Enhanced Dynamic Frequency Hopping Performance in Cognitive Radio IEEE 802.22 Standard

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Abstract

Enhanced Dynamic Frequency Hopping Performance in Cognitive Radio IEEE 802.22 Standard

Aikaterini Dimogiorgi

IEEE 802.22 is a Cognitive Radio based standard designed for Wireless Regional Area Networks (WRAN) for the purpose of providing wireless broadband access to rural and remote areas. The standard relies on the utilization of the unoccupied spectrum that became available after the TV signal was converted from analog to digital. In this thesis, we present an enhanced scheme for the operation of the Dynamic Frequency Hopping (DFH) technique in the IEEE 802.22 standard for WRANs. The performance of the DFH is analyzed thoroughly for various types of channels and for a Multiple-input Multiple-output (MIMO) systems.

The core of this research is based on the coexistence of the incumbent users and the WRANs in the TV white spaces (TVWS). The proposed technique, aims at protecting the licensed users from interfering with the cognitive broadband access in the TV spectrum. In order to achieve that, spectrum sensing is performed in the intended working channel in DFH while spectrum monitoring with the energy-ratio (ER) algorithm is applied during the WRAN data transmission in the currently working channel. Hence, in the *DFH-ER* algorithm the reappearance of an incumbent user in a band occupied by the WRANs would be detected immediately, providing interference free performance for the licensed user as well as reliable data transmission for the unlicensed one. Simulation results of the proposed DFH-ER technique compared to the conventional DFH scenario exemplify the enhancement of the WRAN data transmission while protecting the incumbent users.

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Contents

List of Figures

List of Tables

Nomenclature

AWGN	Additive White Gaussian Noise
BS	Base Station
CP	Cyclic Prefix
CPE	Custom Service Equipment
CR	Cognitive Radio
DFH	Dynamic Frequency Hopping
DH	Double Hopping
DS	Downstream
DSL	Digital Subscriber Line
DTV	Digital Television
ED	Energy Detector
EGC	Equal Gain Combining
ER	Energy Ratio
FAP	Frequency Assignment Problem
FCC	Federal Communication Commision
FDM	Frequency Division Multiplexing
FIR	Finite Impulse Response
HF	Very High Frequency
ICI	Inter Channel Interference
IFFT	Inverse Fast Fourier Transform
ISI	Inter Symbol Interference
LOS	Line Of Sight
MIMO	Multiple Input Multiple Output

MISO	Single Output Multiple Input
MMSE	Minimum Mean Square Error
MRC	Maximum Ration Combining
NBI	Narrow Band Interference
OFDM	Orthogonal Frequency Division Multiplexing
OP	Operation Period
PDF	Probability Density Function
PHY	Physical
PNR	Primary to Noise Ratio
PU	Primary User
QoS	Quality of Service
QP	Quite Period
ROC	Receiver Operating Characteristics
RT	Reserved Tone
SIMO	Single Input Multiple Output
SISO	Single Input Single Output
SM	Spectrum Manager
SNR	Signal to Noise Ratio
SPR	Secondary to Primary Ratio
SPTF	Spectrum Policy Task Force
SSDT	Simultaneous Data Transmission and Spectrum Sensing
SU	Secondary User
TVBD	Television Band Devices
TVWS	Television White Spaces
UHF	Ultra High Frequency
US	Upstream
UWB	Ultra Wide Band
WISP	Wireless Internet Service Providers
WRAN	Wireless Regional Area Networks
ZF	Zero Forcing

Chapter 1

Introduction

1.1 Cognitive Radios

Over the past decades, there has been a tremendous increase of the wireless devices and applications in use (computers, laptops, smart phones, smart televisions, tablets, remote controlling devices). As a result, the majority of the spectrum is already allocated to multiple users through various wireless standards. However, the spectrum occupancy among the various wireless applications is not uniformly distributed [1]. As a matter of fact, some parts of the spectrum are over-utilized while others under-utilized. Observing the distribution of a spectrum, it becomes clear that there is an important issue of unbalanced usage that needs to be tackled. Hence, it is vital to find solutions for future wireless communication systems. Presently, the radio-frequency (RF) spectrum is allocated according to a fixed access model. The licensed holders of the spectrum are enabled to utilize their assigned band without any other user being allowed. A *Cognitive-Radio (CR)* system represents a promising solution to this inefficient usage model of the spectrum. The objective of a CR is to improve the spectrum usage efficiency and, most importantly, minimize the problem of spectrum over-crowdedness. Consequently, modern technologies will be able to support more and more wireless devices and applications as the consumers demand. Along with that, the requirement for higher data rates would be met. The ultimate target is to provide Quality of Service (QoS) to unlicensed users and reliable data transmission while maintaining the licensed users protected. For this reason, it is vital to provide accurate spectrum sensing in order to detect the licensed users instantly and protect them from interfering with unlicensed users. Moreover, the performance of the licensed users need to be kept unaffected by the continuous sensing of the spectrum for the presence of incumbent users.

