposed solution of spectrum scarcity.

In the second chapter, we provide the physical and data link layer specifications of GSM system in the band 900 MHz (GSM-900) as PS. In addition, we present in details the fundamental of OFDM technology and system modelling. Also, MATLAB simulation results for the two systems in terms of BER are discussed.

In chapter 3, we discuss different interference cancellation techniques that used in overlay CR to mitigate the interference caused by spectrum sharing between PS and SS. Among these techniques, we focus on ZFBF in which multiple antennas should be used to lead beams to a wanted user. The interference equations are derived and we propose solutions to eliminate these interferences. Then, we present MATLAB simulation results based on measuring the BER for:

1. CR system where the OFDM is used in PS and SS.
2. CR system where the GSM-900 is considered as PS and OFDM is the SS.

Finally, chapter 4 addresses the conclusion of the thesis and provide some suggestions and perspectives for future works.

Chapter 2

Cellular Systems: GSM versus 4G (OFDM)

Contents

2.1. Overview

The access to information and communication technologies varies a lot from one country to another. Indeed, some countries have already deployed the fourth generation (4G) network whereas others are still with the global system for mobile communication (GSM), which is the case in Palestine.

In this chapter, we review the fundamental of cellular mobile communication system including the channel characteristics and equalization. Then, we present the system model of the GSM and the 4G mobile communication based on OFDM technology. Also, we present simulation results for the two systems in terms of probability of error.

2.2. Cellular Communication Systems

Cellular systems accommodate a large number of mobile subscribers over a large area within a limited frequency spectrum. In a cellular network, the problem of spectral congestion and user capacity is solving by dividing the total area into smaller areas called cells. The cells are usually roughly circular, but are easier to model as hexagons. Each cell has a number of determined channels. The available channels are divided into set of cells to form a cluster. The frequencies used in a given cell area are simultaneously reused non-adjacent cells in other clusters. For example, a typical cluster has seven cells as shown in Fig. 2.1. Cells that have the same channel frequency are called co-channel cells; they cause co-channel interference. The available channels can be reused many times necessary as long as the co-channel interference is kept below acceptable levels.

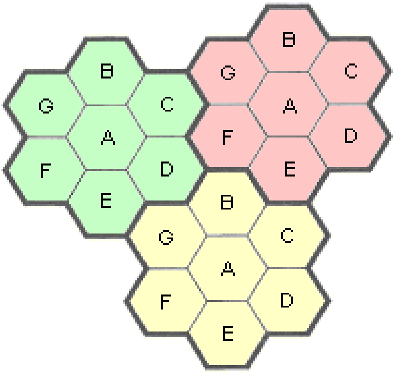

Figure 2.1: Cellular system concept.

The mobile station represents a transceiver in the cellular system and the transmission media is the wireless channel. The wireless channel incorporates a number of stochastic effects including thermal noise (or additive noise), fading and interference. Fig. 2.2 shows the general model of the fading channel.

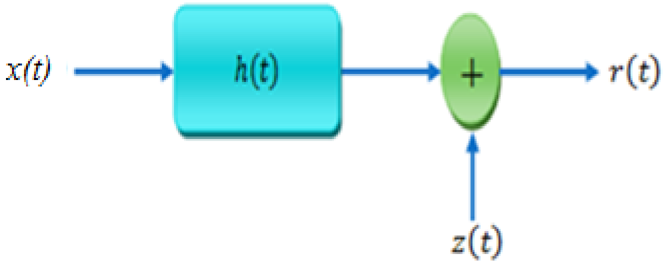

Figure 2.2: Fading channel model.

The received signal $r(t)$ can be expressed as:

$$r(t) = h(t) * x(t) + z(t) \tag{2.1}$$

where (*) is the convolution product, $x(t)$ is the transmitted signal, $h(t)$ is the channel impulse response and $z(t)$ is the additive white Gaussian noise (AWGN) with zero mean and variance σ_z^2.

In that case, (2.1) can be written in matrix as:

$$\boldsymbol{r} = \boldsymbol{H}\boldsymbol{x} + \boldsymbol{z} \tag{2.2}$$

where $\boldsymbol{x}$ is the transmitted symbols vector, $\boldsymbol{H}$ is the channel matrix and $\boldsymbol{z}$ is the additive white noise vector.

In the following subsections, we present a review for mobile channel characteristics, the different classifications of the channel, and an overview of mobile channel equalization.

2.2.1. Channel Characterization

The wireless channel suffers from the multipath problem which causes the so-called fading[1]. Multipath effect is a phenomenon in which versions of the signal reach the receiver from different paths due to the propagation mechanisms. Thus, at the receiver antenna there is a collection of direct and other multipath copies (components of the transmitted signal) and each component has different delay, phase and amplitude. The

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[1] Fading is the fluctuation of the signal strength as it propagates through wireless channel.

impulse response of the fading channel is random time-varying in which they generate random changes in the amplitude, delays and phase of multipath component. The standard time-variant channel impulse response is:

$$h(t) = \sum_{n=1}^{L_p} a_n(t) e^{-j\varphi_n(t)} \delta(t - \tau_n(t)) \qquad (2.3)$$

where L_p is the number of multipath components, $a_n(t)$ is n^{th} multipath amplitude, $\varphi_n(t)$ is n^{th} multipath phase shift and $\tau_n(t)$ is n^{th} multipath delay time.

The statistical nature of the channel can be categorized into many distributions such as Rayleigh, Rician and Nakagami [1]. In this thesis, we consider Rayleigh fading channel model which has proven useful in rich scattering environments to describe the envelope distribution of the received signal. The effect of multipath propagation causes two main problems in wireless system:

1. Delay spread: the time between the first arrival component and the last arrival component of the transmitted signal at the receiver due to the different propagation delays for each component is called spread time delay. The analogous parameter of delay spread in frequency domain is the coherence bandwidth of the channel, which is defined as the range of frequencies that are strongly correlated when they pass through the channel.
2. Inter symbol interference (ISI): when the maximum delay spread is greater than symbol time, the components from different signal overlap and interfere with each other. It is called ISI. At the receiver, the combinations of the overlapped components are added constructively or destructively due to the relative phase shift between multipath signal components. This causes rapid fluctuation in the received signal power. Fig. 2.3 shows overlapping between two copies of the transmitted symbol, $\boldsymbol{S}$, at the receiver due to ISI.

In addition to multipath problem, the mobile channel face a serious challenge depends on the speed of the mobile, Doppler frequency shift. It is the apparent change in wavelength of the transmitted signal when there is relative movement between the transmitter and the receiver. On the one hand, when the transmitter and or the receiver are moving toward each other, the frequency of the received signal is higher than the transmitted signal. On the other hand, when they are moving away from each other the frequency of the received signal is less than the transmitted signal [1][2].

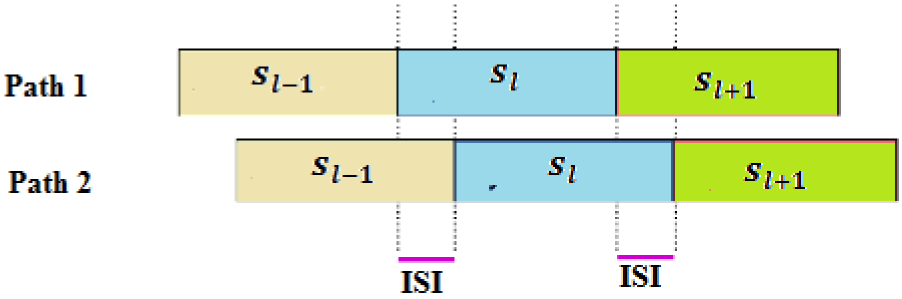

Figure 2.3: ISI between two copies of the transmitted signal.

Doppler shift can cause significant problems if the transmission technique is sensitive to carrier frequency offsets (CFO)[2] or the relative speed is high. The analogous to the Doppler frequency in time domain is called coherence time which is characterized the time varying nature of the dispersive channel.

Depending on the time and frequency characteristics of the wireless channel, there are four types of fading channel:

- Slow or fast fading based on Doppler spread and coherence time.
- Flat or frequency-selective fading based on time delay spread and coherence bandwidth.

On the one hand, in a fast fading channel, the channel impulse response changes rapidly within the symbol duration of the signal. Due to Doppler spreading, signal undergoes frequency dispersion leading to distortion. However, in a slow fading, the rate of the change of the channel impulse response is much less than the transmitted signal. The channel is considered to be slow faded if the channel almost constant over at least one symbol duration.

On the other hand, flat fading occurs when the bandwidth of the transmitted signal is less than the coherence bandwidth of the channel or equivalently if the symbol period, T_s, of the signal is more than the root mean square (RMS) delay spread of the

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[2] CFO is a deviation in the transmitted frequency due the velocity of the mobile.

channel, σ_τ, then the fading is flat fading. A rule of thumb for a channel to have flat fading is if $\frac{\sigma_\tau}{T_s} \leq 0.1$.

Frequency selective fading occurs when the signal bandwidth is more than the coherence bandwidth of the mobile radio channel. In this type, the channel introduces ISI. To overcome the ISI problem, an equalizer should be used at the receiver.

2.2.2. Channel Equalization

Mobile communication systems require signal processing techniques that improve the connection performance. Equalization, diversity and channel coding are channel impairment improvement techniques. Equalization compensates ISI created by multipath fading within time dispersive channels. An equalizer is a filter at the mobile receiver that overcomes the average range of expected channel amplitude and delay characteristics. Diversity is another technique used to compensate fast fading and it is usually implemented using multiple antenna system. Channel coding improves mobile communication link performance by adding redundant data bits in the transmitted signal. There are two categories of symbol by symbol equalizers, linear forward equalizers and nonlinear decision feedback equalizers. On the one hand, a **linear** forward equalizer consists of a transversal filter with adjustable tap coefficients, zero forcing (ZF) equalizer and minimum mean square error (MMSE) are two types of linear forward equalizer. On the other hand, the **nonlinear** decision feedback equalizer (DFE) is proposed to mitigate noise enhancement. To eliminate the ISI, the estimated symbols are fed back through the feedback filter of the DFE. However, this introduces error propagation which can seriously degrade the performance of the DFE and complicate analysis of its performance. DFE and other nonlinear and adaptation equalization techniques are proposed and discussed in [2].

In the following section, we present in detail the physical and data link architecture of the second generation (2G) cellular system, GSM-900.

2.3. GSM-900 System Architecture

GSM is a 2G digital cellular technology used to transmit voice and data services. GSM was proposed by European telecommunications operators and manufactures in the early of 1990s. It operates in the 900 MHz frequency band, and then it is upgraded into another two frequency bands 1800 MHz and 1900 MHz [26].

2.3.1. Channel Access

In this work, we consider GSM based on 900 MHz (GSM-900), which is the main frequency band used in Palestine. In that case, GSM-900 system uses the frequency bands 890-915 MHz for the uplink and 935-960 MHz for the downlink. Depending on frequency division multiple access (FDMA), each band is divided into 125 channels with a bandwidth of 200 KHz. Every subscriber needs two channels, uplink channel to transmit services and downlink channel to receive services. As 2G is based on time division multiple access (TDMA), every channel is time shared between eight subscribers. Therefore, every 200 KHz channel carries services of 8 subscribers [27].

2.3.2. Network Layers

The GSM-900 network is divided into three basic subsystems: mobile station (MS), base station subsystem (BSS) and network switching subsystem (NSS) as shown in Fig. 2.4.

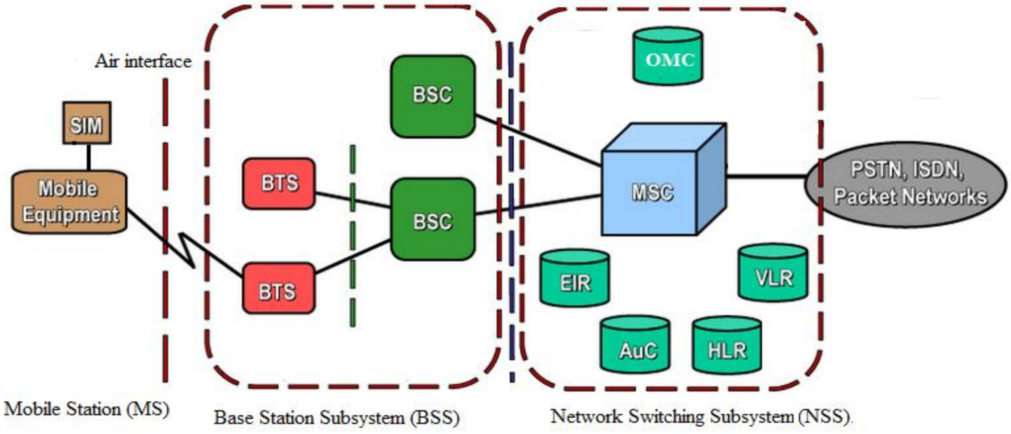

Figure 2.4: GSM Network Architecture [27].

2.3.2.1. Mobile Station (MS)

The MS is used by GSM subscriber. It includes two elements, the GSM mobile phone set, i.e., mobile equipment, and the subscriber identity module (SIM). The main functions of the MS are to transmit, receive, encode and decode voice transmissions.

The SIM card provides authentication, information storage, and subscriber related information [8][27]

2.3.2.2. Base Station Subsystem (BSS)

The BSS provides a wireless connection between the subscriber, MS, of a limited area and the NSS through air interface. The BSS consists of one or more base transceiver station (BTSs) and one base station controller (BSC). The BTS includes all radio and transmission interface equipment needed within one cell. The BTS communicate with MS of the users. In that case, one frequency is used to transmit signals to the MS and one to receive signals from the MS. In addition, BSC is the central part of BSS. It controls and monitors the operation a set of BTSs. BSC communicate with BTS via a so-called Abis interface [26][27].

2.3.2.3. Network Switching Subsystem (NSS)

NSS acts as an interface between wireless and fixed public switched telephone network (PSTN). It consists of switches and databases that manage and control the GSM network functions such as handovers[3] between BSS's, worldwide user localization, user accounts, call charges, and management of roaming which enables a MS to automatically access the services when travelling outside the geographical coverage area of their home network on the same SIM card. The main components of the NSS are [27]:

1. Mobile switching center (MSC), is an exchange that represents the core of the GSM network. MSC performs many functions such as: coordinates setup calls between GSM users, controls several BSCs, handover between BTSs and BSCs, etc.
2. Home location register (HLR), a database to store and management permanent data of subscribers.
3. Visitor location register (VLR), a database to store temporary information about subscribers. It is needed by MSC in order to serve visiting subscribers.

---

[3] It is the process when the MS transfers from channel to another without turning-off the call.

The operations and maintenance center (OMC) is connected to all equipment in the NSS and the BSC. The implementation of OMC is called the operation and support system (OSS), which monitors and controls the GSM network [8].

2.4. GSM-900 Physical Layer

In this section, we show the system model of the GSM-900 system including the mathematical models of the signals in the transmitter and the receiver. A block diagram of a GSM transceiver system is shown in Fig. 2.5. In the following subsections, we explain each process of this model for transmitter. It should be noted that an inverse of process is considered for the receiver.

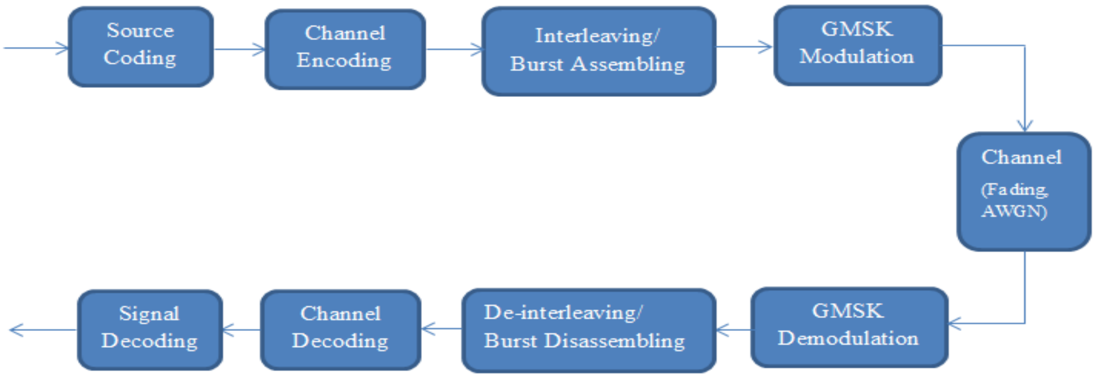

Figure 2.5: GSM-900 transceiver.

2.4.1. Source Coding

The speech signal from the MS is converted from analog to digital using analog to digital converter (ADC). The sampling rate in ADC is 8000 sample/s and every quantization level is encoded into 13 bits. Thus, the data rate is 104 kbps. Hence, the bit rate of eight subscribers on each channel, i.e., 200 KHz, is 832 kbps. This bit rate is high to transmit over 200 KHz channel. Therefore, source coding or speech coding should be introduced in order to overcome this problem using coding algorithms, such as linear prediction coding (LPC) [26]. In that case, the speech signal is divided into number of segments. Each segment has duration of 20 ms and 160 samples of speech signal. The segment is encoded into 260 bits. Therefore, the bit rate becomes $\frac{260}{20\,ms} =$ 13 kbps.

2.4.2. Channel Coding

In GSM-900 system, the channel coding is one of mechanisms used to enable detection and correction of transmission errors. GSM-900 system uses a combination of several channel coding procedures: besides a block code, which generates parity bits for error detection, a convolutional code generates the redundancy needed for error correction. The generated segment, i.e., 260 bits, from source coding process is encoded using channel encoder to produce 456 bits as shown in Fig. 2.6.

A convolutional encoder with a code rate of $R = \frac{1}{2}$ is applied on 182 bits, among these 182 bits, the 50 most significant bits are parity encoded by adding 3 redundancy bits through block coder. After parity encoding, the resulting 53 bits are combined with 132 bits, and a tail sequence of four zeros are added to the block. The total number of bits is 189, and this block is sent to convolutional encoder and the result is composed of 378 bits. The 78 non-protected bits must of course be added to these 378 bits, leading to a coded block length of 456 bits. The data rate now becomes $\frac{456}{20\ ms} =$ 22.8 kbps.

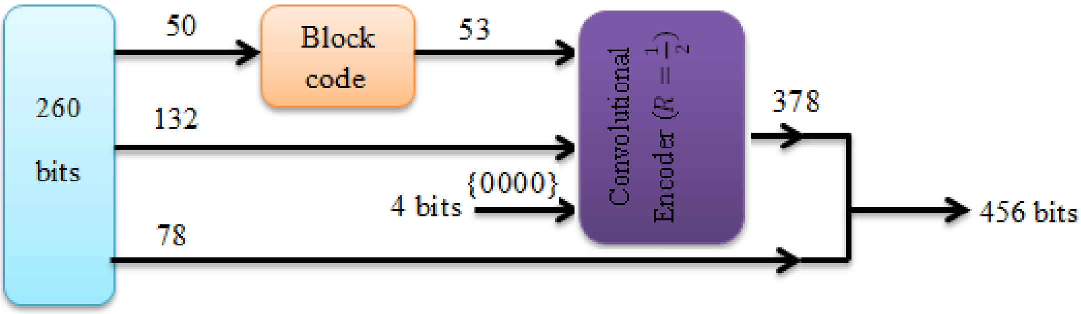

Figure 2.6: GSM channel encoder.

2.4.3. Interleaving and Burst Assembling

Interleaving is a process that used to prevent the original data from the channel effects. In this process, the 456 bits from channel encoder is divided into eight blocks, each block has 57 bits. The burst is formed from two interleaved blocks from two different 456 bits segments [27].