The introduction of CRs in wireless telecommunication field, has led to the new unlicensed market growing rapidly. Regulatory bodies like the Federal Communication Commission (FCC) through its Spectrum Policy Task Force (SPTF), initiated an investigation on the current way the spectrum is utilized [2]. As indicated in [2], the FCC witnessed significant fluctuations on the spectrum allocation. Therefore, an attempt to enhance the uneven spectrum occupancy was made by allowing the operation of unlicensed users employing CR technologies on the vacant broadcast TV channels created when the TV signal was converted from analogue to digital. Based on that, the IEEE 802.22 was constituted to support the operation of Wireless Regional Area Networks (WRAN) in order to provide wireless broadband access to rural and remote areas. The WRANs are to utilize the channels in Ultra-High-Frequency (UHF) and Very-High-Frequency (VHF) bands assigned to the Television Broadcast Services in the frequency range between $54MHZ - 862MHz$. The availability of frequency band is combined by the geographic location of the WRAN, database services and spectrum sensing. A WRAN consists of a Base Station (BS) which can provide high-speed Internet up to 512 Custom-Service-Equipments (CPEs). The BS assumes different QoS requirements for each CPE, always with regard to the protection of the incumbent users. The cognitive feature of the standard relies on the dynamic spectrum management [3].

1.2 Motivation

IEEE 802.22 devices utilizing the CR technology, will be able to determine their operation based on information from spectrum sensing, geographical location and the database services. As specified in [4], the availability of the TVWS is related to the rules governing the particular regulatory domain where the device intends to operate. Thereafter, having established the spectrum activity, WRAN operations must enthrall two basic requirements, assure the QoS satisfaction for WRAN services while providing reliable and timely spectrum sensing for guaranteeing the licensed user protection. Therefore, a WRAN before occupying a band needs to sense it (according to mentioned sensing techniques) in order to decide whether it will initiate an operation or not. The channel management in the WRANs employed in the standard will select the appropriate information about the unoccupied bands in a specific geographical location and sort them according to the state of each channel. Assuming the sensed band is deemed idle, the WRAN is allowed to transmit information for a maximum period of time of 2seconds [5]. Every 2sec the WRAN has to suspend its operation to sense the currently working channel for the presence of an incumbent signal. The period of time dedicated for spectrum sensing is called a *Quite Period (QP)*, during which the WRAN is not able to perform data transmission. As a consequence, the operation of a WRAN is suspended every 2sec. Such interruptions have an impact on the QoS and the throughput of the SU. In order to deal with this requirement, our focus on the Dynamic Frequency Hopping technique is developed as follows.

1.2.1 Dynamic Frequency Hopping

Dynamic Frequency Hopping (DFH) was introduced in [6], in order to overcome the challenge of the continuous interruption of the WRAN operation. In the DFH technique, a WRAN follows a hopping pattern over a specified set of channels and performs data transmission and spectrum sensing simultaneously (SSDT) [6]. Hence, each WRAN operating in the DFH mode does not have to interrupt the data transmission for spectrum sensing every 2 seconds. Most research presented in the implementation of the DFH is with regard to the network functionality. On the other hand, we focus on the modeling of the physical layer operation of a WRAN included in the DFH. The most essential operations of the WRAN would be the *data transmission* and *spectrum sensing* which will lead to the decision on the next intended working channel. These topics need to be thoroughly analyzed theoretically as well as with simulation results. A variation of channels are investigated while extending the DFH introduced in literature for system with more that one output/input.

1.2.2 Energy Ratio Algorithm

Another intriguing solution to the continuous interruption of the secondary users data transmission for spectrum sensing was proposed in [7], were the *Energy Ratio(ER) algorithm* is introduced for spectrum monitoring. A system model for Orthogonal Frequency Division Multiplexing

(OFDM)-based Cognitive Radio Networks is implemented, providing extended analysis on the performance of the algorithm. Based on the presented research on the algorithm, our focus is to evaluate the efficiency of ER. The capability of detecting accurately the PU presence is the major objective. A variety of system models for the ER algorithm need to be examined in order to have complete overview of its effectiveness. Since the prior focus is to thoroughly survey the operation of DFH, the ER algorithm is applied in order to introduce methods that can enhance the DFH performance.

1.2.3 Proposed DFH-ER Algorithm

As stated formerly, in DFH the WRAN is able to perform data transmission continuously without interrupting the operation for spectrum sensing. However, this implies that a WRAN once it initiates the transmission of the desired information it will not be aware of the reappearance of an incumbent user during its operation period (OP). According to [4], the term *incumbent user* refers to all the "*Licensed transmission systems operating in the TV bands on a primary or secondary basis according to international and local regulatory rules*". Such licensed transmission systems include the fixed TV band-devices (TVBD), personal/portable TVBD and wireless microphones. Hence, if an incumbent user was deemed idle before the SU initiates data transmission and that condition alters during the 2 seconds of the OP, interference will be caused to the PU by the coexistence with the WRAN.

A proposed method is represented in order to diminish as much as possible the effect of a possible interference performing *spectrum monitoring* to the operating channel according to the ER algorithm. Therefore, the WRAN being aware instantly about the activity of the incumbent signal will be able to vacate the channel and reassure the incumbent protection. The DFH scheme is combined with the ER to constitute the proposed *DFH-ER* algorithm. This enhanced scheme is designed in order to preserve the licensed users while providing a reliable data transmission to the WRANs included in the DFH scenario. In the introduced technique, both spectrum sensing in the intended working channel and spectrum monitoring in the currently operating channel are implemented in order to compose an enhanced as well as resistant to interference DFH. The efficiency of the technique utilized for sensing and monitoring is demonstrated through analysis and simulations under various parameters. In order to evaluate the interference caused in a possible coexistence scenario, the data transmission of the WRAN in DFH is simulated for the conventional DFH operation and the proposed DFH-ER algorithm. The illustration of DFH-ER together with simulation results, exemplify the way this enhanced technique is capable of protecting the licensed users while maintaining the reliability of the WRANs performance.