The GSM-900 frame contains 8 time slots on one radio frequency or channel. The time duration of each slot is 0.577 ms. Each time slot contains 156.25 bits with 8.25

bits are used as guard period between consecutive slots. The structure of normal GSM burst is shown in Fig. 2.7.

The burst structure contains two encrypted blocks of 57 bits; each block carries digitized data or information. The tail of the burst has 3 bits set to zero and placed at the beginning and the end of a burst as synchronizing fields. The two flags bits are used to indicate whether the burst carry user or control traffic. The so-called training sequence, i.e., 26 bits, is used to estimate the channel effect. The guard period of length 8.25 bits is used to prevent the overlap between time consecutives slots. Thus, the system transmits at a bit rate of $\frac{156.25\ \text{bits}}{0.577\ \text{msec}} = 270.834$ Kbps. This resultant bit transmission corresponds to a channel utilization of 1.35 bits/Hz over the 200 kHz channel bandwidth [28].

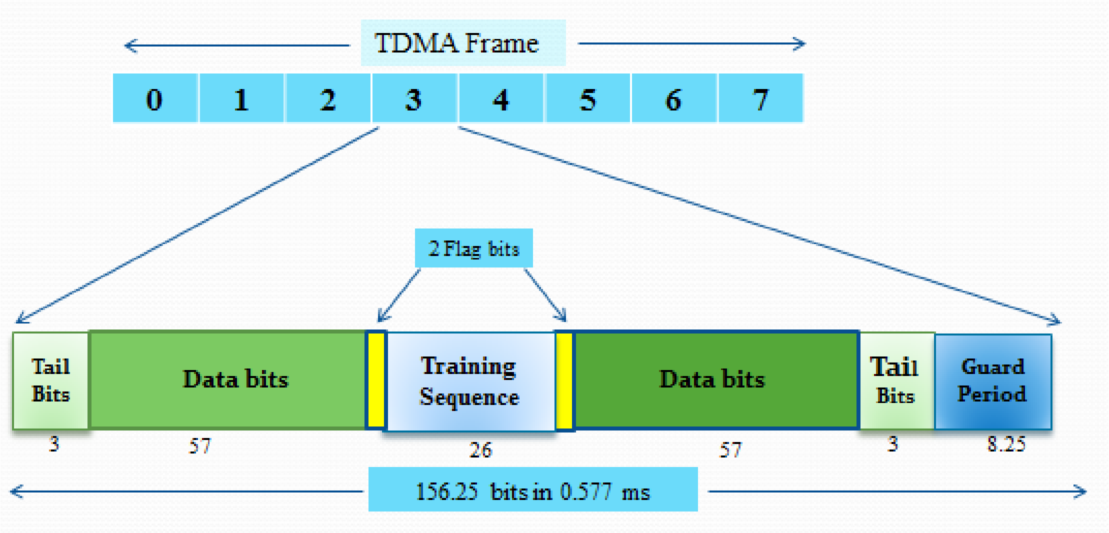

Figure 2.7: Normal GSM burst structure.

2.4.4. Digital Modulation

The aim of digital modulation is to transfer a digital baseband data bits over an analog band pass channel. The analogue signal designed to match the transmission requirements of the medium and reduce the out of band power to mitigate the interference in the wireless channel [27].

GSM-900 system uses a special digital modulation technique called Gaussian minimum shift keying (GMSK). GMSK modulation is based on the minimum shift keying (MSK), which is a form of continuous-phase frequency-shift keying with modulation index $m = 0.5$ [29]. In MSK schemes, the signal envelope is kept constant and the phase varies in a continuous manner. This ensures that MSK signals are compact spectrum. Indeed, there are no sharp changes in the signal envelope at high frequency components. The transmitted MSK signal is written as follows:

$$s(t) = A_c cos\left(2\pi f_c t + \varphi(t)\right) \tag{2.4}$$

where A_c is the amplitude of the signal, f_c is the radio frequency of the carrier and the phase $\varphi(t)$ contains the information and it is given by:

$$\varphi(t) = \pi m \sum_{k=0}^{\infty} d(k) p(t - kT) \tag{2.5}$$

with the modulation index m, the data $d(k) \in \{\pm 1\}$, and $p(t)$ related to the pulse shape of the modulation scheme.

2.4.5. GMSK transmitter

GMSK is attractive digital modulation scheme due to its excellent spectral and power efficiencies [26]. It is used in many wireless communication systems. The baseband implementation of GMSK modulator is based on the quadrature modulator as shown in Fig. 2.8. The non-return to zero (NRZ) signal, which is obtained from a binary sequence {0,1} and comprised of *d(k)* $\in \{\pm 1\}$, is passed through a Gaussian filter [30]. The impulse response of the Gaussian filter, $g(t)$, is given by:

$$g(t) = \frac{\alpha}{\sqrt{\pi}} e^{-(\alpha t)^2} \tag{2.6}$$

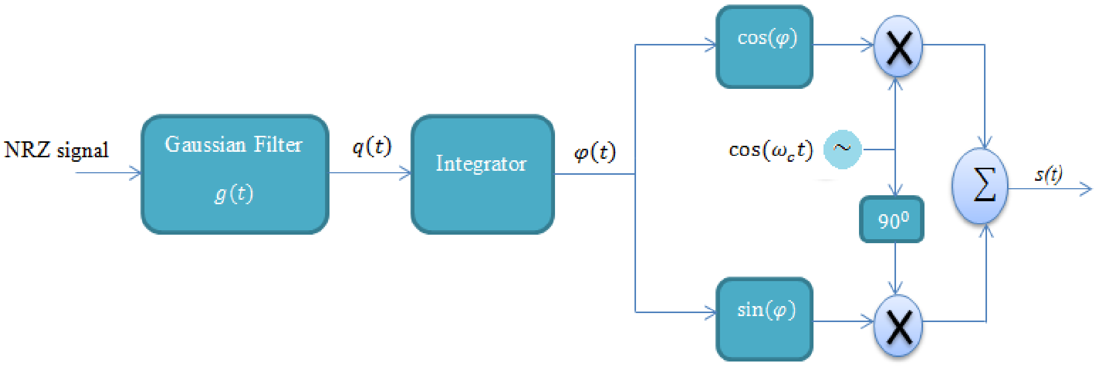

Figure 2.8: GMSK modulator.

where $\alpha = \pi\beta\sqrt{\frac{2}{\ln(2)}}$ and β is the bandwidth of the Gaussian filter.

The NRZ signal can be written as:

$$x_{NRZ}(t) = \sum_{k=0}^{\infty} d(k)rect(t - kT) \tag{2.7}$$

where T is the period of the NRZ symbol, and $rect(t)$ denoted for the rectangular signal, it can be written as:

$$rect(t) = \begin{cases} 1 & |t| < \frac{T}{2} \\ 0 & otherwise \end{cases} \tag{2.8}$$

The response of the filter to the rectangular NRZ signal can be defined as follows:

$$\begin{aligned} q(t) &= g(t) * x_{NRZ}(t) \\ &= \int_{-T/2}^{T/2} \frac{\alpha}{\sqrt{\pi}} e^{-(\alpha(t-\tau))^2}\, d\tau \\ &= \frac{1}{\sqrt{\pi}} \int_{\alpha(t-\frac{T}{2})}^{\alpha(t+\frac{T}{2})} e^{-(u)^2}\, du \end{aligned} \tag{2.9}$$

In that case, (2.9), can be written in terms of the error function (erf)[4] as following:

$$q(t) = \frac{1}{2}[erf\left(-\alpha T\left(\frac{t}{T} - \frac{1}{2}\right)\right) + erf\left(\alpha T\left(\frac{t}{T} + \frac{1}{2}\right)\right)] \tag{2.10}$$

A GMSK is adapted by the European GSM-900 system. In GSM-900 system, the normalized bandwidth of βT is 0.3, which is a trade-off between bit error rate (BER) and out-of-band interference, i.e., both the side lobe power level and the width of the main lobe can be reduced by introducing a baseband Gaussian-shaped filtering of rectangular pulses before modulation [26].

---

[4] It is defined as: $erf(t) = \frac{2}{\sqrt{\pi}}\int_0^t e^{-u^2}\, du$.

The impulse response, $q(t)$, over different values of βT product is shown in Fig. 2.9. The normalized power spectral density (PSD) of GMSK at different values of βT is shown in Fig. 2.10. The BER exponentially increases due to the reduction in signal power if βT drops below 0.3.

The result of Gaussian filter is then integrated in order to compute the phase, $\varphi(t)$. The integrated phase is given by:

$$\varphi(t) = \frac{\pi}{2}\sum_{k} d(k)\, p(t-kT) \tag{2.11}$$

where:

$$p(t) = \int_{-\infty}^{t-kT} q(\tau)d\tau \tag{2.12}$$

This phase determines the I-channel and the Q-channel signals by using the following equations:

$$s_I(t) = \cos\big(\varphi(t)\big) \tag{2.13.a}$$

$$s_Q(t) = \sin\big(\varphi(t)\big) \tag{2.13.b}$$

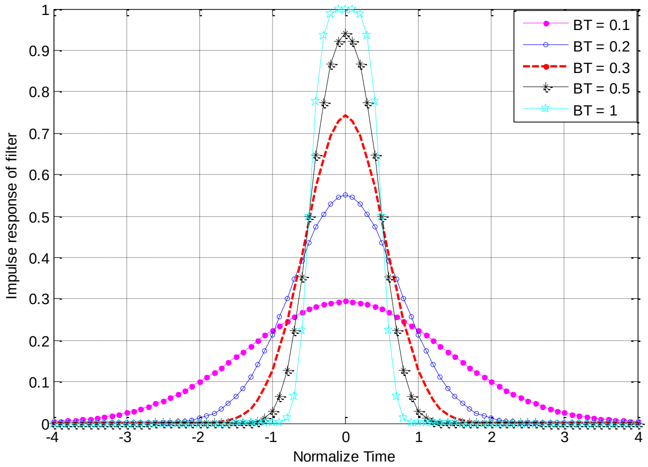

Figure 2.9: Gaussian response filter with different values of βT.

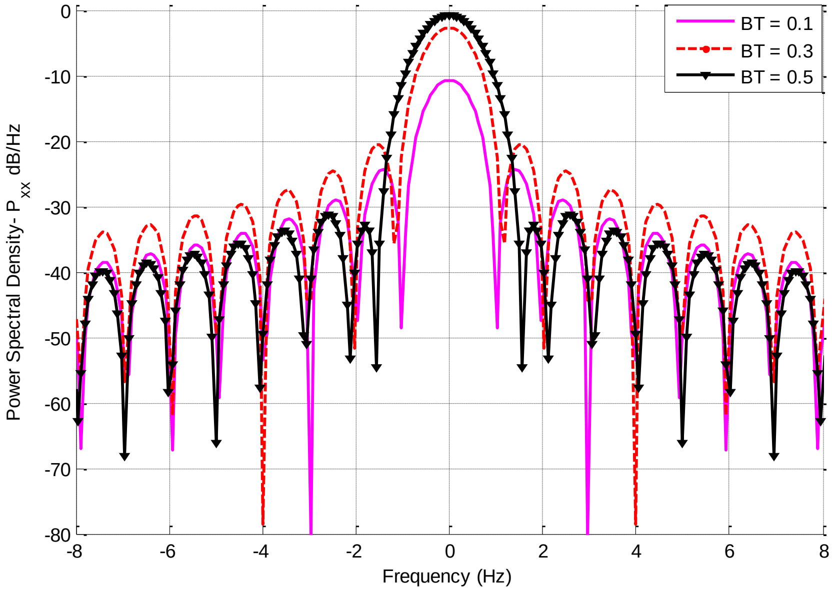

Figure 2.10: Power spectral density of GMSK with different values of βT.

The baseband form of the signal $s(t)$, takes the form of quadrature signal[5]. In that case, given (2.11), the baseband signal $x(t)$ of $s(t)$ can be written as follows:

$$\begin{aligned} x(t) &= e^{j\varphi(t)} \\ &= e^{j\frac{\pi}{2}\sum_k d(k)p(t-kT)} \end{aligned} \tag{2.14}$$

However, GMSK is not linear because of the phase modulation and Gaussian filtering. Therefore, a linear approximation of GMSK is preferable and can be realized with a usual I/Q-Modulator for PSK or QAM.

Laurent approximation showed that any binary continuous phase modulation (CPM) signal with a modulation filter duration L can be expressed as the sum of 2^{L-1} PAM signals [29][30]. Applying this result to GMSK with $\beta T = 0.3$, $L = 3$, and L basis functions, $\psi_n(t)$, in which each basis is weighted by a complex coefficients, $A_n(k)$, we can write the approximated transmitted GMSK signal as:

$$x(t) = \sum_{\mathrm{n}=0}^{3} \sum_{k} e^{j\frac{\pi}{2}A_n(k)}\, \psi_{\mathrm{n}}(t - \mathrm{kT}) \tag{2.15}$$

---

[5] The term quadrature means that the phase of a signal is in quadrature or 90 degrees to another one.

It found that the basis $\psi_0(t)$ contains 99 % of the total GMSK pulse energy [29]. The following linear approximation of $x(t)$ can be rewritten as:

$$x(t) = \sum_{k} y(k)\,\psi_0(t - kT) \tag{2.16}$$

where

$$\psi_0(t) = \prod_{i=0}^{3} \sin(\frac{\pi}{2}(1 - p(t - iT)) \qquad 0 \leq t \leq 3T \tag{2.17}$$

and

$$y(k) = e^{j\frac{\pi}{2}\sum_{i=0}^{k} d(i)} \tag{2.18}$$

2.4.6. GMSK Receiver

In a GSM-900 system, the training sequence of a known pattern which has good autocorrelations is located in the middle of the burst. This training sequence is used by the equalizer to create the channel model. The mobile channel impulse response is finite and approximately time invariant for the length of one GSM burst, i.e., there is no fast fading degradation during one slot [26][29]. If we know the impulse response of the channel, we can recover the transmitted data. The coherence bandwidth[6] is approximately equal 30 KHz [29]. The GSM-900 signal bandwidth is 200 KHz. Therefore, the received signal results in a serious ISI problem. To mitigate the effects of ISI, an equalizer must be used. The general GMSK receiver structure is shown in Fig. 2.11.

Recall that the GSM burst contains 148 bits. The discrete received symbol, $r(n)$, for the discrete transmitted symbol, $x(n)$, is:

$$r(n) = \sum_{i=0}^{L_p} x(n - i)h(i) + z(n) \qquad , n = 0, 1, \ldots 147 \tag{2.19}$$

---

[6] Is a measure of the range of frequencies over which the channel fading can be considered flat.

where $h(n)$ is the discrete form of $h(t)$ which is the convolution of the pulse shaping function $p(t)$ and the channel impulse response with length $L_p + 1$. In addition, $z(n)$ is an additive white Gaussian noise.

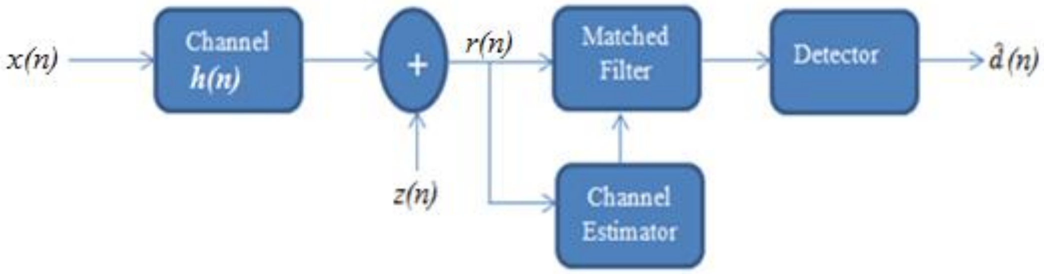

Figure 2.11: GMSK receiver structure.

The channel estimation uses the K known training symbols $x_{tr.s}(n)$, $n = 0, \dots, K-1$, and the received training symbols $r_{tr.s}(n) = r(60 + l), l = 0, \dots, K-1$, to estimate $h(n)$, $n = 0, \dots, L_p$. For the GSM-900, the number of multipath taps, L_p, is usually 5 and K is 26 symbols [29]. The received and the transmitted training sequences are related as follows:

$$\boldsymbol{r}_{\boldsymbol{tr.s}} = \mathbf{X}_{\boldsymbol{tr.s}}\mathbf{h} + \mathbf{z} \tag{2.20}$$

where $\boldsymbol{r}_{\boldsymbol{tr.s}} = [r_{tr.s}(0) \quad \dots \quad r_{tr.s}(K-1)]^T, , \mathbf{z} = [z(0) \quad \dots \quad z(K-1)]^T$, $\mathbf{h} = [h(L_p) \quad \dots \quad h(0)]^T$ and the matrix $\mathbf{X}_{\boldsymbol{tr.s}}$ containing the training sequence with known symbols $x_{tr.s}(n)$ according to (2.19) and it is given by:

$$\mathbf{S}_{\boldsymbol{tr.s}} = \begin{bmatrix} x_{tr.s}(0) & \cdots & x_{tr.s}(L_p) \\ \vdots & \ddots & \vdots \\ x_{tr.s}(K-1) & \cdots & x_{tr.s}(K-L_p-1) \end{bmatrix} \tag{2.21}$$

In order to estimate $\boldsymbol{h}$, one can use the minimum least square error as follows:

$$\widehat{\boldsymbol{h}} = (\boldsymbol{S}^{\boldsymbol{H}}_{\boldsymbol{tr.s}}\mathbf{S}_{\boldsymbol{tr.s}})^{-\mathbf{1}}\boldsymbol{X}^{\boldsymbol{H}}_{\boldsymbol{tr.s}}\boldsymbol{r}_{\boldsymbol{tr.s}} \tag{2.22}$$

where $\boldsymbol{X}^{\boldsymbol{H}}_{\boldsymbol{tr.s}}$ is the Hermitian transpose of $\mathbf{X}_{\boldsymbol{tr.s}}$.

It should be noted that, the GSM system uses slow frequency-hopping spread-spectrum (FHSS) with 217 hops per second as a diversity mechanism. Mobiles and base stations are capable of hopping from frequency channel to another frequency channel each frame, following a specified hopping pattern, to compensate the effect of fading [8].

The GSM receiver must involves insertion of a filter to remove the effect of frequency-selective distortion. To accomplish this goal, the Viterbi equalizer is typically implemented. The Viterbi equalizer is maximum-likelihood sequence estimation (MLSE) equalizer where the implementation of this equalizer is based on the Viterbi decoding algorithm [31].

The MLSE equalizer, proposed by Forney, is optimally minimized the probability of a sequence error by tests all possible data sequences, rather than decoding each received symbol by itself, and chooses the data sequence that is the most probable of the candidates [31].

The GSM system is required to provide mitigation for distortion due to signal dispersions of approximately 15–20 μs. Recall from Fig. 2.7, the bit duration is $\frac{577\,\mu s}{156.25} \cong 3.69\,\mu s$. Thus, the Viterbi equalizer used in GSM has a memory of 4–6 bit intervals. For each L_0 bit interval in the message, the function of the Viterbi equalizer is to find the most likely L_0 bit sequence out of the 2^{L_0} possible sequences that might have been transmitted [32].

Several equalization algorithms are proposed in literatures for GSM systems. The channels of time division multiple access (TDMA) systems such as GSM introduce multipath interference. Two approaches to achieve equalization are considered by [33]; an equalizer based on the Viterbi Algorithm (VA) and a decision feedback equalizer (DFE). The performance of MMSE-DFE is compared with maximum likelihood sequence estimation (MLSE) for the GSM system as in [34].

Zero forcing (ZF) equalizer is used as equalization scheme for GSM with multiple antennas, the demodulation of the equalized GMSK signal is done by an implementation of the VA employing decision metrics based on the amplitude of the equalized signal [35].

In this work, we use two linear equalization schemes; ZF and minimum mean square error (MMSE). ZF and MMSE equalizers are introduced in the next two subsections.

2.4.6.1. ZF equalizer

The process of ZF aims to find a set of filter coefficients, $c(n)$, that achieve the following equation:

$$h(n) * c(n) = \delta(n) \tag{2.23}$$

where $\delta(n)$ is the unit impulse signal.

The ZF equalization result in the following signal:

$$\begin{aligned} r_{ZF}(n) &= c(n) * x(n) * h(n) + c(n) * z(n) \\ &= x(n) + b(n) \end{aligned} \tag{2.24}$$

with $b(n) = c(n) * z(n)$ is additive white noise with $\sigma_b^2 = \sigma_z^2$.

The generation of $c(n)$ coefficients is done by toeplitz matrix, which is a representation of convolution operation. Let the number of channel taps, L_p, is five taps as the case in GSM system [29], then the channel coefficients can be written as follows:

$$\boldsymbol{h} = [h_1 \ h_2 \ h_3 \ h_4 \ h_5] \tag{2.25}$$

The number of equalizer coefficients (or weights), L_e, should be greater than or equal the number of channel taps, i.e, $L_e \geq L_p$. If we have five taps ZF equalizer, then the equation, $h(n) * c(n) = \delta(n)$, can be converted to multiplication matrix as follows:

$$\begin{bmatrix} h_1 & 0 & 0 & 0 & 0 \\ h_2 & h_1 & 0 & 0 & 0 \\ h_3 & h_2 & h_1 & 0 & 0 \\ h_4 & h_3 & h_2 & h_1 & 0 \\ h_5 & h_4 & h_3 & h_2 & h_1 \\ 0 & h_5 & h_4 & h_3 & h_2 \\ 0 & 0 & h_5 & h_4 & h_3 \\ 0 & 0 & 0 & h_5 & h_4 \\ 0 & 0 & 0 & 0 & h_5 \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_5 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{2.26}$$

The equalizer coefficients, $\boldsymbol{c}$, can be determined as follows:

$$\boldsymbol{c} = (\boldsymbol{H})^{-1} \boldsymbol{\delta} \tag{2.27}$$

where $\boldsymbol{H}$ is the $(L_p + L_e - 1) \times L_p$ toeplitz matrix that containing the channel coefficients, $\boldsymbol{c} = [c(1) \ \ \dots \ \ c(L_p)]^T$ and $\boldsymbol{\delta} = [0 \ 0 \ 0 \ 0 \ 1 \ 0 \ 0 \ 0 \ 0]^T$.

It should be noted that the matrix $\boldsymbol{H}$ is not necessary a square matrix, so that the inverse can be done through Pseudo inverse process.

2.4.6.2. MMSE equalizer

Our task is to design a finite length equalizer, $c(n)$, with $2K + 1$ taps such that its outputis written as follows:

$$r_{MMSE}(n) = c(n) * r(n) \qquad (2.28)$$

where $r(n) = x(n) * h(n) + z(n)$.

We can optimize $c(n)$ to combat the ISI and the noise using MMSE. In particular, the linear MMSE criterion corresponds to choosing $c(n)$ that will minimize the mean squared error (MSE) between the decision statistic, $r_{MMSE}(n)$, and the desired symbol, $x(n)$, defined as:

$$MSE = \mathbb{E}[(x(n) - r_{MMSE}(n))^2] = \mathbb{E}\left[\left(x(n) - \sum_{j=-K}^{K} c(j)r(n-j)\right)^2\right] \qquad (2.29)$$

Minimizing the MSE in this fashion leads to minimizing the contribution due to ISI and noise at the correlator output, which is clearly a desirable outcome. By invoking the orthogonality principle, this optimization problem is solved by taking the taps $\{c(j)\}_{j=1}^{2K+1}$such that the error, $x(n) - r_{MMSE}(n)$, is orthogonal to the signal $r(n-l)$, $|l| \leq K$; that is:

$$\mathbb{E}\left[\left(x(n) - \sum_{j=-K}^{K} c(j)r(n-l)\right)r(n-j)\right] = 0 \qquad (2.30)$$

Due to linearity of the expectation, we obtain:

$$\sum_{j=-K}^{K} c(j)\mathbb{E}[r(n-l)\,r(n-j)] = \mathbb{E}[x(n)r(n-j)] \qquad (2.31)$$

Let we define the following:

$$\boldsymbol{p} = \mathbb{E}[x(n)r(n-j)] = h(-l) \qquad 0 \leq l \leq K \qquad (2.32.a)$$

$$\boldsymbol{R} = \mathbb{E}[r(n-l)r(n-j)\,] = \phi_{hh}(l-j) + \frac{\sigma_z^2}{2}\delta(l-j) \qquad (2.32.b)$$

where $\phi_{hh}(l-j)$ is the channel autocorrelation.

In that case, (2.31), can be written in matrix form as follows:

$$\boldsymbol{cR} = \boldsymbol{p} \tag{2.33}$$

where $\boldsymbol{c}$ denotes the column vector of $2K + 1$ coefficients of the equalizer.

The equalizer taps can now be found by:

$$\boldsymbol{c} = \boldsymbol{R}^{-1}\boldsymbol{p} \tag{2.34}$$

In the next section, we present in details the OFDM based 4G as a secondary system used in our contribution.

2.5. OFDM system

Orthogonal frequency division multiplexing (OFDM) is a multiple access technique that considers for a 4G standard. In the following subsections, we present an overview of OFDM technology as well as the OFDM system model.

2.5.1. Fundamentals of OFDM multicarrier system

The OFDM is a multicarrier technique that converts the sequential high data rate stream into multiple parallel low data rate streams. These parallel streams are used to modulate different orthogonal subcarriers and they simultaneously transmitted by single antenna. The motivations behind emerge the OFDM technology in communication system over single carrier system are:

1. High transmission data rate.
2. Maximize the bandwidth efficiency by selecting a special set of orthogonal carrier frequencies.
3. Increase the robustness against frequency selective fading and narrowband interference.

The applications of OFDM technology have been extended from high frequency radio communication to telephone networks, digital audio broadcasting, and digital television terrestrial broadcasting. The advantages of OFDM, especially in the multipath propagation, interference and fading environment, make the technology a promising alternative in digital broadcasting and communications [5].

The orthogonality between subcarriers is a key feature in OFDM indicates that there is a precise mathematical relationship between the frequencies of the carriers in the system. Thus, it is possible to arrange the subcarriers in an OFDM signal so that the sidebands of the individual subcarriers overlap and the signals are still received without adjacent carrier interference. The minimum space frequency between two successive subcarriers that used to apply orthogonality condition can be given as:

$$\Delta f = \frac{1}{T_s} \tag{2.35}$$

where T_s is the OFDM symbol time.

It should be noted that the OFDM system suffers from two main serious problems; carrier frequency offset (CFO) and high peak to average power ratio (PAPR). On one hand, CFO causes inter carrier interference (ICI) and lead to frequency mismatch between transmitter and receiver oscillators, i.e., frequency synchronization problem. On the other hand, OFDM consists of multiple sinusoids summed together, which it can create a huge PAPR, since this large peaks introduce a serious degradation in performance when the signal passes through a nonlinear high power amplifier [36][37].

Fig. 2.12 shows the spectrum of an OFDM signal which is a *sinc*[7] function. Since the spectrum of an OFDM signal is not strictly band limited, the multipath propagation introduces an ISI. To eliminate the ISI, we add a guard interval (GI) between successive OFDM symbols. The GI is inserted in the form of the so called cyclic prefix (CP)[8] to avoid higher spectral components results from sudden change of waveform. In that case, the OFDM signal is cyclically extended and therefore the ICI is eliminated [5][36].

The general block diagram of the conventional OFDM transceiver is shown in Fig. 2.13.The system model of OFDM shows that the inverse fast Fourier transform (IFFT) is applied at the transmitter side and the fast Fourier transform (FFT) is applied at the

---

[7] The *sinc* function is defined as $sinc(x) = \frac{\sin(x)}{x}$

[8] It is a copy of the last samples of each OFDM symbol is inserted at the beginning of each OFDM symbol [2].

receiver side. The CP is used to overcome ISI and ICI, but it also adds an overhead that reduces the bandwidth efficiency. This CP is removed at the receiver side.

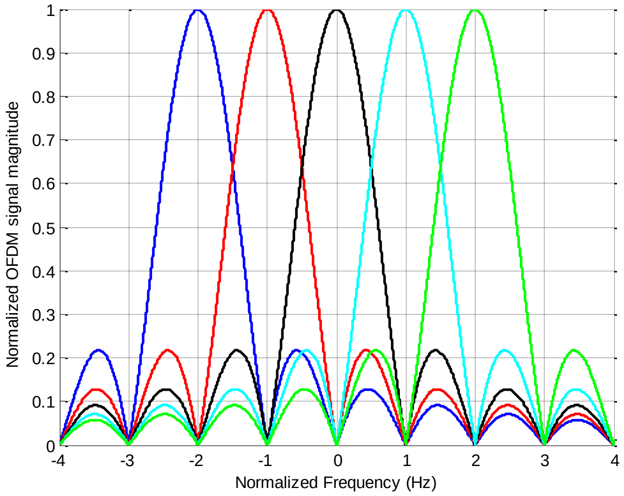

Figure 2.12: OFDM spectrum.

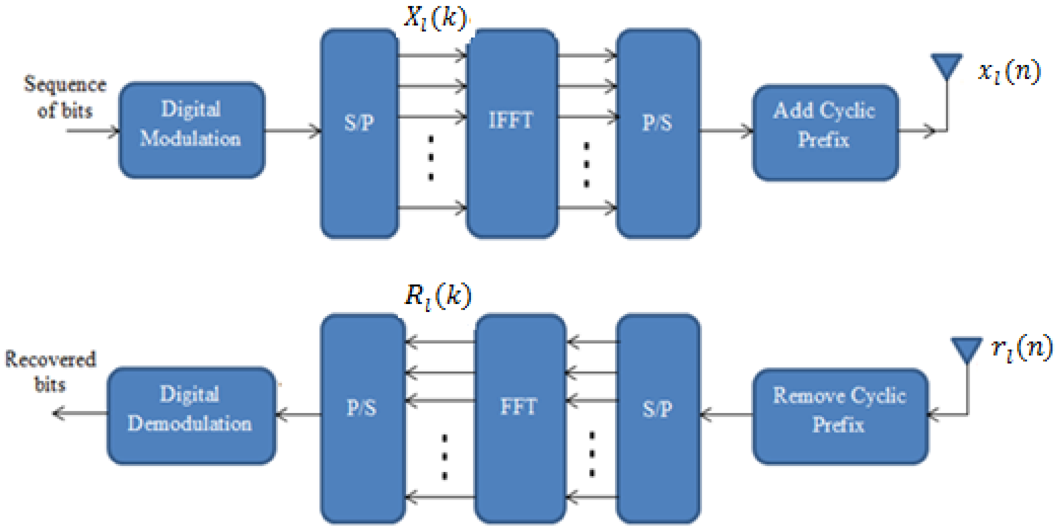

Figure 2.13: OFDM transceiver system model.

The transmitted passband OFDM signal can be defined as follows:

$$x(t) = \sum_{l=-\infty}^{\infty} \sum_{m=1}^{N_c} X_l(m)\, e^{j2\pi f_m (t-lT)} g_p(t-lT) \tag{2.36}$$

where N_c is the number of subcarriers, $X_l(m)$ is the l^{th} information symbol at the m^{th} subcarrier, T is the sum of the length of OFDM symbol (T_s) and the length of the GI (T_g), i.e, $T = T_s + T_g$, $g_p(t)$ is the rectangular pulse waveform of the symbol given as:

$$g_p(t) = \begin{cases} 1 & -T_g < t \leq T_s \\ 0 & t \leq -T_g, t > T_s \end{cases} \tag{2.37}$$

In addition, f_m is the frequency of the m^{th} subcarrier is given by:

$$f_m = \frac{m-1}{T_s} \tag{2.38}$$

In the following sections, we describe the transmitter model, the channel model and the receiver structure of the OFDM system.

2.5.2. OFDM transmitter using IFFT

Implementation of OFDM system needs a modulator for each subcarrier, which is become difficult and more expensive for hardware implementation when the number of subcarriers increases. Digital signal processing solves this problem by using the Fast Fourier Transform algorithms. OFDM transmitter can be easily implemented by using IFFT process as shown in Fig. 2.14.

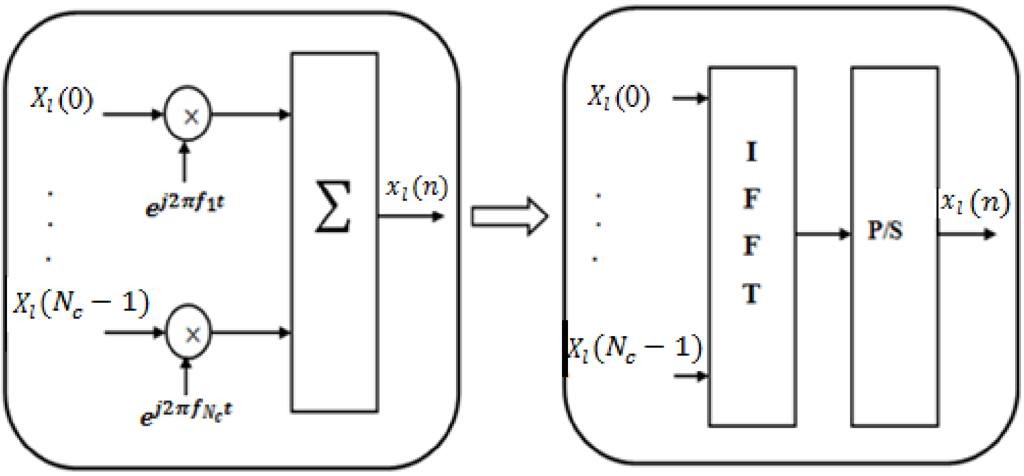

Figure 2.14: Equivalent generation of OFDM signal using IFFT.

IFFT generate N_c orthogonal subcarrier frequencies in which every subcarrier is used to carry one symbol data source. The transmitted block can be written as follows:

$$x_l(n) = \frac{1}{N_c}\sum_{k=0}^{N_c-1} X_l(k)e^{j2\pi\frac{kn}{N_c}} \qquad 0 \le n \le N_c - 1 \qquad (2.39)$$

where $x_l(n)$ is the IFFT of the signal $X_l(k)$ and $X_l(k)$ denote the l^{th} transmit symbol at the k^{th}subcarrier, $l = 0,1,2,\dots,\infty$.

The transmitted signal $x_l(n)$ passes through the wireless channel, which introduces signal distortion and additive noise.

2.5.3. Channel model

The transmitted OFDM signal is assumed to go through a frequency selective fading channel. In addition to fading, the signal also contaminated by an additive white Gaussian noise (AWGN) as shown in Fig. 2.15. One advantage of the OFDM system, it is possible to convert a wide band frequency selective fading channel into many frequency flat fading subcarriers.

An OFDM system is very sensitive to CFO, which may be introduced in the radio channel, so accurate frequency offset synchronization is essential. The orthogonality of an OFDM system is only preserved when the receiver and the transmitter use the same frequency. Thus, the receiver has to estimate and correct the carrier frequency offset of the received signal [37].

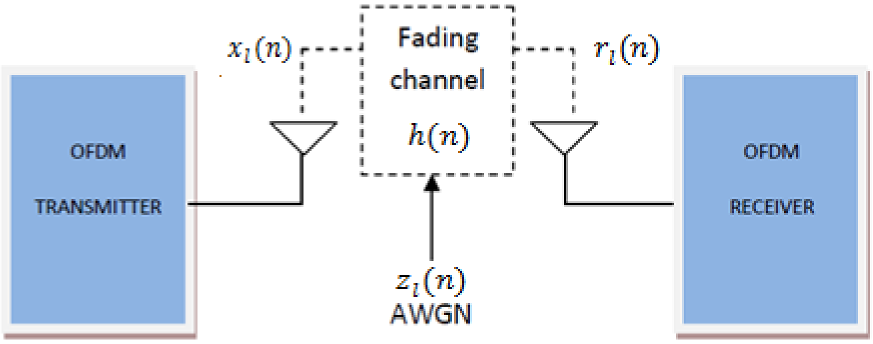

Figure 2.15: Fading channel with AWGN modeling for OFDM system.

2.5.4. OFDM Receiver using FFT

The receiver operations are essentially the reverse of those in the transmitter. The received signal of the l^{th} symbol can be written as follows:

$$r_l(n) = h(n) * x_l(n) + z_l(n) \tag{2.40}$$

where $h(n)$ is the channel fading impulse response and $z_l(n)$ is the additive noise.

The signal $r_l(n)$ is passed through FFT process after the guard interval being removed [36]. Thus the output signal, $R_l(k) = FFT\{r_l(n)\}$, is expressed by:

$$\begin{aligned} R_l(k) &= \sum_{n=0}^{N_c-1} r_l(n)\, e^{-j2\pi\frac{kn}{N_c}} \\ &= \sum_{n=0}^{N_c-1} \left\{ \sum_{m=0}^{\infty} h(m) x_l(n-m) + z_l(n) \right\} e^{-j2\pi\frac{kn}{N_c}} \\ &= \sum_{n=0}^{N_c-1} \sum_{m=0}^{\infty} h(m) x_l(n-m) e^{-j2\pi\frac{kn}{N_c}} + \sum_{n=0}^{N_c-1} z_l(n) e^{-j2\pi\frac{kn}{N_c}} \end{aligned} \tag{2.41}$$

Let we define that $Z_l(k) = \sum_{n=0}^{N_c-1} z_l(n) e^{-j2\pi\frac{kn}{N_c}}$, then the $R_l(k)$ can be written as:

$$\begin{aligned} R_l(k) &= \frac{1}{N_c} \sum_{n=0}^{N_c-1} \sum_{m=0}^{\infty} h(m) \sum_{u=0}^{N_c-1} X_l(u) e^{j2\pi\frac{u(n-m)}{N_c}}\, e^{-j2\pi\frac{kn}{N_c}} + Z_l(k) \\ &= \frac{1}{N_c} \sum_{n=0}^{N_c-1} \sum_{m=0}^{\infty} h(m) e^{-j2\pi\frac{um}{N_c}} \sum_{u=0}^{N_c-1} X_l(u) e^{j2\pi\frac{un}{N_c}}\, e^{-j2\pi\frac{kn}{N_c}} + Z_l(k) \\ &= \frac{1}{N_c} \sum_{u=0}^{N_c-1} \sum_{m=0}^{\infty} h(m) e^{-j2\pi\frac{um}{N_c}} X_l(u) \sum_{n=0}^{N_c-1} e^{j2\pi\frac{un}{N_c}}\, e^{-j2\pi\frac{kn}{N_c}} + Z_l(k) \end{aligned} \tag{2.42}$$

At this point, we have two factors:

a.

$$\sum_{n=0}^{N_c-1} e^{j2\pi\frac{un}{N_c}}\, e^{-j2\pi\frac{kn}{N_c}} = \delta(u-k) = \begin{cases} 1 & u = k \\ 0 & u \neq k \end{cases} \tag{2.43}$$

b.

$$H_l(k) = \sum_{m=0}^{\infty} h(m) e^{-j2\pi \frac{km}{N_c}} \tag{2.44}$$

In that case, $R_l(k)$ will be written as:

$$R_l(k) \;= \frac{1}{N_c} \sum_{u=0}^{N_c-1} H_l(k)\, X_l(k) + Z_l(k) \tag{2.45}$$

Hence, $\sum_{u=0}^{N_c-1} H_l(k)\, X_l(k) = N H_l(k) X_l(k)$. Thus,

$$R_l(k) \;=\; H_l(k) X_l(k) + Z_l(k) \tag{2.46}$$

After the FFT process, the system should equalize the received signal. The OFDM equalizer is simple and it just divide the received signal on the spectrum response of the channel. The estimated received signal, assuming normalized $H_l(k)$, can be written as:

$$\widehat{X}_l(k) = R_l(k) H_l{}^{*}(k) = \; X_l(k) + Z_l(k) H_l{}^{*}(k) \tag{2.47}$$

If the additive noise power is zero, i.e, $Z_l(k) = 0$, then we have:

$$\widehat{X}_l(k) = X_l(k) \tag{2.48}$$

In the next section, we present simulation results based on BER for GMSK based GSM and OFDM based 4G.