1.3 Summary of Contributions

The thesis is divided into three main chapters. Initially, we implement all the aforementioned techniques and the proposed scheme for AWGN channel. The probability of detecting the incumbent users is represented through theoretical analysis as well as evaluated in simulations. Additionally, for the DFH scheme we define the *blocking probability* for a channel included in the operation. Moreover, the throughput of the WRAN is determined via analysis and simulations. Having the results from the examination of DFH and ER, we introduce the theoretical information for the proposed DFH-ER algorithm. Afterwards, the DFH-ER method is simulated and compared to the conventional DFH scenario demonstrating the enhanced performance.

In the next chapter, the system model established in the former chapter is implemented for a fading channel. The DFH technique along with the ER and the DFH-ER algorithm are investigated under the effect of the Ricean fading channel. Theoretical analysis is provided for the system model simulated. In the last chapter, the proposed scheme as well as the conventional techniques are extended for a MIMO system. Analytical and simulation results exemplify the performance improvement compared to the single-input-single-output (SISO) system. The contributions are summarized as follows:

- We investigate the operation of the DFH scheme. The detailed procedure of the spectrum sensing and the data transmission of the SU according to the activity model of the PU is presented.
- We define the blocking probability and derive theoretical expressions. In addition, extended analysis is presented on the SU throughput in DFH.
- The detection, blocking probability, Receiver Operating Characteristics (ROC) as well as the

SU throughput are implemented for various types of channels (AWGN, Ricean). Moreover, an extended overview is presented for MIMO system.

- We develop the ER algorithm in order to verify its efficiency under various channels (AWGN, Ricean). Additionally, the ER is implemented for a MIMO model.

- The proposed DFH-ER scheme is introduced, providing detailed operation of the algorithm. The effectiveness of DFH-ER is inspected for fading and non fading channels. Furthermore, we elevate the performance of our algorithm with the MIMO extension.

- We compare the DFH-ER scheme with the conventional DFH scenario for all the examined system models and under various conditions.

1.4 Thesis Overview

The organization of the thesis is as follows. In chapter 2, background information is provided based on the concepts implemented in the thesis.

In chapter 3, the system model for our proposed method is examined for non fading channel. The performance of DFH is evaluated, demonstrating results on the detection probability, blocking probability, throughput, ROC. Moreover, the ER algorithm is explored providing results on the detection probability and ROC that will contribute on the assembling of DFH-ER. Thereafter, the proposed DFH-ER algorithm is analyzed thoroughly. The performance of the SU in DFH-ER and the conventional DFH are compared.

In chapter 4, the fading channel is included in our system model. A research on the effects of Ricean fading channel on DFH, ER and DFH-ER is presented. The inclusion of the Ricean fading channel is explored through theoretical analysis and simulation results.

In chapter 5, we introduce an extension of the DFH-ER algorithm to MIMO. Each technique applied in the DFH-ER, is evaluated independently in order to verify their efficiency in a MIMO system model. Afterwards, the enhanced SU operation is demonstrated in the DFH-ER.

Chapter 2

Background

2.1 Digital Communications

Over the last decades there has been an unparalleled growth in communication services. The ultimate goal is to develop applications with high QoS while maintaining a high data rate for the customers. A constant effort is carried out, in order to upgrade communication systems to fulfill these requirements. More specifically, communication systems intend to transmit information generated from a source to a destination [8]. In modern technologies, digital communications prevail over the equivalent analogue due to the advanced system performance links along with the digital technology that can provide more reliable media transmission [9].

2.1.1 Fading Channels

An essential subject of digital communications is the physical channel through which the information is transmitted [10]. In wireless communication systems, electromagnetic energy is connected to the propagation medium by an antenna that representes a radiator [10]. The antenna is defined by its physical size and configuration with regard to the frequency of operation. The distortion caused to a telecommunication signal over certain propagation media is referred to as *fading*. Fading results from the superposition of transmitted signal that have experienced variations in attenuation, delay, phase-shift while traveling from source to destination. Therefore, it is significant to survey the performance of data transmission exposed to the fading effect.

As stated in [11], there is a variety of probability distributions that can model the statistical characteristics of a fading channel. Applying the central limit theorem for the case of a channel with large number of scatterers, the channel impulse response can be expressed as a Gaussian process model. Based on that, we will introduce basic categories of fading channels according to their statistical characteristics.

Ricean Fading Channels

The first type of fading channels representing the case when there is a line-of-sight (LOS) among the transmitter and the receiver, is the Ricean channel. A LOS exists when the transmittes is able to "see" the receiver without any obstacles interferring. We need now to provide the statistical components for a channel fading according to the Ricean distribution. Adhere to the analysis in [11], the parameter $Y = X_1^2 + X_2^2$ is defined where the X_i factors share the same variance σ^2 and each has a mean m_i. The distribution that Y follows is a non-central chi-square with $s^2 = m_1^2 + m_2^2$. Therefore, the probability density function (PDF) of the random variable $R = \sqrt{Y}$ is expressed according to (2.1.1) and illustrated in Figure 2.1 for various κ values.

$$p_R(r) = \frac{r}{\sigma^2} e^{-\frac{(r^2+s^2)}{2\sigma^2}} I_o\left(\frac{rs}{\sigma^2}\right), \quad r \geq 0 \tag{2.1.1}$$

where $I_o(x)$ is the modified Bessel function of the first kind of order zero. A basic constant that characterizes the Ricean fading channels is the κ-*factor* due to the presence of the LOS. The value of κ-*factor*, is a measure of the severity of fading in a channel with $\kappa = 0$ representing the most severe case of fading and $\kappa \to \infty$ when no fading exists [12][13]. The equations expressing the κ-factor in terms of the mean value and the variance of the channel along with the mean and variance representation are [10] :

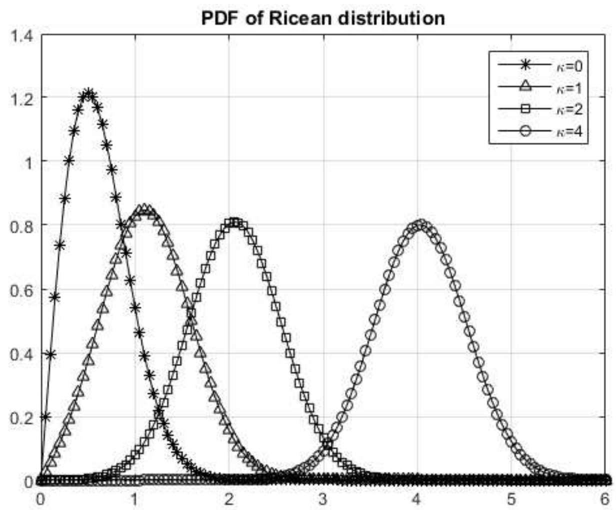


Figure 2.1: PDF of Ricean distribution for various κ values

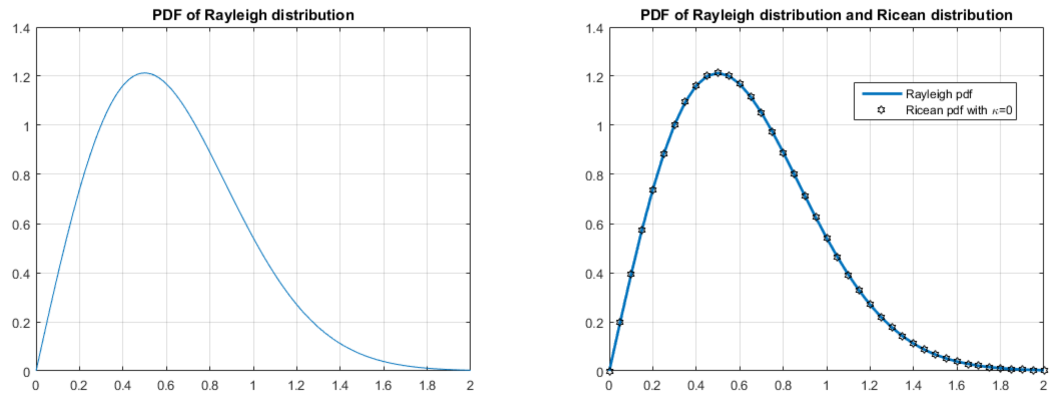
$$\kappa = \frac{m^2}{2\sigma^2} \tag{2.1.2}$$

$$m = \sqrt{\frac{\kappa}{\kappa+1}} \tag{2.1.3}$$

$$\sigma = \sqrt{\frac{1}{2(\kappa+1)}} \tag{2.1.4}$$

Rayleigh Fading Channels

The general case of fading channels with a Ricean distribution was presented when there exists a LOS between the transmitter and receiver. However, there is a special case where the receiver is not visible by the transmitter and hence we have absence of LOS. Such channels fade according to a Rayleigh distribution, and are utilized mostly to model communication in urban areas where the signal has to travel through multiple paths to reach the destination. Thus, the statistical characteristics of a channel fading according to a Rayleigh distribution should be determined. Equivalent to the Ricean channels, the parameter $Y = X_1^2 + X_2^2$ is defined. However, the mean of X_i now is equal to zero (no LOS) and each one having variance σ^2. Therefore, the PDF of R is expressed as:



(a) PDF of Rayleigh distribution

(b) PDF of Ricean distribution for $\kappa = 0$ and Rayleigh compared

Figure 2.2: Rayleigh and Ricean distribution PDF relation

$$p_R(r) = \frac{r}{\sigma^2} e^{-\frac{(r^2)}{2\sigma^2}}, \qquad r \geq 0 \tag{2.1.5}$$

Observing (2.1.5), we see that it is a reduced representation of (2.1.1) for $s = 0$ making the $I_o\left(\frac{rs}{\sigma^2}\right)$ part equal to one and form the special case of a Rayleigh fading channel. This observation can be clear from the Rayleigh distribution PDF curve drawn in Figure 2.2a. In Figure 2.2b, the Ricean distribution is derived as well as the Rayleigh for $\kappa = 0$ in order to demonstrate their relation.

2.1.2 OFDM Systems

In addition to the challenges as the distortion caused by fading channels, there are other impairments that can disrupt reliable communications. The spreading of the pulses of a signal beyond their allotted time interval can cause interference [14]. This phenomenon is well known in telecommunications as the Inter Symbol Interference (ISI). Similar to the ISI, the Inter Channel Interference (ICI) is generated in communications systems. The ICI is an outcome of the loss of sub-channel orthogonality due to the time variations of the channels included in the data transmission [15]. OFDM was introduced to mitigate these challenges [9][16][17]. OFDM is a special case for the Frequency Division Multiplexing (FDM). In FDM the total available bandwidth is divided into a set

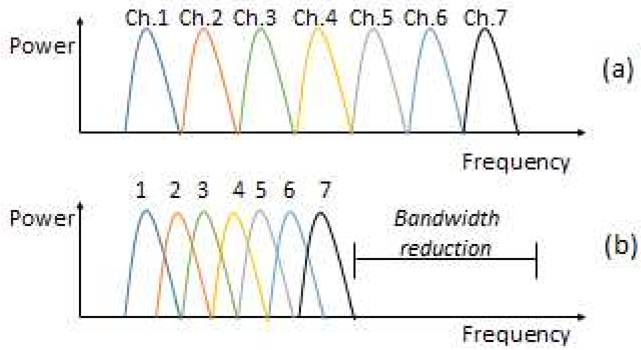


Figure 2.3: (a)conventional FDM (b)OFDM

of non-overlapping frequency sub-bands. OFDM allows the sub-bands to overlap by having all the sub-carries *orthogonal* to each other. Hence, the bandwidth is utilized more efficiently, as illustrated in Figure 2.3.