2.6. Simulation Results for GSM and OFDM systems

In this part we show some of simulation results including GMSK spectrum and BER and the performance of GMSK based GSM system in AWGN and fading channels as well BER performance of quadreture phase shift keying (QPSK) and the OFDM system. The probability of error or BER is the number of bit errors divided by the total number of transferred bits during time interval is used to measure the performance of communication system. The theoretical bit error rate of GMSK in AWGN channel, P_{GMSK}, is given by:

$$P_{GMSK} = Q\left(\sqrt{\frac{2\gamma E_b}{N_0}}\right) \tag{2.49}$$

where $Q(.)$ is the Q-function with $Q(x) = 0.5\,(1 - erf\left(\frac{x}{sqrt(2)}\right))$, $\frac{E_b}{N_0}$ is the bit energy to noise energy value and γ is a constant related to 3-dB bandwidth bit duration product (βT) of the Gaussian filter by:

$$\gamma \cong \begin{cases} 0.68 & \text{for GMSK } (\beta T = 0.3) \\ 0.85 & \text{for MSK } (\beta T = \infty) \end{cases} \tag{2.50}$$

The theoretical probability of bit error of GMSK in Rayleigh fading channel, which is the average of the P_{GMSK}, is given by:

$$\bar{P}_{GMSK} = \frac{1}{2}\left(1 - \sqrt{\frac{\gamma\Gamma}{\gamma\Gamma + 1}}\right) \tag{2.51}$$

where $\bar{P}_{GMSK}$ is the probability of error for GMSK in Rayleigh channel and $\Gamma = \frac{E_b}{N_0}$ is the average signal-to-noise ratio.

GMSK is type of two level modulation schemes. In this work the performance of Gaussian Minimum Shift Keying (GMSK) modulation is compared with that of QPSK and QAM modulation scheme. GMSK is used in GSM-900 as digital mapping while QPSK is usually used in OFDM. The theoretical BER for QPSK in AWGN, P_{QPSK}, and Rayleigh channels, $\bar{P}_{QPSK}$, can be written as:

$$P_{QPSK} = \mathrm{Q}\left(\sqrt{\frac{2\mathrm{E_b}}{\mathrm{N_0}}}\right) \tag{2.52}$$

$$\bar{P}_{QPSK} = \frac{1}{2}\left(1 - \sqrt{\frac{\Gamma}{\Gamma + 1}}\right) \tag{2.53}$$

2.6.1. Performance of GMSK and QPSK

Fig. 2.16 shows the spectrum power level in dB versus frequency normalized to bit rate for GMSK, BPSK and QPSK. The GMSK spectrum shows that the side lobes have weaker power compared to side lobes in BPSK and QPSK.

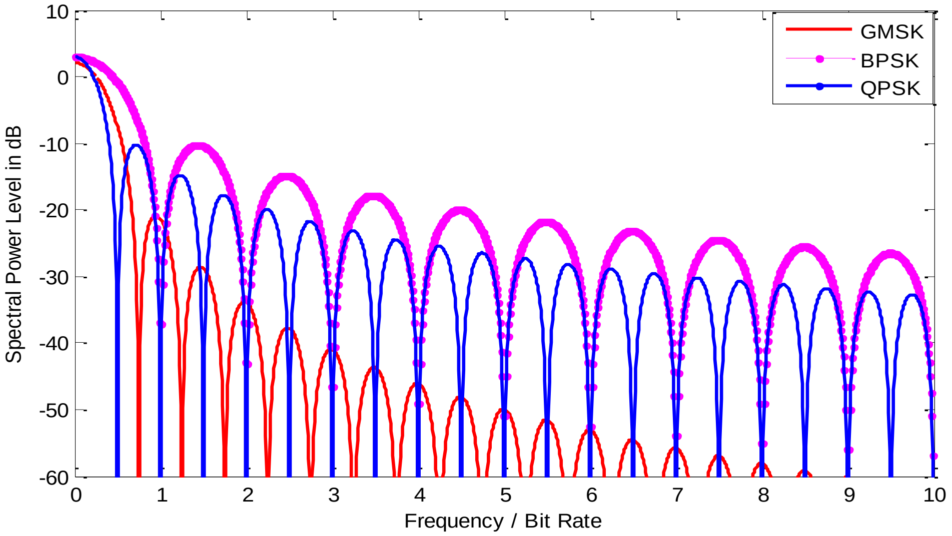

Figure 2.16: Power spectrum versus normalized frequency to bit rate for GMSK, BPSK and QPSK.

Fig. 2.17 shows the BER performance for GMSK and QPSK in AWGN and Rayleigh fading channels with $\gamma = 0.68$. It is observed that QPSK outperforms GMSK modulation in terms of bit error rate in two channels. This degradation in performance of GMSK due to spread the modulating NRZ bit over several bit periods. This gives rise to induced ISI. It can be shown from Fig. 2.9, as βT decreased, the ISI is increased since the frequency shaping pulse of Gaussian filter has a duration greater than bit period T. However, a smaller value of βT results in a more compact power density spectrum since the Gaussian pre-modulation baseband filter suppress the high frequency components in the data. Hence, there is a trade off in the choice of βT. In bandwidth limited systems, smaller BT product is required to achieve more bandwidth efficient. For example, the GSM uses GMSK modulation having a βT product equal to 0.3 Hz/(b/s).

2.6.2. BER of GMSK based GSM-900

Fig. 2.18 shows the simulation results for BER performance of GSM-900 system in three channel scenarios, AWGN, Rayleigh flat fading and Rayleigh frequency selective fading channels. The simulation results are compared to theoretical probability of error. In the case of selective fading, we consider five independent time invariant multipath and ZF equalizer at receiver side.

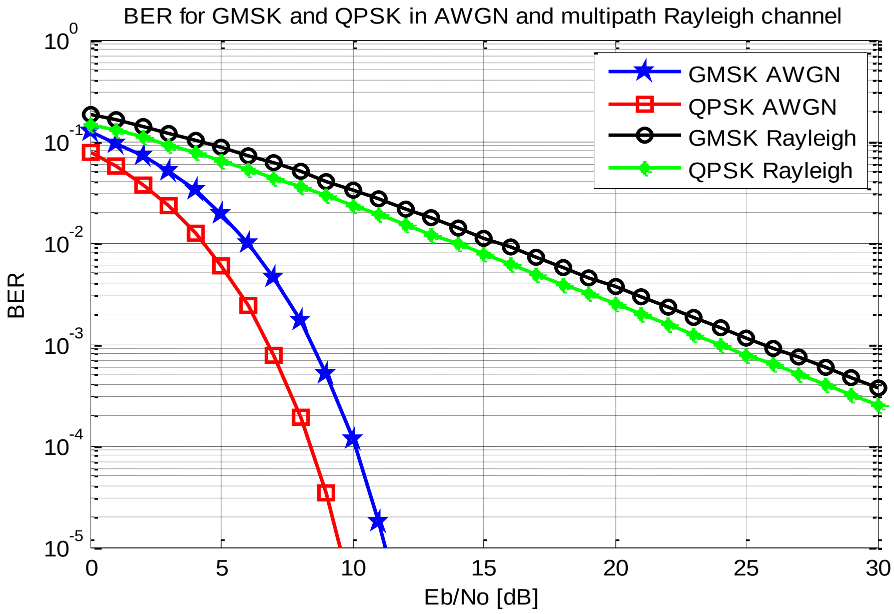

Figure 2.17: BER for GMSK and QPSK in AWGN and Rayleigh channels.

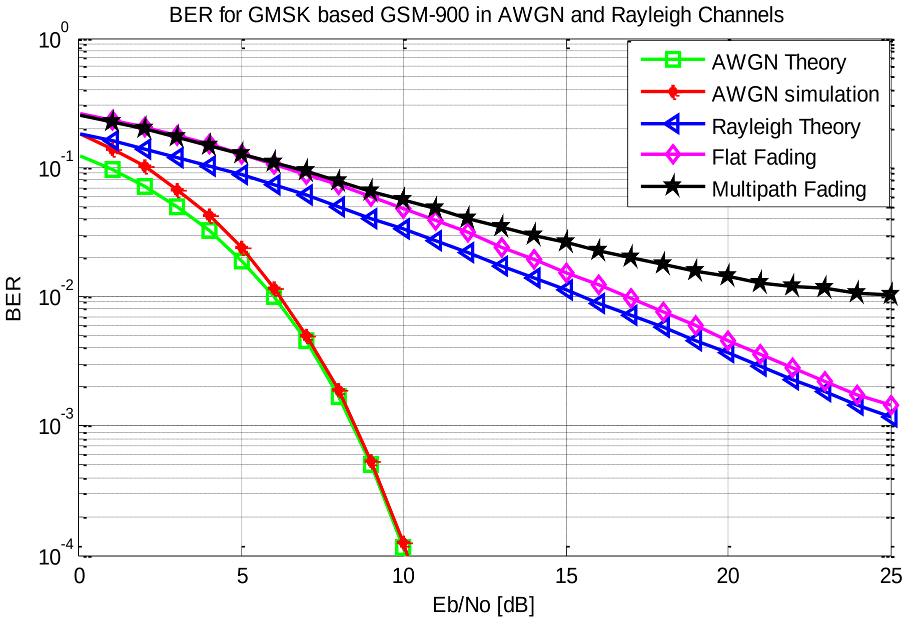

Figure 2.18: BER of GSM-900 in AWGN and Fading channels.

2.6.3. BER of QPSK based OFDM system

In this section, we show the BER for OFDM system where we have 64 subcarriers and the length of CP is 16 and QPSK as modulation scheme. The BER based simulation results is measured under AWGN channel and Rayleigh fading channel and compared with theoretical equations of QPSK modulation as shown in Fig. 2.19.

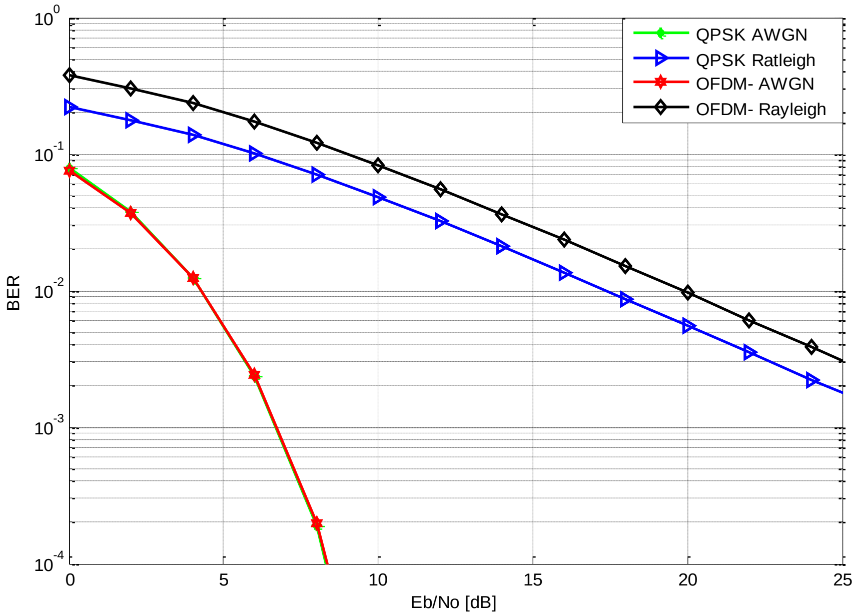

Figure 2.19: BER of OFDM in AWGN and Fading channels.

In this chapter, we have investigated the signal modelling for GSM and OFDM based 4G. In that case, we have studied the performance of OFDM and GSM in terms of BER. For GSM receiver, we have used two equalizer techniques, ZF and MMSE. In the next chapter, we study the relevance of applying overlay CR using 4G-OFDM as SS for efficient utilization of the existing GSM spectrum. In that case, we use the zero forcing beamforming (ZFBF) as interference cancellation technique at SS.

Chapter 3

Overlay CR based Cellular Systems

Contents

3.1. Overview

The cognitive radio (CR) is a technology that revolutionizes the wireless spectrum shortage by utilizing advanced radio and signal processing to support new wireless users or secondary users (SU) operating in the existing spectrum that is used by primary users (PU). There are three main ways to access to the channel in CR [38][39]:

1. Underlay: The CR system is assumed to know the acceptable interference level of the PU. Cognitive user or SU can transmit simultaneously with PU as long as interference is below an acceptable limit.
2. Interweave: it was the original of CR. Cognitive user, SU, uses the spectral whitespace when the PU is not using them. Thus, secondary system (SS) avoids collisions with the primary system (PS).
3. Overlay: In that case, the SS simultaneously transmits with the PS while mitigating the interferences, by taking into account that some *a priori* information of the PU is known at the SU transmitter. Sophisticated encoding techniques can be defined to cancel or mitigate the interferences at the PU receiver from SU transmitter and the interference from PU transmitter at the SU receiver.

Our proposed system is based on an overlay CR platform where the global system for mobile communication (GSM) is considered as PS and 4G based on orthogonal frequency division multiplexing (OFDM) system is the SS. Fig. 3.1 shows our contribution in this thesis.

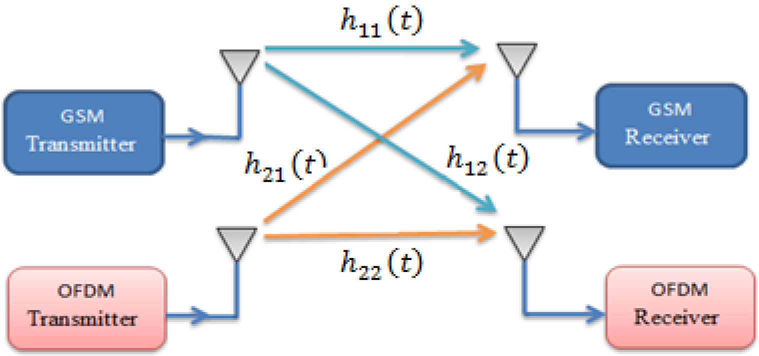

Figure 3.1: CR based on GSM-900 for PS and 4G based on OFDM for SS.

The received signal at the antenna of the GSM-900 receiver is given by:

$$r_p(t) = h_{11}(t) * x_p(t) + h_{21}(t) * x_s(t) + z(t) \tag{3.1}$$

where the index "1" refer to GSM system (primary) and "2" for the OFDM system (secondary) in all variables, $x_p(t)$ is the transmitted signal from GSM and $x_s(t)$ from OFDM and $z(t)$ is the additive white noise with zero mean and variance σ_z^2.

One can be notice that the interference term in (3.1), $h_{21}(t) * x_s(t)$, should be cancelled in order to do no effect on PU.

3.2. State of the Art on CR

As mentioned in chapter one, CR has been introduced by Mitola in 1999 as an extension to software radio [11][12]. The CR technology with its three paradigms has been investigated widely in the literature [38].

The feasibility of an overlay CR system in which the SU is a cellular network coexistent with a TV system in the same frequency band is introduced by [40]. In [15], an overlay CR technology was integrated into 4G cellular networks for the sharing of TV spectrum. In [24], a hybrid transmission system that exploits both overlay and underlay is proposed using multicarrier code division multiple accesses (MC-CDMA) due to its interference rejection and diversity exploitation capabilities.

The achievable rate of an OFDM-based CR system sharing the spectrum with an OFMDA-based PS is studied in [41]. The authors propose a rate loss constraint (RLC) instead of conventional interference power constraint in order to protect the primary system from secondary interference. The merits and challenges of cognitive radio based on OFDM technology is investigated in [42]. The authors present some of the requirements for CR and explain how OFDM can fulfil these requirements.

CR based on OFDM has drawn many interests in designing efficient radio resource allocation schemes. Most of the existing works considered the cognitive scenario under perfect knowledge of system state. In [43], a transmitter architecture for OFDM-based overlay CR has been proposed to reduce the spectral leakage of SU. The power spectral density of the proposed scheme has been calculated and compared with other spectral precoding schemes.

A comparison of two types of multicarrier communications: conventional OFDM with cyclic prefix (CP) and filter bank multicarrier (FBMC) based CR networks in terms of the averaged channel capacity, which depends on the resource allocation strategy adopted by the CR system is proposed in [44]. Simulation results show that FBMC can achieve higher channel capacity than OFDM.

A hybrid CR where a filter bank multicarrier (FBMC) is used for the SU whereas the PU are based on OFDM was proposed in [19]. The relevance of the FBMC/OQAM over OFDM for the secondary user in a hybrid overlay multiuser CR system was investigated where the zero forcing beam forming (ZFBF) as interference cancellation method was considered. Simulation results confirmed that the FBMC based CR is superior OFDM in terms of the spectral and bit error rate efficiencies. The bit error rate performance of OFDM CR transmission over 900 MHz GSM band with frequency hopping in urban area and rural areas are simulated in [45].

In the following section, we present the model of the GSM as PS and OFDM as SS.

3.3. System Model for PS and SS

The mathematical models for GSM and OFDM systems were presented in chapter 2. In this chapter, we show the system model used in our contribution.

3.3.1. GSM based PS

The discrete transmitted GMSK signal of the (2.4) can be written as follows:

$$s(n) = A_C cos\big(2\pi f_c n + \varphi(n)\big) \tag{3.2}$$

where A_C is the amplitude of the signal, f_c is the radio frequency of the carrier and the discrete phase $\varphi(\mathrm{n})$ contains the information is given by:

$$\varphi(n) = \frac{\pi}{2} \sum_{i=-\infty}^{\infty} d(i)\, p(n - iN_s) \tag{3.3}$$

with the data $d(i) \in \{\pm 1\}$, $p(n)$ related to the pulse shape of the modulation scheme and N_s the number of sample in a bit period.

Fig. 3.2 shows the GMSK receiver which consists of equalizer and GMSK demodulator. Recalling Fig 2.11, the equalizer consists from matched filter and channel estimator and the detector is just two channel (I-channel and Q-channel) Gaussian filter. The received baseband signal at the input of GMSK receiver can be written as:

$$r(n) = x_p(n) * h(n) + z(n) \tag{3.4}$$

where $x_p(n)$ is the primary baseband signal of $s(n)$, i.e., $x_p(n) = e^{j\varphi(n)}$, $h(n)$ is the impulse response of the frequency selective fading channel and $z(n)$ is the additive white noise with zero mean and variance σ_z^2.

In modulator, the time varying phase function $\varphi(n)$ is used to generate the inphase and the quadrature components of the GMSK signal. The process occurred on GMSK demodulator in order to completely regain the information signal of bit stream. The equalized signal, $y(n)$, is decomposed into I/Q components which are the the same components that were generated in the modulator. The decomposed I/Q channels are filtered by the Gaussian filter, $q(n)$. The discrete Gaussian response of (2.8) can be written as:

$$q(n) = \frac{1}{2}\left[erf\left(-\alpha T\left(n - \frac{1}{2}\right)\right) + erf\left(\alpha T\left(n + \frac{1}{2}\right)\right)\right] \tag{3.5}$$

where $\alpha = \pi\beta\sqrt{\frac{2}{\ln(2)}}$, β is the bandwidth of the Gaussian filter and T is the bit duration.

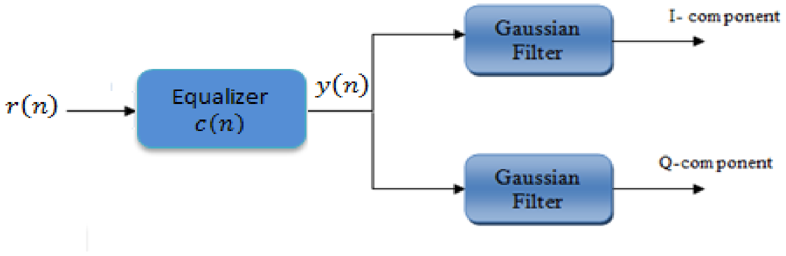

Figure 3.2: GMSK receiver.

The next process is phase computation for filters symbols from the result of I-channel and Q-channel signals to detect bit data with level 0 or 1. An equalizer is a digital filter that is used to mitigate the effects of inter symbol interference (ISI) that is introduced by a time dispersive of the channel as discussed in chapter 2. In this work, we use the two linear equalization schemes; zero forcing (ZF) and minimum mean square error (MMSE). The ZF algorithm has less computational complexity and simple structure compared with MMSE. However, the performance of MMSE is superior to ZF in terms of minimizing the error.

3.3.2. 4G-OFDM based SS

An OFDM system is considered to be a good candidate for CR where individual carriers can be switched off for frequencies occupied by a licensed user or interfering subcarriers [15][41].

OFDM is adapted as one of the best transmission scheme for CR systems. The features and the ability of the OFDM system makes it fit for the CR based transmission system. OFDM provides spectral efficiency, which is most required for CR system. This is because the subcarriers are very closely spaced and are overlapping, with no interference. Another advantage of OFDM is that it is very flexible and adaptive. The subcarriers can be turned on and off according to the environment and can assist CR system dynamically. Also, OFDM can be easily implemented using the Fast Fourier Transform (FFT), which can be done by digital signal processing using software [41]. In our contribution, we propose the OFDM technology based 4G as secondary system in order to expand the GSM mobile network spectrum. The transmitted OFDM signal can be defined as follow:

$$\boldsymbol{x} = \left[\underbrace{x(-L_{cp}) \quad \cdots \quad x(-1)}_{CP} \quad x(0) \quad \ldots \quad x(N_c - 1)\right] \tag{3.6}$$

with

$$x(n) = \frac{1}{\sqrt{N_c}} \sum_{k=0}^{N_c - 1} X(k) e^{j2\pi \frac{kn}{N_c}} \qquad 0 \leq n \leq N_c - 1 \tag{3.7}$$

where L_{cp} is the length of cyclic prefix (CP) extension and N_c is the number of OFDM subcarriers.

3.4. Interference Cancellation techniques for Overlay CR

Several interference cancellation techniques exist in order to compensate for the interference generated by cognitive radio system such as [39]:

1. Dirty paper coding (DPC), firstly proposed by Costa [21], DPC enables the effect of interference to be cancelled subject to the interference being known at the primary transmitter. In this scheme, the primary and secondary system can cooperate by sharing the information.
2. Interference alignment (IA), firstly proposed by Maddah Ali [46], IA is a linear precoding technique that attempts to align interfering signals in time, frequency, or space. The main idea of IA is to align the transmission of signals from different transmitters such that all the unwanted interference at each receiver overlaps with each other. This allows a transmitter-receiver pair to communicate interference free over the remaining interference free dimensions [20][46].
3. Vandermonde frequency division multiplexing (VFDM), VFDM allows two radios to operate while sharing the band with no interferences [47]. It is used only and only if OFDM is considered in the primary system. VFDM exploits the unused resources created by frequency selectivity and the use of guard symbols in block transmission systems at the primary system, such as OFDM. VFDM ensures interference cancelation irrespective of the primary and secondary systems transmitted data or power allocation.
4. Zero forcing beamforming (ZFBF), is one of the powerful interference cancellation techniques in multiple antenna systems. In order to apply ZFBF, which is considered as a spatial signal processing, multiple antennas should be used to lead beams to a wanted user. It hence increases the SNR while forming nulls at the unwanted users to avoid the interferences. This beamforming can be generated in both the transmitter and the receiver by using the appropriate precoding and postcoding, respectively. This kind of coding is linear and has a low implementation complexity compared with other interference cancellation techniques [48]. Therefore, ZFBF is considered as an attractive technique to be

used in MIMO systems. Moreover, ZFBF becomes a "good" choice in the field of CR [49][50].

5. Block diagonalization (BD): is one approach for linear precoding in the multiuser multiple inputs multiple outputs (MIMO) broadcast channel. BD is a generalization of ZFBF for multiple antennas transmission to each user. One of the limitations of the BD is that the sum rate does not grow linearly with the number of users and transmit antennas at low and medium signal to noise (SNR) ratio regime, since the complete suppression of multiuser interference is achieved at the expense of noise enhancement. Also it has poor performance under imperfect channel state information [36][51].

However, each technique requires a priori knowledge at the SU. Thus, in DPC the exchanged messages at the PU side have to be known. In IA, a priori information about the PU channels must be known by the SU. ZFBF is low complex compared with other techniques. Also, it maximizes the signal to noise power (SNR) due to spatial diversity. This motivates us to use ZFBF to be performed at the SS. In the following subsections, ZFBF is considered for two scenarios for an overlay CR where GSM-900 is considered for the PU and OFDM for the SU. In addition, a comparative study with 4G OFDM CR for both the PS and the SS is carried out.

3.5. Overlay CR based on GSM-900

In this section, we evaluate the relevance of the proposed hybrid overlay CR where the primary system is considered GSM-900, which uses Gaussian minimum shift keying (GMSK) as a modulation technique. The secondary system is a 4G system based on OFDM as shown in Fig. 3.3. In that case, the primary system and the secondary system are considered to be a single-input single output (SISO) system and multiple-input multiple output (MIMO) system, respectively. We derive the interference expression due to SS at the PS receiver as well as the interference expression due to PS at the SS receiver. To cancel the interferences, a precoding based on ZFBF is considered at the SS transmitter, while a postcoding is employed at the SS receiver as will discussed in the following subsections.

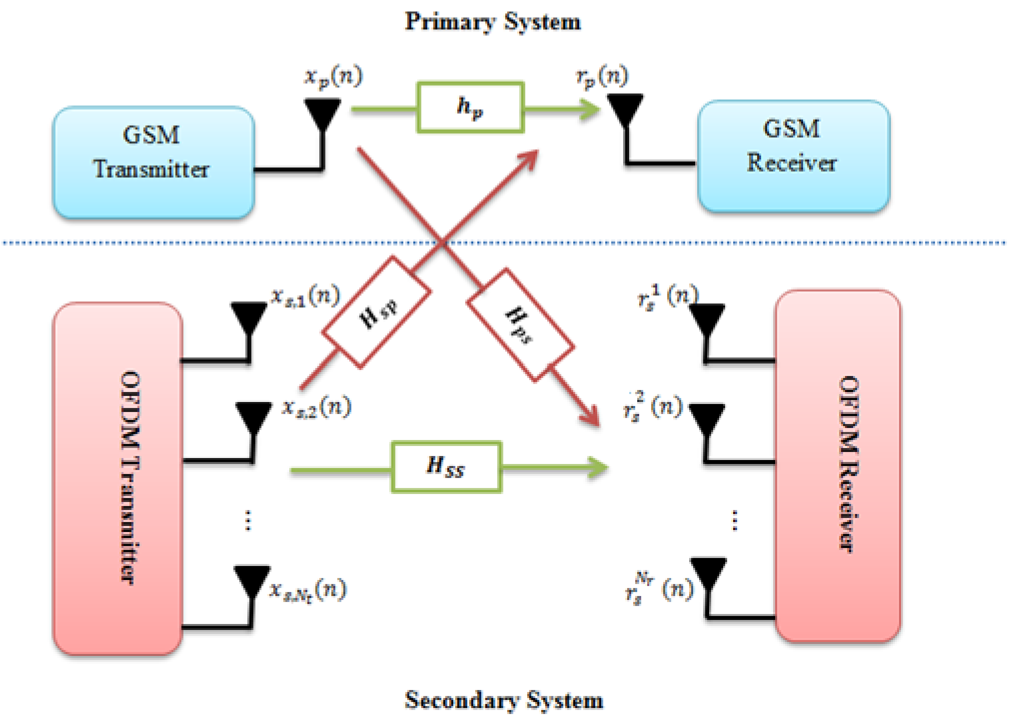

Figure 3.3: Hybrid overlay CR based on GSM as PS and OFDM as SS.

3.5.1. Interference cancellation at PS receiver

In this scenario, the transmitted symbols at SS transmitter are precoded before transmission. The received signal at the GSM receiver is corrupted by interference from secondary system since they transmit in the same band.

ZFBF is considered as a spatial signal processing and can be implemented priori in the transmitter or posteriori in the receiver. The key of interference cancellation at PS receiver is the use of a precoding in the secondary system transmitter. In this model, we propose to use precoding after the process of IFFT in OFDM system. In order to apply a precoding technique to mitigate the interferences, we consider a multiple input single output (MISO) at secondary system. Thus, the secondary data is transmitted over several numbers of antennas. Fig. 3.4 describes the precoding scheme for interference cancellation at PS receiver side.

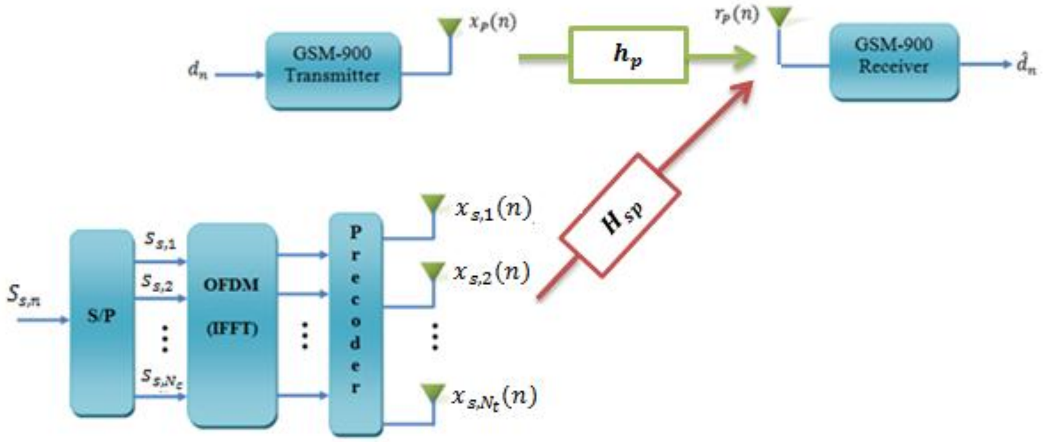

Figure 3.4: Interference cancellation at PS receiver.

It should be noted that the number of antennas at SS transmitter, N_t, is related to the number of multipath taps, L_p, where the number of antenna is at least greater than number of multipath taps by one, i.e, $N_t \geq L_p + 1$. The received signal $r_p(n)$ can be expressed as:

$$r_p(n) = h_p(n) * x_p(n) + \sum_{a=1}^{N_t} h_{sp,a}(n) * x_{s,a}(n) + w(n) \qquad (3.8)$$

where $x_p(n)$ is the transmitted signal of the primary system (GSM-900), and $x_{s,a}(n)$ is the transmitted signal of the secondary system (OFDM) on the a^{th} antenna. Also, $h_p(n)$ is the channel effect on the $x_p(n)$, $h_{sp,a}(n)$ is the channel effect on the $x_{s,a}(n)$ and $w(n)$ is the additive white noise at the primary receiver.

The interference due to SS transmission in the band of the PS is represented by:

$$i(n) = \sum_{a=1}^{N_t} h_{sp,a}(n) * x_{s,a}(n) \qquad (3.9)$$

The a^{th} signal from SS, under the assumption that all the symbols to be equal on each antenna, can be written as:

$$x_{s,a}(n) = z_a x_s(n) \qquad (3.10)$$

where z_a is the preceded data or beamformer of a^{th} antenna and $x_s(n)$ is the OFDM symbol with N_c subcarriers, it is related to digital data $X_s(m)$ according to IFFT process as follows:

$$x_s(n) = \frac{1}{\sqrt{N_c}} \sum_{m=0}^{N_c-1} X_s(m) e^{j2\pi\frac{mn}{N_c}} \tag{3.11}$$

Thus, the interference can be written as:

$$i(n) \ = \sum_{a=1}^{N_t} \sum_{k=0}^{L_p-1} h_{sp,a}(n)\, z_a x_s(n-k) \tag{3.12}$$

In GSM system, the number of taps in multipath fading channel, L_p, usually equal to 5, therefore the minimum required number of antenna is $N_t = 6$. With these two values we get:

$$\begin{aligned} i(n) = {} & z_1\big[h_{sp,1}(0)x_s(n) + h_{sp,1}(1)x_s(n-1) + \cdots + h_{sp,1}(4)x_s(n-4)\big] \\ & + z_2\big[h_{sp,2}(0)x_s(n) + h_{sp,2}(1)x_s(n-1) + \cdots + h_{sp,2}(4)x_s(n-4)\big] \\ & \vdots \\ & + z_{N_t}\big[h_{sp,N_t}(0)x_s(n) + h_{sp,N_t}(1)x_s(n-1) + \cdots + h_{sp,N_t}(4)x_s(n-4)\big] \end{aligned} \tag{3.13}$$

In that case, $i(n)$ can be rewritten in a matrix form as follows:

$$i = \boldsymbol{z}\boldsymbol{H}_{\boldsymbol{sp}}\boldsymbol{x}_{\boldsymbol{s}} \tag{3.14}$$

where

$$\boldsymbol{z} = \left[z_1\ z_2\ \ldots\ z_{N_t}\right] \tag{3.15}$$

In addition, $\boldsymbol{H}_{\boldsymbol{sp}}$ is the $N_t \times L_p$ matrix that contains all the channels interfering:

$$\boldsymbol{H}_{\boldsymbol{sp}} = \begin{bmatrix} h_{sp,1}(0) & \cdots & h_{sp,1}(L_p-1) \\ \vdots & \ddots & \vdots \\ h_{sp,N_t}(0) & \cdots & h_{sp,N_t}(L_p-1) \end{bmatrix} \tag{3.16}$$

The $L_p \times 1$ vector $\boldsymbol{x}_{\boldsymbol{s}}$ contains the transmitted secondary data as follows:

$$\boldsymbol{x_s} = \begin{bmatrix} x_s(n) & x_s(n-1) & \dots & x_s\left(n-(L_p-1)\right) \end{bmatrix}^T \tag{3.17}$$

The beamformer, $\boldsymbol{z}$**,** vector is designed to set (3.14) to zero, i.e., the interference is cancelled. In that case (3.14) is written as:

$$\boldsymbol{zH_{sp}x_s} \ = 0 \tag{3.18}$$

Since the data should not be zero, then we should find $\boldsymbol{Z}$ that satisfies the following:

$$\boldsymbol{H_{sp}^{H}z^{H}} = \boldsymbol{0} \tag{3.19}$$

where $\boldsymbol{H_{sp}^{H}}$ and $\boldsymbol{z^{H}}$are the Hermitian matrices of the $\boldsymbol{H_{sp}}$ and $\boldsymbol{z}$**,** respectively.

The nontrivial solution of this equation can be done through the singular value decomposition (SVD) property of the channel matrix $\boldsymbol{H_{sp}^{H}}$ where $N_t \geq L_p + 1$. It is well known that the SVD of matrix $\boldsymbol{H_{sp}^{H}}$ can be written as:

$$\boldsymbol{H_{sp}^{H}} = \boldsymbol{U\Sigma V^{H}} \tag{3.20}$$

where

$\boldsymbol{U}$ and $\boldsymbol{V}$ are orthogonal matrices**,** $\boldsymbol{U} = \boldsymbol{H_{sp}^{H}H_{sp}}$ and $\boldsymbol{V} = \boldsymbol{H_{sp}H_{sp}^{H}}$.

$\boldsymbol{\Sigma}$ is $L_p \times N_t$ pseudo-diagonal matrix contains the positive Eigen values of $\boldsymbol{H_{sp}^{H}}$ it can written as follows:

$$\boldsymbol{\Sigma} = \begin{bmatrix} \sigma_1 & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & \sigma_{L_p} & 0 & \cdots & 0 \end{bmatrix} \tag{3.21}$$

Using SVD, by multiplying $\boldsymbol{H_{sp}^{H}}$ with $\boldsymbol{V}_q$, the q^{th} rightmost column of $\boldsymbol{V}$, where $q > L_p + 1$, so we get:

$$\boldsymbol{H_{sp}^{H}V}_q = 0 \Rightarrow \boldsymbol{z}^H = \boldsymbol{V}_q \tag{3.22}$$

3.5.2. Interference cancellation at SS receiver

In this scenario, the received symbols at SS receiver are postcoded. The received signal at the OFDM receiver is corrupted by interference from primary transmitter since they transmit in the same band. In this model, we consider a multiple input multiple outputs (MIMO) at secondary system. Thus, the secondary data is transmitted over several numbers of antennas. Recalling Fig 3.3, the secondary received signal at the j^{th} antenna can be written as:

$$r_s^j(n) = \sum_{q=1}^{N_t} h_{ss,q}^j(n) * x_{s,q}(n) \ + i_{ps}^j(n) + w^j(n) \tag{3.23}$$

where

$h_{ss,q}^j(n)$ is the channel gain that is affected on the signal of the q^{th} transmitter antenna at the j^{th} receive antenna, $w^j(n)$: is the additive noise at the j^{th} receive antenna and $i_{ps}^j(n)$ is the interference from primary transmitter on the secondary receiver at the j^{th} receive antenna.