In communication systems that are based on the OFDM model, the information is transmitted simultaneously using orthogonal sub-carriers. Initially, the data symbols ($d_{n,k}$) are combined into a block of size N as demonstrated in the time-frequency representation of an OFDM frame in Figure 2.4 ; τ_0 is the duration and v_0 the frequency separation of the sub-carriers. Afterwards, they are modulated with a complex exponential waveform $\phi_k(t)_{k=0}^{N}$ as shown in (2.1.6) provided in [9]. According to the analysis in [9], the modulator is implemented using an Inverse Fast Fourier Transform (IFFT) block and expressed as:

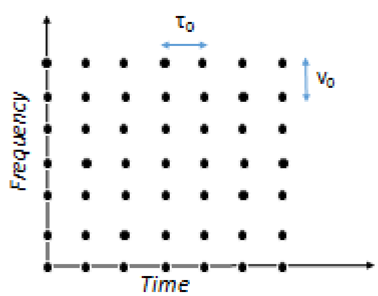


Figure 2.4: Time-Frequency representation of OFDM frame

$$x(t) = \sum_{n=-\infty}^{\infty} \left[\sum_{k=0}^{N-1} d_{n,k} \phi_k(t - nT_d) \right] \tag{2.1.6}$$

$$\phi_k(t) = \begin{cases} e^{j2\pi f_k t}, & 0 \leq t \leq T_d \\ 0, & \text{otherwise} \end{cases} \tag{2.1.7}$$

$$f_k = f_o + \frac{k}{T_d}, \quad k = 0...N-1 \tag{2.1.8}$$

where $d_{n,k}$ is the transmitted symbol during the n^{th} time interval and k^{th} sub-carrier. Moreover, T_d stands for the symbol duration, N is the number of OFDM sub-carriers and f_k the k^{th} sub-carrier frequency with f_o being the lowest. Following the IFFT block is the addition of the *cyclic prefix (CP)*. The CP is the last part of an OFDM symbol, which is copied to the beginning of the transmitted OFDM symbol as illustrated in Figure 2.5. The purpose of the CP is to maintain the orthogonality of the sub-carriers while mitigated the ICI related degradation as stated in [9]. Finally, the block of OFDM symbols is converted from parallel to serial and transmitted through the communication channel. At the receiver side, the inverse process is followed. The CP prefix is removed and then the demodulator is based on the orthogonality of the sub-carriers which is given by [9]:

$$\int_R \phi_k(t)\phi_l^*(t)dt = T_d\delta(k-l) = \begin{cases} T_d, & k = l \\ 0, & \text{otherwise} \end{cases} \tag{2.1.9}$$

Making use of the orthogonality of the sub-carriers, the demodulator is implemented by a FFT of the OFDM signal:

$$d_{n,k} = \frac{1}{T_d} \int_{nT_d}^{(n+1)T_d} x(t) * \phi_k^*(t)dt \tag{2.1.10}$$

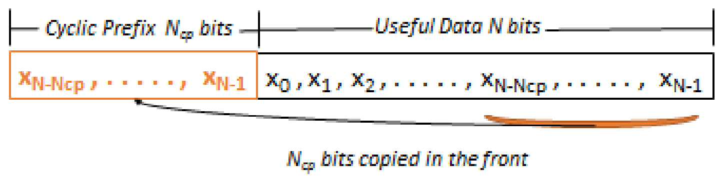


Figure 2.5: Cyclic Prefix representation

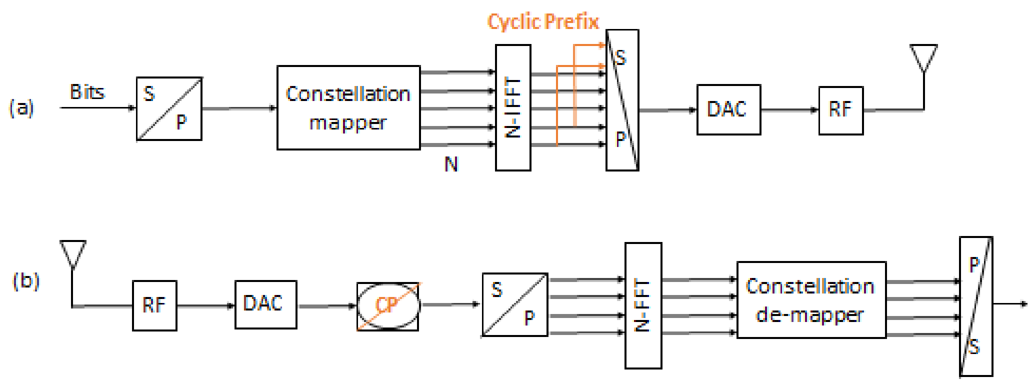


Figure 2.6: (a)OFDM transmitter block diagram , (b)OFDM receiver block diagram

2.1.3 MIMO Systems

It is significant now to provide methods that overcome the distortion a fading channel can cause to a telecommunication system. Multiple-Input, Multiple-Output systems have been a major advancement in the field of telecommunications in the past decades. Employing multiple antennas at the receiver and transmitter side, the performance of a system can be improved by either *spatial-multiplexing* or *diversity*. In the first case, at the transmitter side independent and separately encoded data streams are sent to the receiver side through the communication channel. Therefore, during a time period more than one symbol can be sent and hence an increase in the spectral efficiency of the system [9]. On the other hand, with the diversity mode the same stream of information is assigned to each transmit antenna aiming to boost the reliability of the data transmission. Provided that fading channels are independent among the transmit and receive antennas, if one of them experiences deep fading the signal will be able to be reconstructed more efficiently since multiple replicas of the signal are affected by independent fading channels.

Here we focus on the spatial-multiplexing technique for MIMO systems. A critical step in the

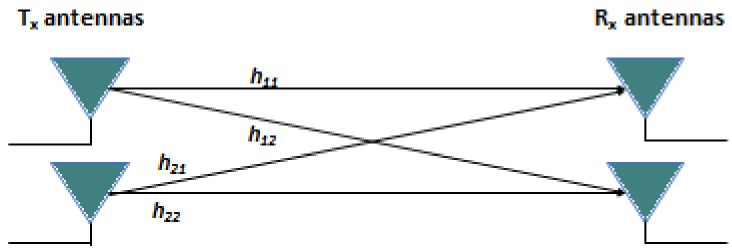


Figure 2.7: 2x2 MIMO system

implementation of MIMO systems is the recovery of the transmitted symbols at the receiver side. This goal is achieved by applying *equalization* to the received information. Some basic methods of equalization are introduced. The upcoming techniques are analyzed for a $2x2$ MIMO as illustrated in Figure 2.7 which can be generalized to MxM MIMO system.

Initially, a vector of the transmitted symbols $\boldsymbol{x} = x_1, x_2, ..., x_n$ is defined. Conventionally, in a SISO system the stream of information will be transmitted by a single antenna with one symbol being sent at every time instance. Now, having two transmit antennas we transfer two symbols at each time slot from each T_x antenna. Therefore, for the n symbols $\frac{n}{2}$ time slots are required to send the information [18]. Thus, the data rate is doubled. Each transmitted symbol from transmit antenna i to receive antenna j for $i, j = 1, .., M$, is affected by the impulse response of the fading channel h_{ij}. Consequently, at each R_x antenna, the received signal is represented according to [18] as:

$$y_1 = h_{11}x_1 + h_{12}x_2 + n1 \tag{2.1.11}$$

$$y_2 = h_{21}x_1 + h_{22}x_2 + n2 \tag{2.1.12}$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} \tag{2.1.13}$$

where (2.1.11),(2.1.12) represent each received stream and in (2.1.13) their expression in form of matrices is demonstrated. Additionally, n_j for $j = 1, .., M$ represents the zero mean additive white Gaussian noise (AWGN) added to the received signal. At the receiver side, it is assumed that the noise power and the channel profile are both known. Therefore, from (2.1.13) we need to recover the transmitted symbols. Some of the basic types of equalization techniques are the zero-forcing (ZF) equalizer and the minimum-mean-square-error(MMSE) [9]-[11],[18]-[21]. In this research the MMSE is analyzed. In the MMSE equalizer, in order to solve for x_1, x_2 it is required to define a coefficient W which minimizes the criterion:

$$E[Wy - x][Wy - x]^H \tag{2.1.14}$$

where $\boldsymbol{A^H}$ represents the Hermitian transpose matrix of $\boldsymbol{A}$ which is equal to the complex conjugate of the transpose of $\boldsymbol{A}$. Based on that, according to [18], the coefficient that can satisfy this criterion is expressed in (2.1.15) where $\boldsymbol{H}$ represents the matrix of the channel gains as shown in (2.1.16), N_o is the noise power and $\boldsymbol{I}$ is the identity matrix.

$$W = (\boldsymbol{H}^H\boldsymbol{H} + N_o\boldsymbol{I})^{-1}\boldsymbol{H}^H \tag{2.1.15}$$

$$\boldsymbol{H}^H\boldsymbol{H} = \begin{bmatrix} h_{11}^* & h_{21}^* \\ h_{12}^* & h_{22}^* \end{bmatrix} \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} = \begin{bmatrix} |h_{11}|^2 + |h_{21}|^2 & h_{11}^*h_{12} + h_{21}^*h_{22} \\ h_{12}^*h_{11} + h_{22}^*h_{21} & |h_{12}|^2 + |h_{22}|^2 \end{bmatrix} \tag{2.1.16}$$

Thus far, the concept of MIMO systems was introduced. A special category of MIMO systems is the case where we have single-output-multiple-output (SIMO) or multiple-input-single-output (MISO) system. In this thesis, we examine the special case of a SIMO along with the aforementioned MIMO model. In this type, a stream of information is transmitted from a single T_x to multiple R_x antennas providing receive diversity. Thereupon, it it crucial to define the way the data is formed at the receiver side. Some classifications for that in literature [18][21] are: the maximal-ratio-combining (MRC) method, selection diversity and equal-gain-combining (EGC). At this point, the MRC technique is examined. A simple scenario of $1x2$ SIMO is illustrated in Figure 2.8 which can be generalized to $1xM$ SIMO system.