We can write the total interference of the PS on SS as following:

$$\begin{aligned} i_{ps}(n) &= \sum_{j=1}^{N_r} i_{ps}^j(n) \\ &= \sum_{j=1}^{N_r} h_{ps}^j(n) * x_p(n) \\ &= \sum_{j=1}^{N_r} \sum_{m=0}^{L_p-1} h_{ps}^j(m)\, x_p(n-m) \end{aligned} \tag{3.24}$$

It is clear, $i_{ps}(n)$, can be written in matrix form as:

$$\boldsymbol{i_{ps}} = \boldsymbol{H_{ps}} \boldsymbol{x_p} \tag{3.25}$$

where

$$\boldsymbol{H_{ps}} = \begin{bmatrix} h_{ps}^1(0) & \cdots & h_{ps}^1(L_p-1) \\ \vdots & \ddots & \vdots \\ h_{ps}^{N_r}(0) & \cdots & h_{ps}^{N_r}(L_p-1) \end{bmatrix} \tag{3.26}$$

and $\boldsymbol{x_p} = \begin{bmatrix} x_p(n) & x_p(n-1) \ldots & x_p(n-L_p+1) \end{bmatrix}^{\boldsymbol{T}}$**.**

We look to force the interference to be zero at the SS receiver. Thus, we should making something at the OFDM receiver to cancel this interference since we cannot do anything at the primary transmitter (GSM system). In that case, we should generate a *postcoding*, $\boldsymbol{z}_{\boldsymbol{ps}}$, on the SS received signal as shown in Fig. 3.5 in order to cancel the interference, i.e., $\boldsymbol{i}_{\boldsymbol{ps}} = \boldsymbol{0}$**.**

Therefore, ZFBF at SS receiver is also applied here and we can write the following:

$$\boldsymbol{i}_{\boldsymbol{ps}} = \boldsymbol{z}_{\boldsymbol{ps}}\boldsymbol{H}_{\boldsymbol{ps}}\boldsymbol{x}_{\boldsymbol{p}} \tag{3.27}$$

$$\boldsymbol{z}_{\boldsymbol{ps}}\boldsymbol{H}_{\boldsymbol{ps}}\boldsymbol{x}_{\boldsymbol{p}} = 0 \tag{3.28}$$

Since the data should not be zero, then we should find $\boldsymbol{z}_{\boldsymbol{ps}}$ that satisfies the following:

$$\boldsymbol{z}_{\boldsymbol{ps}}\boldsymbol{H}_{\boldsymbol{ps}} = \boldsymbol{0} \;\rightarrow\; \boldsymbol{H}_{\boldsymbol{ps}}^{\boldsymbol{H}}\boldsymbol{z}_{\boldsymbol{ps}}^{\boldsymbol{H}} = \boldsymbol{0} \tag{3.29}$$

The nontrivial solution of this equation can be done through the SVD property of the channel matrix $\boldsymbol{H}_{\boldsymbol{ps}}^{\boldsymbol{H}}$ where $N_r \geq L_p + 1$ as discussed in last section. It is well known that the SVD of matrix $\boldsymbol{H}_{\boldsymbol{ps}}^{\boldsymbol{H}}$ can be written as:

$$\boldsymbol{H}_{\boldsymbol{ps}}^{\boldsymbol{H}} = \boldsymbol{U\Sigma V}^{\boldsymbol{H}} \tag{3.30}$$

Using SVD, by multiplying $\boldsymbol{H}_{\boldsymbol{ps}}^{\boldsymbol{H}}$ with $\boldsymbol{V}_q$, the q^{th} rightmost column of $\boldsymbol{V}$, where $q > L_p + 1$, so we get:

$$\boldsymbol{H}_{\boldsymbol{ps}}^{\boldsymbol{H}}\boldsymbol{V}_q = 0 \Rightarrow \boldsymbol{z}_{\boldsymbol{ps}}^{\boldsymbol{H}} = \boldsymbol{V}_q \tag{3.31}$$

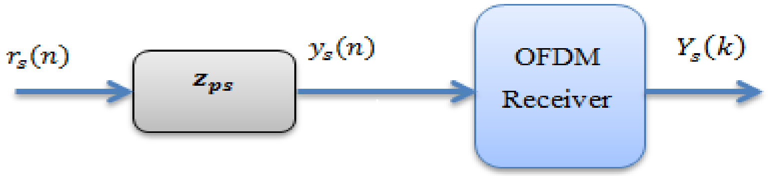

Figure 3.5: Postcoding at SS receiver.

It can be shown from Fig. 3.5, $y_s(n)$, can be written as:

$$y_s(n) = \boldsymbol{z}_{\boldsymbol{ps}} r_s(n) \tag{3.32}$$

In matrix form, $\boldsymbol{y}_{\boldsymbol{s}}$**,** can be written as:

$$\boldsymbol{y_s} = \boldsymbol{z_{ps}}\boldsymbol{H_{ss}}\boldsymbol{x_s} + \boldsymbol{z_{ps}}\boldsymbol{i_{ps}} + \boldsymbol{z_{ps}}\boldsymbol{w} \tag{3.33}$$

It should be noted that the term $\boldsymbol{z_{ps}}\boldsymbol{i_{ps}}$ will be cancelled based on SVD design for $\boldsymbol{z_{ps}}$. The postcoding vector, $\boldsymbol{z_{ps}}$, $1 \times N_r$ complex values vector. Thus, we can multiply j^{th} receive signal with a component of this vector, $z_{ps}^{j}, j = 1, \dots, N_r$. For sake of simplicity, let we assume that $x_s(n) = \left\{x_{s,q}(n)\right\}_{q=1}^{N_t}$, then we can write the received signal on j^{th} antenna after postcoding process as:

$$y_s^j(n) = x_s(n) * \sum_{q=1}^{N_t} z_{ps}^j h_{ss,q}^j(n) + z_{ps}^j i_{ps}^j(n) + z_{ps}^j w^j(n) \tag{3.34}$$

Define $y_s(n) = \sum_{j=1}^{N_r} y_s^j(n)$, then:

$$\begin{aligned} y_s(n) &= \sum_{j=1}^{N_r}\left(x_s(n) * \sum_{q=1}^{N_t} z_{ps}^j h_{ss,q}^j(n)\right) + i_{ps}(n) + w(n) \\ &= x_s(n) * \sum_{j=1}^{N_r}\sum_{q=1}^{N_t} z_{ps}^j h_{ss,q}^j(n) + v(n) \end{aligned} \tag{3.35}$$

where $i_{ps}(n) = \sum_{j=1}^{N_r} z_{ps}^j i_{ps}^j(n)$ is the cancelled interference term, i.e., it is the same as $\boldsymbol{z_{ps}}\boldsymbol{i_{ps}}$**.** The additive noise $w(n) = \sum_{j=1}^{N_r} z_{ps}^j w^j(n)$ and $v(n) = i_{ps}(n) + w(n)$.

The received signal after FFT can be written as:

$$Y_s(k) = X_s(k)H_{ss}(k) + V(k) \tag{3.36}$$

where

$$H_{ss}(k) = FFT\left\{\sum_{j=1}^{N_r}\sum_{q=1}^{N_t} z_{ps}^j h_{ss,q}^j(n)\right\}$$

and $V(k) = FFT\{v(n)\}$.

The equalized signal, $\hat{X}_s(k)$, can be implemented by ZF equalizer and it can be written as:

$$\hat{X}_s(k) = Y_s(k)H_{ss}^*(k) \tag{3.37}$$

3.6. Overlay CR based on OFDM

In this section we evaluate the relevance of the overlay CR where the primary and secondary systems are based on 4G-OFDM. The interference expression due to SS at the PS receiver is derived. However, the interference cancellation due to PS at the SS receiver is the same as discussed in section 3.5.2.

A precoding based on ZFBF is considered at the SS transmitter as shown in Fig. 3.6. The received signal at the primary receiver is given as follows:

$$r_p(n) = x_p(n) * h_{pp}(n) + i(n) + w(n) \tag{3.38}$$

where $x_p(n)$ is the transmitted primary signal, $h_{pp}(n)$ the channel response between transmitter and receiver of the primary side, $w(n)$ is the additive noise with zero mean and variance σ_w^2 and the interferences $i(n)$ is defined as:

$$i(n) = \sum_{a=1}^{N_t} x_s^a(n) * h_{sp}^a(n) \tag{3.39}$$

where $x_s^a(n)$ is the secondary transmitted OFDM signal of the a^{th} antenna and $h_{sp}^a(n)$ is the channel between the a^{th} antenna of SU and PU receiver.

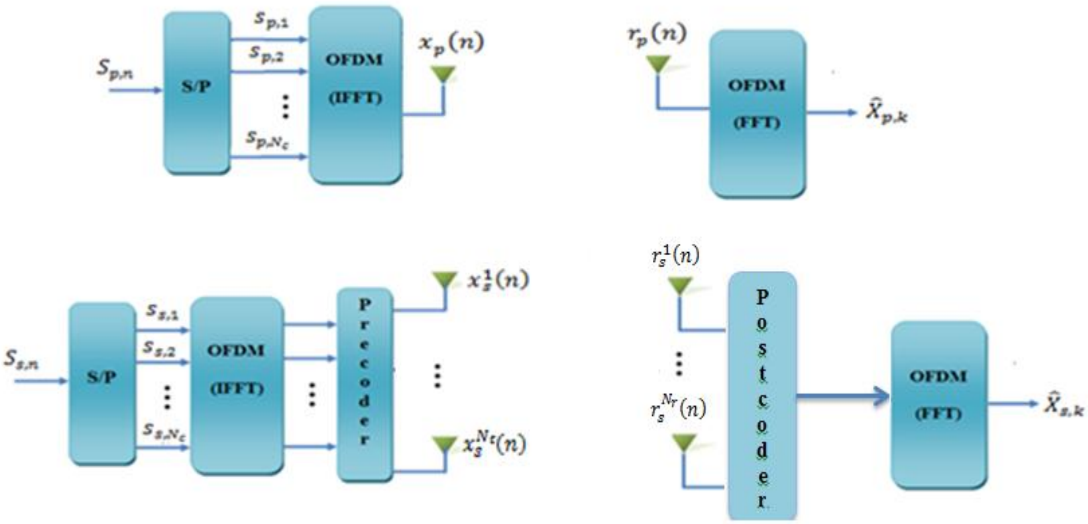

Figure 3.6: Overlay CR based on OFDM at PS and SS.

The received signal after FFT of the PU receiver with N_c subcarriers can be written as follows:

$$\hat{X}_{p,k} = X_p(k)H_{pp}(k) + FFT_k\{w(n)\}_0^{N_c-1} + I(k) \tag{3.40}$$

where $X_p(k)$, $H_{pp}(k)$ and $I(k)$ are the FFT of the $x_p(n)$, $h_{pp}(n)$ and $i(n)$, respectively. Indeed, $I(k)$ can be written as:

$$\begin{aligned} I(k) &= \frac{1}{\sqrt{N_c}} \sum_{n=0}^{N_c-1} \sum_{a=1}^{N_t} [x_s^a(n) * h_{sp}^a(n)] e^{-j2\pi\left(\frac{kn}{N_c}\right)} \\ &= \frac{1}{\sqrt{N_c}} \sum_{n=0}^{N_c-1} \sum_{a=1}^{N_t} \sum_{l=0}^{L_p-1} x_s^a(n-l) h_{sp}^a(l) e^{-j2\pi n\left(\frac{k}{N_c}\right)} \end{aligned} \tag{3.41}$$

The secondary OFDM transmitted signal $x_s^a(n) = \frac{1}{\sqrt{N_c}} \sum_{m=0}^{N_c-1} X_s^a(m) e^{j2\pi\left(\frac{mn}{N_c}\right)}$, thus $I(k)$ can be written as:

$$\begin{aligned} I(k) &= \frac{1}{\sqrt{N_c}} \frac{1}{\sqrt{N_c}} \sum_{n=0}^{N_c-1} \sum_{a=1}^{N_t} \sum_{l=0}^{L_p-1} \sum_{m=0}^{N_c-1} X_s^a(m) e^{j2\pi m\left(\frac{n-l}{N_c}\right)} h_{sp}^a(l) e^{-j2\pi n\left(\frac{k}{N_c}\right)} \\ &= \frac{1}{N_c} \sum_{n=0}^{N_c-1} \sum_{a=1}^{N_t} \sum_{m=0}^{N_c-1} X_s^a(m) \sum_{l=0}^{L_p-1} \left[h_{sp}^a(l) e^{-j2\pi m\left(\frac{l}{N_c}\right)} \right] e^{j2\pi n\left(\frac{m}{N_c}\right)} e^{-j2\pi n\left(\frac{k}{N_c}\right)} \\ &= \frac{1}{N_c} \sum_{a=1}^{N_t} \sum_{m=0}^{N_c-1} X_s^a(m) H_{sp}^a(m) \sum_{n=0}^{N_c-1} e^{j2\pi n\left(\frac{m-k}{N_c}\right)} \end{aligned} \tag{3.42}$$

By recalling that $\sum_{n=0}^{N_c-1} e^{j2\pi n\left(\frac{m-k}{N_c}\right)} = \delta(m-k)$, one has:

$$I(k) = \frac{1}{N_c} \sum_{a=1}^{N_t} \sum_{m=0}^{N_c-1} X_s^a(m) H_{sp}^a(m)\, \delta(m-k) \tag{3.43}$$

Assume that $\hat{H}_{sp,k}^a(m) = H_{sp}^a(m)\delta(m-k)$. Thus, $I(k)$ can be expressed as:

$$I(k) = \frac{1}{N_c} \sum_{a=1}^{N_t} \sum_{m=0}^{N_c-1} X_s^a(m) \hat{H}_{sp,k}^a(m) \tag{3.44}$$

To perform the ZFBF on (3.44), let us set all the symbols to be equal, i.e., $X_s(m) = X_s^a(m)$. In addition, by considering N_{SC} which represents the neighboring subcarriers that mostly affect on the k^{th} PU subcarrier and by introducing the ZFBF z_k^a [19], one has:

$$I(k) = \frac{1}{N_c}\sum_{a=1}^{N_t}\sum_{m=k-N_{SC}}^{k+N_{SC}} z_k^a X_s(m)\widehat{H}_{sp,k}^{a}(m) = 0 \tag{3.45}$$

In that case (3.45) can be rewritten in a matrix form as follows:

$$(\boldsymbol{H_{sp,k}}.\boldsymbol{z_k})^{\boldsymbol{T}}\boldsymbol{X_s} = 0 \tag{3.46}$$

where

$$\boldsymbol{X_s} = [X_s(k - N_{SC}) \ldots.X_s(k + N_{SC})]^T \tag{3.47}$$

$\boldsymbol{H_{sp,k}}$ is the channels interfering matrix with the k^{th} PU subcarrier:

$$\boldsymbol{H_{sp,k}} = \begin{bmatrix} \widehat{H}_{s,k}^{1}(k - N_{SC}) & \cdots & \widehat{H}_{s,k}^{N_t}(k - N_{SC}) \\ \vdots & \ddots & \vdots \\ \widehat{H}_{s,k}^{1}(k + N_{SC}) & \cdots & \widehat{H}_{s,k}^{N_t}(k + N_{SC}) \end{bmatrix} \tag{3.48}$$

and $\boldsymbol{z_k} = [z_k^1 \quad z_k^2 \ldots.z_k^{N_t}]^T$ is the beamformers.

The ZFBF precoding should be selected to achieve the following:

$$\boldsymbol{H_{sp,k}}.\boldsymbol{z_k} = \boldsymbol{0} \tag{3.49}$$

The nontrivial solution can be done through the SVD of the matrix $\boldsymbol{H_{sp,k}}$ when $N_t > (2N_{SC} + 1)$ [19]. It is well known that the SVD of matrix $\boldsymbol{H_{sp,k}^{H}}$ can be done as (3.20), (3.21) and (3.22) in section 3.5.1.

3.7. Simulation Results

The aim of this study is to apply the idea of CR technology in second mobile generation (GSM-900) which is still operate in Palestine with shortage bandwidth. The proposed solution for this spectrum scarcity is built an OFDM system as SS over GSM-900 network as PS with the same GSM band. Simulation performance is measured in terms of BER for:

1. CR system where the OFDM is used in primary and secondary sides, we call it (OFDM-OFDM CR).
2. CR system where the GSM-900 is considered as PS and OFDM is the SS, we call it (GSM-OFDM CR).

The two cases are compared with theoretical BER for QPSK and GMSK in Rayleigh fading channel. The BER performance is measured in PS receiver and SS receiver for both cases.

In this section, we considered a CR scenario where the PS is based on GSM and OFDM for the SS. Then, we compare it with a CR system based on OFDM for both the primary and the secondary systems. In OFDM system, we assume $N_c = 64$ subcarriers are all used and the CP length is set to $L_{cp} = 16$. Both are known by the SU. A QPSK modulation is used in the OFDM system whereas GMSK modulation is used for GSM with bandwidth bit period product of 0.3. In addition, the channels are first assumed to be perfectly known. The number of channel paths in GSM signal is assumed to be $L_p = 5$. According to the constraints $L_p + 1 \leq N_t$ and $L_p + 1 \leq N_r$ we choose the number of antenna at each secondary transmitter and receiver to be six.

Fig. 3.7 shows the BER performance of GSM –OFDM CR system with two equalizer technique for GSM system. It can be shown that the BER performance under using MMSE equalizer is better than using ZF equalizer especially where the E_b/N_0 is greater than approximately 12 dB. The variation in performance between ZF and MMSE is related to the features of MMSE in which the MMSE equalizer minimize the noise power.

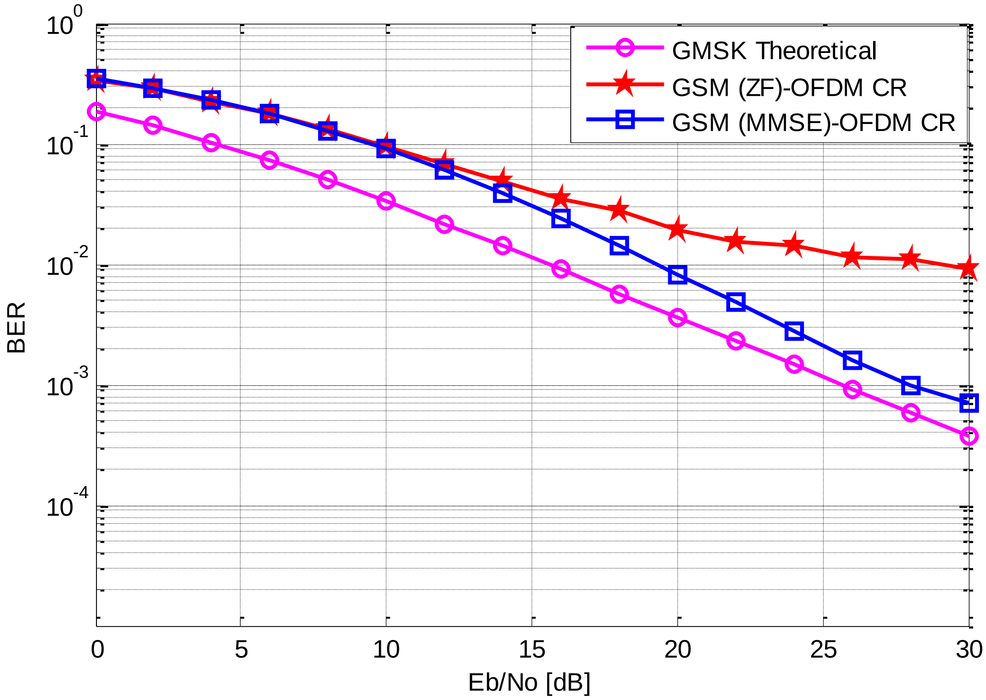

Figure 3.7: BER of GSM-OFDM CR system where the GSM receiver is based on ZF and MMSE.

Fig. 3.8 shows the BER results for GSM-OFDM CR compared with the OFDM-OFDM CR. One can notice that the performance of CR system where the PS is OFDM is better than when it is considered as GSM system with ZF equalization scheme. In that case, the bit error rate of OFDM-OFDM CR is superior to GSM-OFDM CR when $\frac{E_b}{N_0}$ is approximately great the 10 dB. However, when the GSM receiver is based on MMSE equalizer the performance of the two CR configuration is approximately the same.

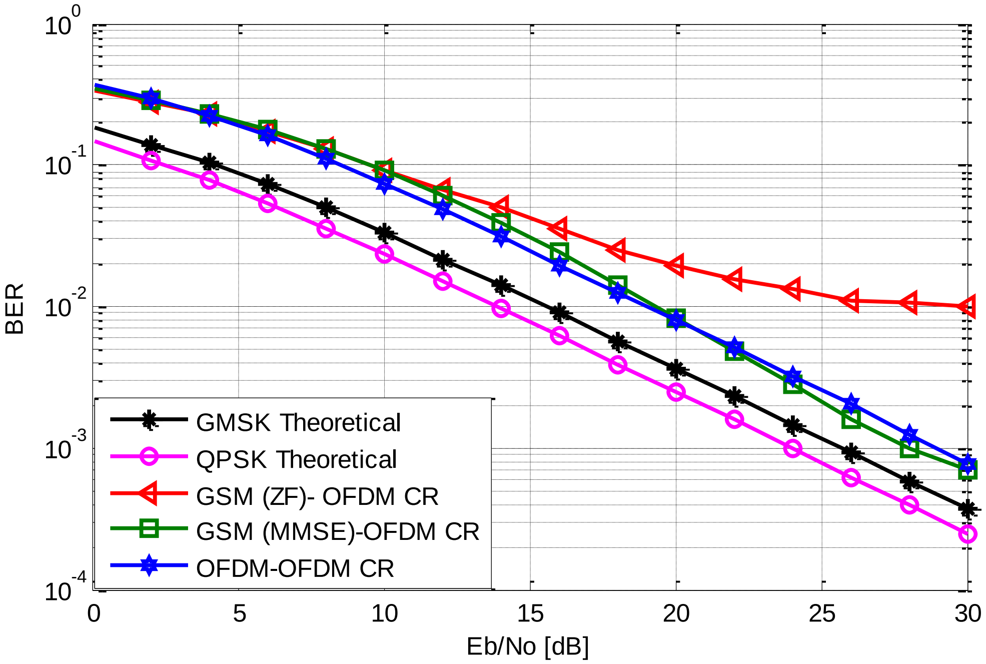

Figure 3.8: Comparative study of overlay CR based OFDM-OFDM and GSM-OFDM where the GSM receiver is based on ZF and MMSE equalizer.

In the previous two figures, the channels between PU and SU are assumed to be known. However, in practice the theses channels need to be estimated and tracked in order to design the ZFBF. In the following figures, we investigate the sensitivity of the proposed system regarding the channel estimation error. In other words, the BER results for GSM-OFDM CR compared with the OFDM-OFDM CR, in the presence of channel estimation errors H_e where a 10% error on the channel is introduced as follows:

$$H_e = H + 0.1\varepsilon H \tag{3.50}$$

where $\varepsilon \in (0,1)$ is a random variable.

The BER performance for GSM (ZF)-OFDM CR, GSM (MMSE)-OFDM and OFDM-OFDM CR with and without channel estimation error (CEE) is shown in Fig. 3.9, 3.10 and 3.11, respectively. It can be noticed that the BER increased when the channel is estimated. However, the sensitivity of the three systems for 10% error in channel is relatively low.

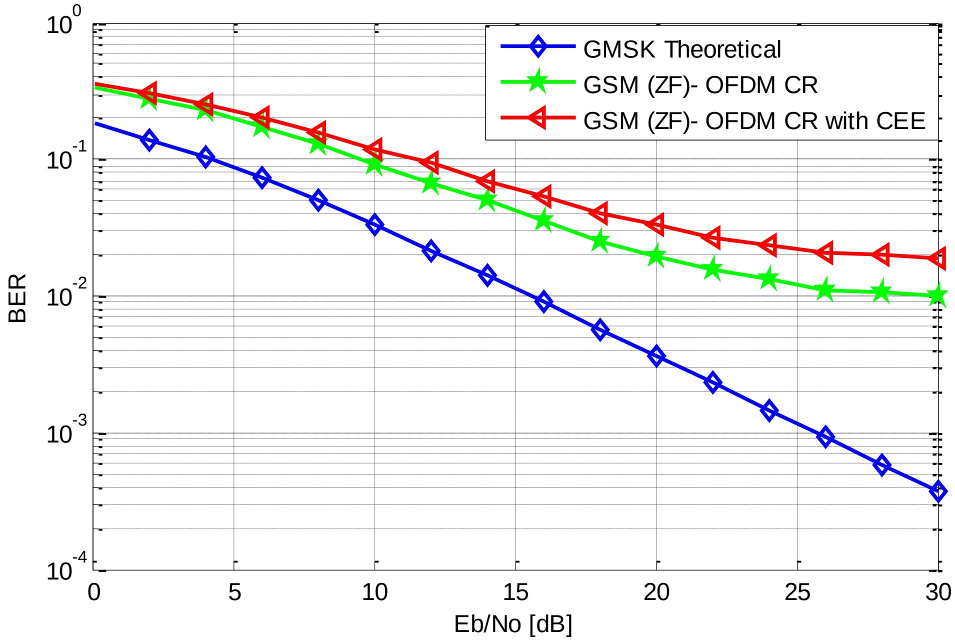

Figure 3.9: BER performance for GSM (ZF)-OFDM CR with and without CEE.

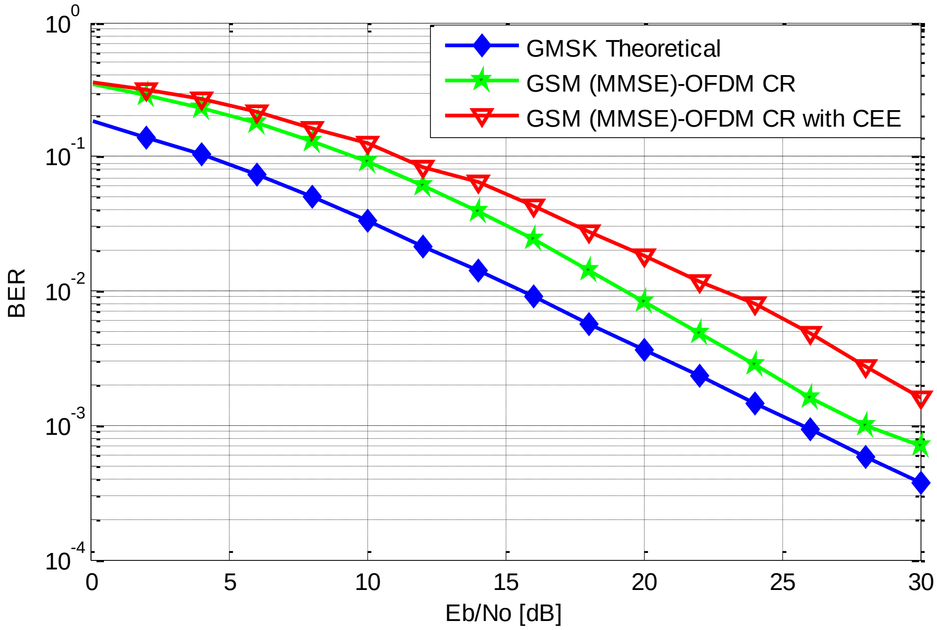

Figure 3.10: BER performance for GSM (MMSE)-OFDM CR with and without CEE.

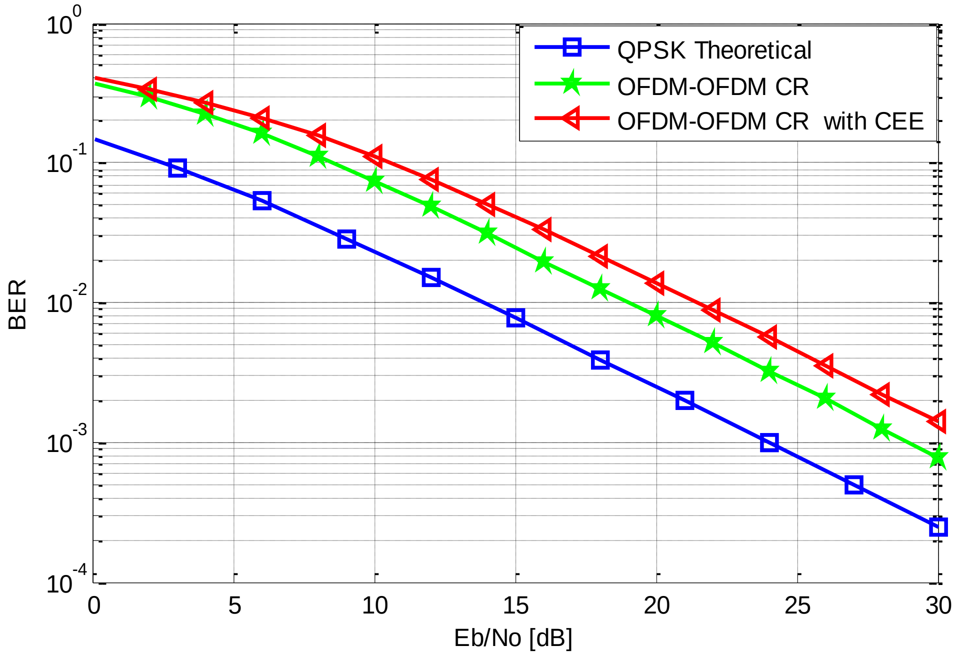

Figure 3.11: BER performance for OFDM-OFDM CR with and without CEE.

Fig. 3.12 shows the BER performance for GSM-OFDM CR compared with the OFDM-OFDM CR, in the presence of channel estimation errors H_e where a 10% error introduced on the channel. It can be noticed that the performance of CR system where the PS is OFDM is better than where it is GSM system with ZF equalization scheme. However, with MMSE equalizer the performance of the two CR configuration is approximately the same. As shown in the figure, the technique is robust to channel estimation error.

Fig. 3.13 shows the simulation results for postcoding at SS receiver for GSM-OFDM CR and OFDM-OFDM CR with and without channel estimation error. In the case of CEE, we consider 10% error in the estimated channel. It can be shown that the results for two systems are approximately the same and it is reasonable since we have the same receiver (OFDM receiver) in two cases.

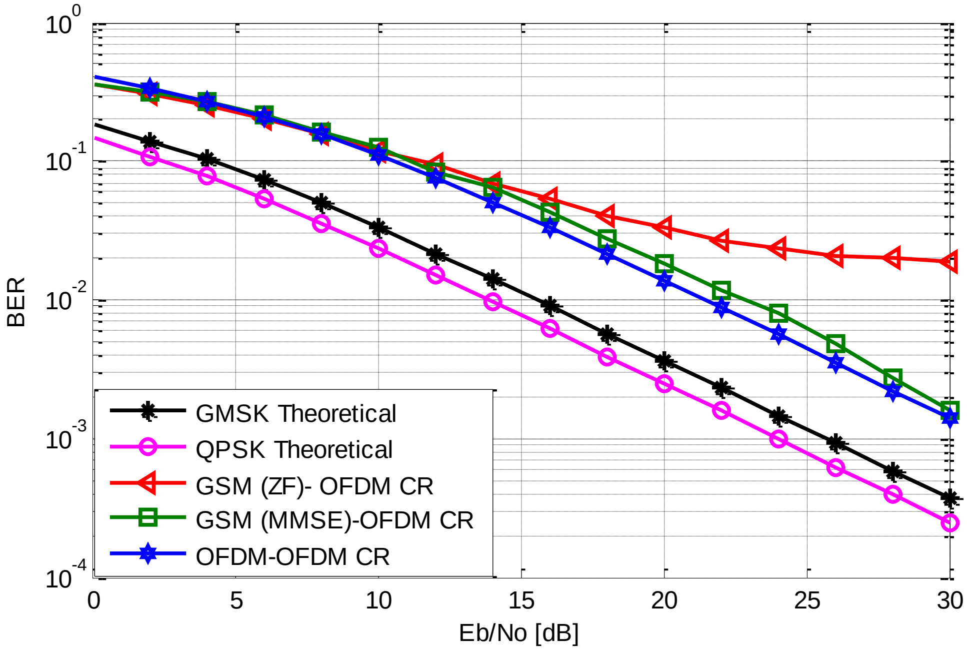

Figure 3.12: Comparative sensitivity of the proposed systems in the presence of the CEE.

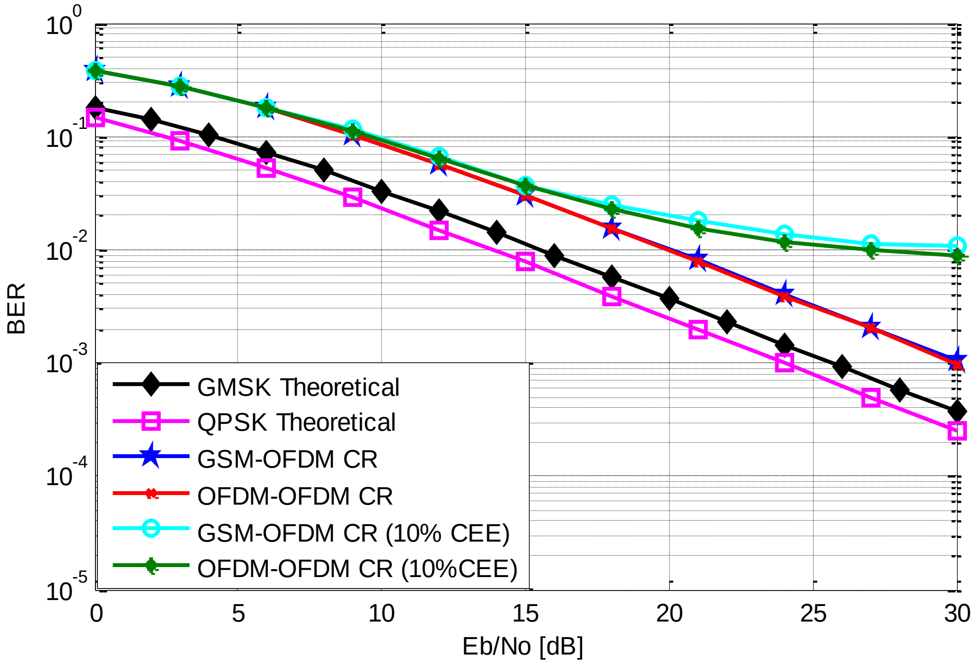

Figure 3.13: BER performance for GSM-OFDM CR and OFDM-OFDM CR with and without CEE.

Chapter 4

Conclusion and Future Work

Contents

4.1. Conclusion

Cognitive radio (CR) provides a promising solution to the spectrum scarcity and system capacity problems for wireless communication systems. Palestinian mobile networks are still using the GSM with very limited bandwidth. In this thesis, we present a solution for spectrum scarcity using the concept of overlay CR.

We have investigated the relevance of applying the concept of overlay CR on the 2G GSM band. GSM is considered for the primary user (PU) and 4G based on OFDM is used for the secondary user (SU). In that case, performing the zero forcing beamforming (ZFBF) at the secondary system (SS) is used to cancel the interference at GSM receiver. Also, we proposed an interference cancellation at SS receiver. Therefore, we can expand the GSM network based on our assumptions and analysis.

The bit error rate (BER) performance of the proposed overlay CR system is compared with an overlay CR based on OFDM for both primary system (PS) and SS. The comparative study we carried-out confirms the BER efficiencies of the proposed system. In addition, it verifies the robustness of the proposed method to channel estimation errors.

4.2. Future Work

In order to develop this research, we suggest the following ideas for future work:

1) Replacement the 4G based on OFDM as a SS with modern wireless communication technologies such as filter bank multicarrier (FBMC), universal filtered OFDM (UF-OFDM)[1], generalized OFDM (GOFDM), etc.
2) As ZFBF depends on the channel, we assume that the channel is known. In practice, the channels between PU and SU need to be estimated and tracked. One contribution on this research is to study different channel estimation techniques such as Kalman-filter (KF) based methods such as extended KF (EKF), unscented KF (UKF), etc.

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[1] Also known as universal filtered multicarrier (UFMC), is a recent technology close to OFDM.

3) We discuss in chapter one three viewpoint to solve the scarcity of GSM-900 spectrum and we concentrate in this thesis on the idea of overlay CR. We suggest studying the performance of the other two viewpoints and comparing with this idea.
4) We use the ZFBF as an interference cancellation technique at the SS. Other techniques such as dirty paper coding (DPC), interference alignment (IA), block diagonlization (BD), etc., can also be investigated.
5) Expand the contribution to a network with multiple users. In this case, one should be careful with number of antennas at SS and the interference cancellation technique.

Acronyms and Abbreviations

1G:	First Generation
2G:	Second Generation
3G:	Third Generation
3GPP:	3G Partnership Project
4G	Fourth Generation
5G:	Fifth Generation
ADC:	Analog To Digital Converter
AMPS:	Advanced Mobile Phone System
ARFCN:	Absolute Radio Frequency Channel Number
AWGN:	Additive White Gaussian Noise
BCCH:	Broadcast Control Channels
BD:	Block Diagonlization
BER:	Bit Error Rate
BSC:	Base Station Controller
BSS:	Base Station Subsystem
BTS:	Base Transceiver Station
CDMA:	Code Division Multiple Access
CEE:	Channel Estimation Error
CFO:	Carrier Frequency Offsets
CP:	Cyclic Prefix
CPM:	Continuous Phase Modulation
CR:	Cognitive Radio
DARPA:	Defence Advance Research Products Agency
DFE:	Decision Feedback Equalizer
DPC:	Dirty Paper Coding
DSA:	Dynamic Spectrum Access
EDGE:	Enhanced Data Rate For GSM Evolution
EKF:	Extended KF
ETSI:	European Telecommunications Standards Institute
FBMC:	Filter Bank Multicarrier
FDMA:	Frequency Division Multiple Access
FFT:	Fast Fourier Transform

FHSS:	Frequency-Hopping Spread Spectrum
FM:	Frequency Modulation
GI:	Guard Interval
GMSK:	Gaussian Minimum Shift Keying
GOFDM:	Generalized OFDM
GPRS:	General Packet Radio Service
GSM:	Global System For Mobile Communication
HLR:	Home Location Register
IA:	Interference Alignment
ICI:	Inter Carrier Interference
IFFT:	Inverse Fast Fourier Transform
IP:	Internet Protocol
IS-95:	Interim Standard 95
ISI:	Inter Symbol Interference
KF:	Kalman-Filter
KPIs:	Key Performance Indicators
LPC:	Linear Prediction Coding
MAC:	Media Access Control
MC-CDMA:	Multicarrier Code Division Multiple Accesses
MIMO:	Multiple Input Multiple Output
MISO:	Multiple Input Single Output
MLSE:	Maximum Likelihood Sequence Estimation
MLSE:	Maximum-Likelihood Sequence Estimation
MMSE:	Minimum Mean Square Error
mmW:	Millimeter Wave
MS:	Mobile Station
MSC:	Mobile Switching Center
MSE:	Mean Square Error
NRZ:	Non-Return To Zero
NSS:	Network Switching Subsystem
OFDM:	Orthogonal Frequency Division Multiplexing
OMC:	Operations And Maintenance Center
OSS:	Operation And Support System
PAPR:	Peak To Average Power Ratio

PS:	Primary System
PSD:	Power Spectral Density
PSTN:	Public Switched Telephone Network
PU:	Primary User
QoS:	Quality Of Service
QPSK:	Quadreture Phase Shift Keying
RLC:	Rate Loss Constraint
RMS:	Root Mean Square
SIM:	Subscriber Identity Module
SISO:	Single-Input Single Output
SNR:	Signal To Noise
SS:	Secondary System
SU:	Secondary User
SVD:	Singular Value Decomposition
TCH:	Traffic Channels
TDMA:	Time Division Multiple Access
TVWS:	Television White Space
UF-OFDM:	Universal Filtered OFDM
UHF:	Ultra High Frequency
UKF:	Unscented KF
UMTS:	Universal Mobile Telecommunication System
VA:	Viterbi Algorithm
VFDM:	Vandermonde Frequency Division Multiplexing
VHF:	Very High Frequency
VLR:	Visitor Location Register
WAP:	Wireless Application Protocol
WCDMA:	Wideband Code Division Multiple Access
ZF:	Zero Forcing
ZFBF:	Zero Forcing Beam Forming

Notations

$r(t)$:	Received signal.
$h(t)$:	Impulse response of a channel.
$x(t)$:	Base band transmitted signal for GSM or OFDM.
$z(t)$:	Additive white noise signal.
$s(t)$:	Pass band transmitted signal.
A_c:	The amplitude of the transmitted signal.
f_c:	Radio (carrier) frequency.
$\varphi(t)$:	Continuous phase containing the information.
$g(t)$:	The impulse response of the Gaussian filter.
βT:	3-db bandwidth bit duration product.
T:	Symbol period.
$x_{NRZ}(t)$:	NRZ signal.
$rect(t)$:	Rectangular NRZ signal.
$q(t)$:	The response of the filter to the rectangular NRZ signal.
$erf(t)$:	The error function.
$s_I(t)$:	I-channel signal.
$s_Q(t)$:	Q-channel signal.
$x(t)$:	The baseband form of the signal $s(t)$.
$p(t)$:	Pulse shaping function.
$\psi_n(t)$:	Basis functions of the approximation form of GSM signal.
L:	Number of basis $\psi_n(t)$.
$A_n(k)$:	Complex coefficients of the basis $\psi_n(t)$.
L_p:	Number of multipath number.
$x_{tr.s}(n)$:	Transmitted training sequence symbols.
$r_{tr.s}(n)$:	Received training sequence symbols.
K:	Number of training symbols.
$\boldsymbol{\hat{h}}$**:**	Estimation channel vector.
$\delta(n)$:	Delta (impulse) function.