The information transmitted from the single antenna is represented as $\boldsymbol{x} = x_1, x_2, .., x_n$. Each symbol is passed through the fading channel with impulse response $\boldsymbol{h_i}$ for $i = 1, .., M$ and at the

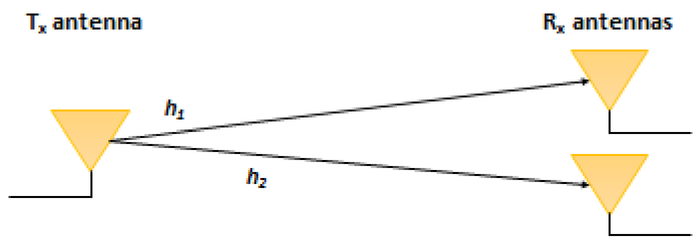


Figure 2.8: 1x2 SIMO system

receiver side zero mean AWGN noise is added. Similar to the MIMO system, it is assumed that the receiver has knowledge of the channel power $|\boldsymbol{h_i}|^2$ and the noise power. Hence, given the signal-to-noise ratio (SNR), γ, which represents the power of the received signal over the noise power at the receiver side, the *average SNR* is defined as $\overline{\gamma} = |\boldsymbol{h_i}|^2\gamma$ [21]. Therefore, the received symbols can represented in form of vectors as:

$$\begin{bmatrix} y_1 \\ y_2 \\ \dots \\ y_M \end{bmatrix} = \begin{bmatrix} h_1 \\ h_2 \\ \dots \\ h_M \end{bmatrix} x + \begin{bmatrix} n_1 \\ n_2 \\ \dots \\ n_M \end{bmatrix} \tag{2.1.17}$$

$$\boldsymbol{y} = \boldsymbol{hx} + \boldsymbol{n} \tag{2.1.18}$$

Therefore, according to [21] the resulting equalized symbol with MRC is given by (2.1.19) where $\boldsymbol{h}^H\boldsymbol{h}$ represents the inverse of matrix $\boldsymbol{h}$ and is equal to the summation of the channel power across all the receive antennas. The effective SNR for the SIMO case can be defined as $\gamma_M = \sum_{i=1}^{M} |\boldsymbol{h_i}|^2\gamma = \sum_{i=1}^{M} \overline{\gamma} = M\overline{\gamma}$.

$$\widehat{x} = \frac{\boldsymbol{h}^H \boldsymbol{y}}{\boldsymbol{h}^H \boldsymbol{h}} = \frac{\boldsymbol{h}^H \boldsymbol{h} x}{\boldsymbol{h}^H \boldsymbol{h}} + \frac{\boldsymbol{h}^H \boldsymbol{n}}{\boldsymbol{h}^H \boldsymbol{h}} = x + \frac{\boldsymbol{h}^H \boldsymbol{n}}{\boldsymbol{h}^H \boldsymbol{h}} \tag{2.1.19}$$

$$\boldsymbol{h}^H \boldsymbol{h} = \sum_{i=1}^{M} |\boldsymbol{h}_i|^2 \tag{2.1.20}$$

2.2 Cognitive Radios

According to [22], the term *Cognitive Radio* refers to *'an intelligent wireless communication system that is aware of its surrounding environment to allow changes in certain operating parameters for the objective of providing reliable communications and efficient utilization of the radio spectrum '*. CRs contribute to the efficient usage of the spectrum as they offer dynamic spectrum access, enabling the sharing of a wireless channel [23]-[26]. In [22], the spectrum is classified into three basic categories: the *black, grey* and *white* spaces. The first and second type of spaces represent the bands occupied by high-power and low-power users. Moreover, white space or *spectrum hole* is the part of the spectrum that contains only noise. An example of a CR network is demonstrated in Figure 2.9. Two unlicensed users base stations (BS) are employed to occupy an available band provided by the licensed user.

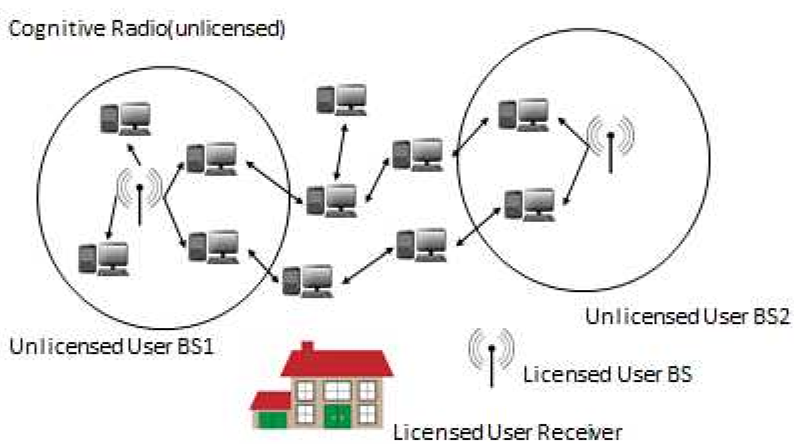


Figure 2.9: A Cognitive Radio Network

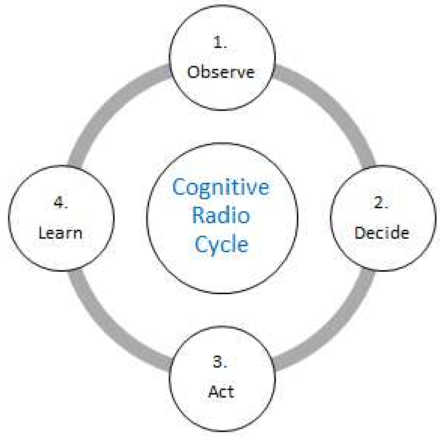


Figure 2.10: Cognitive Radio Cycle

Based on that, in a CR environment there are two types of users that are taken into consideration, the licensed users known as *Primary Users (PUs)*, that are able to access and occupy the spectrum at any time since there is part of the spectrum allocated totally to them. However, the PUs do not utilize continuously the spectrum providing time periods through which the specific bands are available. Therefore, there is another type of users that could occupy those bands during the idle moments of the PUs activity. The other type of users, being employed with CRs to dynamically access the spectrum, are the *Secondary Users (SUs)*. The SUs will be able to utilize the licensed band as long as interference to PU activity in minimal and confined.