$c(n)$:	Equalizer taps.
$\mathbb{E}[.]$:	Expectation or mean of the signal.
$\phi_{hh}(n)$:	Autocorrelation of the channel.
Δf:	The minimum space frequency between two successive subcarriers.
T_s:	OFDM symbol time.
$g_p(t)$:	Pulse shaping of OFDM signal.
T_g:	Length of the guard interval.
f_m:	Is the frequency of the m^{th} subcarrier
$x_l(n)$:	IFFT of the signal $X_l(k)$.
$X_l(k)$:	FFT of the signal $x_l(n)$.
N_c:	Number of subcarriers.
$r_l(n)$:	Is the l^{th} Received OFDM signal.
$R_l(k)$:	Is the FFT of the $r_l(n)$.
$H_l(k)$:	Is the FFT of the channel impulse response $h(n)$.
P_{GMSK}:	The theoretical bit error rate of GMSK in AWGN channel.
$\frac{E_b}{N_0}$:	Is the bit energy to noise energy value.
γ:	Constant related to βT.
$\bar{P}_{GMSK}$:	The theoretical bit error rate of GMSK in Rayleigh channel.
P_{QPSK}:	The theoretical bit error rate of QPSK in AWGN channel.
$\bar{P}_{QPSK}$:	The theoretical bit error rate of QPSK in Rayleigh channel.
$x_p(t)$:	Is the primary signal.
$x_s(t)$:	Is the secondary signal.
$s(n)$:	Discrete form of the $s(t)$ Signal.
$\varphi(n)$:	Discrete form of the $\varphi(t)$ Signal.
N_t:	The number of antennas at SS transmitter.
N_r:	The number of antennas at SS receiver.
$h_p(n)$:	The channel effect on the primary signal.
$r_p(n)$:	Received primary signal.
$x_{s,a}(n)$:	The transmitted signal of the secondary system (OFDM) on the a^{th}

	Antenna.
$h_{sp,a}(n)$:	Is the channel effect on the $x_{s,a}(n)$.
$i(n)$:	Interference from SS on PS.
Z_a:	Is the preceded data or beamformer of a^{th} Antenna.
$\boldsymbol{Z}$**:**	Precoding vector.
$\boldsymbol{H_{sp}}$**:**	Matrix of fading channel from secondary to primary.
$\boldsymbol{x_s}$**:**	Secondary signal vector.
$(.)^{\boldsymbol{H}}$**:**	Hermitian of the matrix.
$r_s^j(n)$:	The secondary received signal at the j^{th} Antenna.
$h_{ss,q}^{j}(n)$:	Is the channel gain that is affected on the signal of the q^{th} transmitter antenna at the j^{th} receive antenna.
$w^j(n)$:	Is the additive noise at the j^{th} receive antenna.
$i_{ps}^{j}(n)$:	Is the interference from primary transmitter on the secondary receiver at the j^{th} receive antenna.
$\boldsymbol{H_{ps}}$**:**	Matrix of fading channel from primary to secondry.
$\boldsymbol{i_{ps}}$**:**	Interference vector from PS to SS.
$\boldsymbol{x_p}$**:**	Primary signal vector.
$\boldsymbol{z_{ps}}$**:**	Postcoding vector.
$y_s^j(n)$:	The received signal on j^{th} Antenna after postcoding process.
$\hat{X}_s(k)$:	Equalized signal at SS.
$I(k)$:	FFT of the interference $i(n)$.
ε:	Is a random variable $\in (0,1)$.

References

[1] T. Rappaport, *Wireless communications: principles and practice*, Prentice Hall, 2001.

[2] G. Stuber, *Principles of mobile communication*, Georgia Institute of Technology Atlanta, Kluwer Academic Publishers, 2002.

[3] A. Kumar, Y. Liu and J. Sengupta, “Evolution of mobile wireless communication networks: 1G to 4G”, *International Journal of Electronic and Communication Technology*, Vol.1, No. 1, pp. 68–72, December 2010.

[4] A. Jamalipour, T. Wada and T. Yamazato, “A tutorial on multiple access technologiesfor beyond 3G mobile networks,” *IEEE Communications Magazine*, Vol. 43, No. 2, pp. 110–117, February 2005.

[5] S. Hara and R. Prasad, *Multicarrier techniques for 4G mobile communications*, Artech House, Boston, MA, 2003.

[6] H. Sampath, S. Talwar, J. Tellado, V. Erceg and A. Paulraj ‘‘A fourth-generation MIMO-OFDM broadband wireless system: design, performance, and field trial results,’’ *IEEE Communication Magazine*, Vol. 40, No. 9, pp. 143–149, September 2002.

[7] The World Bank Group, “The Telecommunication Sector in the Palestinian Territories: A Missed Opportunity for Economic Development, Note for the Palestinian Ministry of Telecommunications and Information Technology,” January 2016.

[8] B. Mkheimer and A. Jamoos, “Evaluation and Optimization of GSM Network in Jenien City, Palestine,” *International Journal of Mobile Network Design and Innovation*, Vol. 4, No. 4, pp. 201-213, December 2012.

[9] S. Rangan, T. Rappaport and E. Erkip, “Millimeter wave cellular wireless networks: potentials and challenges,” *Proceeding of the IEEE*, Vol. 102, No. 3, pp. 366–385, March 2014.

[10] X. Lin and H. Viswanathan, ‘‘Dynamic Spectrum Refarming with Overlay for Legacy Devices,’’ *IEEE Transactions on Wireless Communications*, Vol. 12, No. 10, pp. 5282-5293, October 2013.

[11] S. Bhattarai, J. Park, B. Gao, K. Bian, and W. Lehr, “An overview of dynamic spectrum sharing: ongoing initiatives, challenges, and a roadmap for future research,” *IEEE Transactions On Cognitive Communications And Networking*, Vol. 2, No. 2, June 2016.

[12] J. Mitola and G. Maguire, "Cognitive radio: making software radios more personal," *IEEE Personal Communications*, Vol. 6, No. 4, pp.13-18, August 1999.

[13] I. Akyildiz, W. Lee, M. Vuran, and S. Mohanty, "Next generation / dynamic spectrum access/ cognitive radio wireless networks: A survey," *Computer Networks Journal (Elsevier)*, Vol. 50, No. 13, pp. 2127–2159, September 2006.

[14] S. Haykin, "Cognitive radio: brain-empowered wireless communications," *IEEE Journal on Selected Areas in Communications*, Vol. 23, No. 2, pp. 201–220, February 2005.

[15] S. Sun, Y. Ju and Y. Yamao, "Overlay cognitive radio OFDM system for 4G cellular networks," *IEEE Wireless Communications*, Vol. 20, No.2, pp. 68–73, April 2013.

[16] B. Kouassi, D. Slock, I. Ghauri and L. Deneire, "Enabling the implementation of spatial interweave LTE cognitive radio," *Proceeding of the EURASIP-European Signal Processing Conference (EUSIPCO)*, pp. 1–5, 2013.

[17] A. Alizadeh, H. Bahrami, M. Maleki, and S. Sastry, "Spatial sensing and cognitive radio communication in the presence of a K-user interference primary network," *IEEE Journal on Selected Areas in Communications*, Vol. 33, No. 5, pp. 741–754, May 2015.

[18] L. Zhang, H. Yang and H. Mazen, "Area spectral efficiency of underlay cognitive radio transmission over Rayleigh fading channels," *Proceeding of the IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 2988–2992, July 2013.

[19] A. Abdou, G. Ferre, E. Grivel and M. Najim, "Interference cancellation in multiuser hybrid overlay cognitive radio," *Proceeding of the EUSIPCO*, pp. 1-5, September 2013.

[20] B. Liang, H. Huang and X. Jing, "Dynamic power allocation for spectrum sharing in interference alignment (IA)-based cognitive radio," *The16th International Symposium on Communications and Information Technologies (ISCIT)*, pp. 646-650, September 2016.

[21] M. Costa, "Writing on dirty paper," *IEEE Transaction on Information Theory*, Vol. 29, No. 3, pp. 439–441, 1983.

[22] S. Shellhammer, A. Sadek and W. Zhang, "Technical challenges for cognitive radio in the TV white space spectrum", *Information Theory and Applications Workshop*, pp. 323-333, February 2009.

[23] J. Xiao, R. Hu, Y. Qian, L. Gong and B. Wang, "Expanding LTE network spectrum with cognitive radios: from concept to implementation," *IEEE Wireless Communications*, Vol. 20, No. 2, pp. 12-19, April 2013.

[24] F. Jasbi and D. So, "Hybrid overlay/underlay cognitive radio network with MC-CDMA," *IEEE Transactions on Vehicular Technology*, Vol. 65, No. 4, pp. 2038-2047, April 2016.

[25] A. Abdou, O. Najajri and A. Jamoos, “Expanding GSM-900Mobile Network Spectrum With Overlay Cognitive Radio,” Accepted to the 3rd International Congress on Advanced Technologies 2017, April 12-14, 2017, Safi- Morocco.

[26] M. Asha, *GSM System Engineering*, Artech House ,Inc, 1996.

[27] Ian Poole, *Cellular Communications Explained From Basics to 3G*, British Library Cataloguing in Publication Data, 2006.

[28] B. Bjerke and J. Proakis, “GSM Data Receivers: An Overview,” *Electronics and Energetics*, Vol. 12, No. 2, pp. 1-32, 1999.

[29] A. Wiesler, R. Machauer and F. Jondral, “Comparison of GMSK and linear approximated GMSK for use in software radio,” *IEEE Transaction on Communications*, Vol. 2, pp. 557 – 560, September 1998.

[30] D. Devi and A. Sharma, “BER performance of GMSK using MATLAB”, *International Journal of Advanced Research in Computer Engineering & Technology (IJARCET)*, Vol. 2, No. 4, pp. 1389-1392, April 2013.

[31] G. Forney, “The Viterbi algorithm,” *Proceeding of the IEEE*, Vol. 61, No. 3, pp. 268–278, March 1978.

[32] E. Suthan and S. Suthersan, *Mobile Communications Handbook*, Boca Raton: CRC Press LLC, 1999.

[33] D. Johnson, S. Wales and P. Waters, “Equalisers for GSM”, *IEE Colloquium (Digest), IEEE*, No. 21, pp. 1-6, January 1990.

[34] B. Bjerke, J. Proakis, M. Lee and Z. Zvonar, “A comparison of decision feedback equalization and data directed estimation techniques for the GSM system”, *IEEE 6th International Conference on Universal Personal Communications Record*, Vol. 1, pp. 84-88, October 1997.

[35] M. Joham, T. Krauss and M. Zoltowski, "Channel estimation and equalization for GSM with multiple antennas", *In Proceedings of the 49th Vehicular Technology Conference, IEEE*, Vol. 2, May 1999.

[36] Y. Cho, J. Kim, W. Yang and C. Kang, *MIMO-OFDM Wireless Communications with MATLAB*, Wiley Publishing, 2010.

[37] A. Abdou, *Estimation of Autoregressive Time-Varying fading Channels: Application to OFDM Systems*, Al-Quds University, May 2008.

[38] A. Goldsmith, S. Jafar, I. Maric and S. Srinivasa, “Breaking spectrum gridlock with cognitive radios: an information theoretic perspective”, *Proceeding of the IEEE journal*, Vol. 97, No.5, pp. 894 – 914, May 2009.

[39] A. Abdou, *Designing an Overlay Hybrid Cognitive Radio Including Channel Estimation Issues*, PhD thesis, (in French), L’UNIVERSITÉ DE BORDEAUX, 2014.

[40] J. Sachs, I. Maric and A. Goldsmith, "Cognitive cellular systems within the TV spectrum," *Proceeding 2010 IEEE Symposium on New Frontiers in Dynamic Spectrum*, pp. 1-12, April 2010.

[41] X. Kang, H. Garg, Y. Liang and R. Zhang, “Optimal power allocation for OFDM-based cognitive radio with new primary transmission protection criteria,” *IEEE Transaction on Wireless Communication*, Vol. 9, No. 6, pp. 2066-2075, June 2011.

[42] H. Mahmoud, T. Yucek and H. Arslan, "OFDM for cognitive radio: merits and challenges," *IEEE on Wireless Communication*, Vol. 16, No. 2, pp. 6-15, April 2009.

[43] M. Mukherjee, R. Chang and V. Kumar, “OFDM-based overlay cognitive radios with improved spectral leakage suppression for future generation communications,” *2015 IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 434-439, March 2015.

[44] H. Zhang, D. Ruyet, D. Roviras and H. Sun, “Capacity analysis of OFDM/FBMC based cognitive radio networks with estimated CSI,” *Proceeding of the International Conference on Cognitive Radio Oriented Wireless Networks Communications (CROWNCOM),* pp. 1–5, 2010.

[45] I. Budiarjo, H. Nikookar and L. Ligthart, “Performance evaluation of OFDM based Cognitive Radio system with wiener filter channel estimation using frequency hopping GSM channel model at 900 MHz”, *In Proceedings of the 10th European Conference on Wireless Technology (ECWT),* pp. 74–77, October 2007.

[46] M. Maddah-Ali, A. Motahari and A. Khandani, “Communication over MIMOX channels: interference alignment, decomposition, and performance analysis,” *IEEE Transaction on Information Theory,* Vol. 54, No. 8, pp. 3457–3470, 2008.

[47] M. Cardoso, Y. Kobayashi, Y. Ryan and M. Debbah, “Vandermonde frequency division multiplexing for cognitive radio,” *Proceeding of the IEEE Signal Processing Advances in Wireless Communications (SPAWC),* pp. 421–425, 2008.

[48] S. Kaviani and W. Krzymien, “On the optimality of multiuser zero-forcing precoding in MIMO broadcast channels,” *Proc. of the IEEE Vehicular Technology Conference (VTC),* pp. 1–5, 2009.

[49] L. Li, F. Khan, M. Pesavento and T. Ratnarajah, “Power allocation and beamforming in overlay cognitive radio systems,” *Proceeding of the IEEE Vehicular Technology Conference (VTC),* pp. 1–5, 2011.

[50] C. Verikoukis, M. Odeh and N. Zorba, “Spatial cognitive access in zero forcing beamforming scenarios” *Proceeding of the IEEE International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC),* pp. 564–569, September 2010.

[51] K. Lee and I. Lee “MMSE based block diagonalization for cognitive radio MIMO broadcast channels,” *IEEE Transactions on Wireless Communications,* Vol. 10, No. 10, pp. 3139-3144, October 2011.

تطوير شبكة متنقلة ثانوية في نطاق شبكة **GSM** الفلسطينية باستخدام تكنولوجيا الراديو الادراكي.

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ملخص :

زيادة الطلب على شبكات البيانات الخلوية يتطور بشكل سريع في العالم، مما يؤدي إلى ارتفاع الطلب على الطيف الاتصالات المتنقلة. تسببت سياسات تنظيم الطيف التقليدية الثابتة مشكلة ندرة الطيف في أنظمة الاتصالات اللاسلكية. ولذلك تم طرح وصول الطيف الحيوي (DSA) كحل لهذه المشكلة. DSA يستخدم عرض النطاق الترددي مرخصة من قبل تقاسم الطيف الديناميكي بين أنظمة متعددة. الراديو الإدراكي (CR) هي تقنية تمكن لـ DSA أن يسمح النظام الثانوي (SS) للعمل في الطيف المرخص القائمة دون تداخل ضار.

تكنولوجيا CR تشارك الطيف بين ما يسمى المستخدم الأساسي (PU) والمستخدم الثانوي (SU) باستخدام نماذج مختلفة. ثلاث أنواع لـ CR: ,overlay, interweave ,underlay. في interweave CR ، يعد أصل CR، يمكن لـ SU الاستفادة من الترددات غير المستخدمة في النظام الأساسي (PS), وهو ما يسمى الثقوب أو المساحات البيضاء. وهذا يتطلب الطيف تقنيات الاستشعار من أجل تجنب تداخل اشارات SU مع اشارات PU، وقد اقترحت مخططات الاستشعار عن عدة الطيف للعثور على كفاءة الثقوب PS لاستخدامها في الاتصالات CR في الثانوية. في underlay CR، يمكن لـ SU نقل في وقت واحد مع PU في نفس النطاق الترددي في ظل قيود على قدرة ارسال النظام الثانوي. في هذه الحالة، لا ينبغي أن يتم تمرير التداخل قيمة عتبة محددة مسبقا. في overlay CR، يمكن لـ SU الارسال مع PU في نفس النطاق ونفس الزمن ولكن يتطلب ذلك اضافة تشفير أو ترميز معين على معلومات النظام الثانوي (precoding).

على الرغم من أن النظام العالمي للاتصالات المتنقلة (GSM)، الجيل الثاني للاتصالات المتنقلة (2G)، أصبحت الآن تكنولوجيا قديمة والأوساط البحثية تركز بدلا من ذلك على الجيل الخامس (5G) ، هذه الأطروحة يعالج مشكلة حقيقية في بعض البلدان التي لا يمكن التعامل مع التطورات التكنولوجية لأسباب اجتماعية وسياسية واقتصادية متعددة. على وجه الخصوص، الطيف المخصص لفلسطين محدودة جدا بسبب القيود التي تفرضها إسرائيل من خلال اتفاق أوسلو. مشغلي شبكات الهاتف النقال في فلسطين ما زالت تقوم على GSM.

في هذه البحث، نقترح للتحقيق في أهمية تطبيق overlay CR لتوسيع نطاق ترددات GSM. لذلك اقترحنا استخدام نظام الجيل الرابع (4G) المبني على أساس تقنية التقسيم الترددي المتعامد (OFDM) للنظام الثانوي في حين أن نظام المحمول GSM المبني على أساس تضمين الازاحة الجاوسي (GMSK) يعتبر النظام الاساسي. تقنية 4G-OFDM، والذي يستخدم على نطاق واسع في الأنظمة القياسية، ويعتبر كمرشح محتمل لـ overlay CR. تم اشتقاق المعادلات الرياضية للتداخل (interference) من النظام الثانوي على النظام الاساسي ومن النظام الاساسي على النظام الثانوي. للقضاء على هذه التداخلات، تم إدخال تقنية precoding على أساس طريقة الغاء التداخلات ZFBF في النظام الثانوي في جهة الاستقبال لالغاء التأثير على النظام الاساسي.، في حين يتم إدخال postcoding في جهة الاستقبال في النظام الثانوي لالغاء التداخلات من النظام الأساسي على النظام الثانوي. وبالإضافة إلى ذلك، لالغاء تأثير القناة اللاسلكية في النظام الاساسي تم استخدام ZF و MMSE. تم مقارنة النتائج للنظام المقترح على اساس معدل الخطأ (BER) مع نظام overlay CR بحيث يكون النظام الأساسي والثانوي مبنيان على تقنية 4G-OFDM.