2.2.1 Cognitive Radio Cycle

The way a CR system functions could be envisioned as in human brain. In order to process some information and perform properly, it needs to observe, decide its actions, initiate them and eventually learn from the results of the actions. Figure 2.10 shows the cycle a CR follows in order to be meticulous. The initial step of the Cognitive Radio cycle is the 'observe' part. In this, the CR has the ability to sense the available RF spectrum. Afterwards, at the 'decide' part the results of the 'observing' part are analysed in order to decide on the appropriate mode of operation (reviewed in upcoming subsection). Following the 'decide' part is the 'act' part. As the name indicates, the cognitive radio changes the mode of operation based on the decision made previously from the sensing of the RF signals. A CR might alter its operation in terms of allowed transmitted power, modulation scheme or operating frequency. Finally, there is the 'learn' step. It is probably the most significant capability of a CR system, since a CR is capable of learning from previous channel activities in order to predict future outcomes, as explained in [28].

2.2.2 Operation Modes of a Cognitive Radio

As mentioned previously, a CR system may operate in various modes accordnig to the desired functionality of the system. The three type of operations of a CR according to [27] are shown in Figure 2.12 and are:

(1) ***Interweave mode***

The Interweave mode of operation is the common type used in CRs. The basic difference between the interweave and other modes, is that the SU and the PU are not allowed to occupy a band at the same time. Hence, a SU in the interweave mode of operation *opportunistically* accesses the spectrum in order to detect the available band. An opportunity is that part of the spectrum where the PU is not present, also known as *white spaces* or *spectrum holes*, as illustrated in Figure 2.11. The SU in order to reach to the decision that the spectrum is available for utilization, needs to sense it for the presence of a licensed user. In the case that a SU senses the intended frequency band for operation, and identifies an incumbent user has to evacuate the band immediately since the licensed user should not be affected by the SU presence.

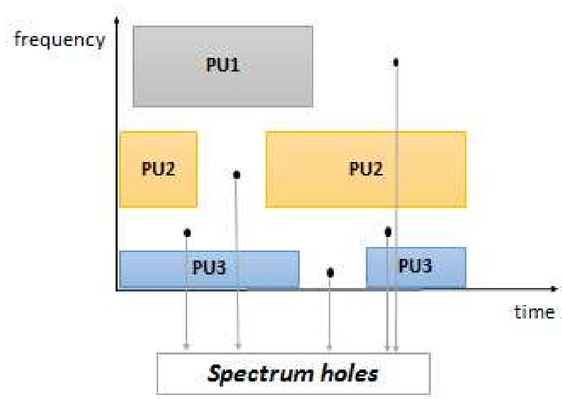


Figure 2.11: Spectrum Holes

(2) ***Underlay mode***

In contrast to the Interweave mode of operation, in the underlay, the SU is able to exploit a band regardless of the activity of the PU. However, there is a constraint to the SU's performance. The aggregated interference from all unlicensed users should be below some predefined threshold. In order to maintain the interference in that level, the SU applies the ultra-wide band (UWB) approach or either the interference temperature approach. In the first approach, the power of SU spans over a wide range, reassuring the constraint. On the contrary, with the interference temperature approach, the SU might be able to transmit in higher power only under the condition of the total power from all SUs is under a predefined threshold.

(3) ***Overlay mode***

According to the overlay mode of operation, the cognitive users retrieve information about the incumbent signal provided by the non-cognitive users. Therefore, the CR is capable of elevating and assisting the PU performance. The goal is to observe the information the incumbent signal contains, and eliminate the interference caused by the PU at the secondary receiver side or improve the primary transmission through relaying its information to the primary receiver. Along with the relay operation, the CR is allowed to transmit information provided that its overall transmit power meets the requirements of the SU and PU communication.

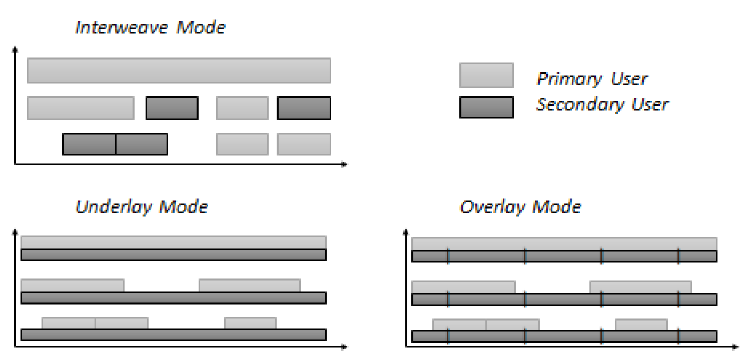


Figure 2.12: Cognitive Radio modes of operation

2.2.3 Spectrum Sensing

As indicated previously, based on the Interweave mode of operation, the SU needs to sense the spectrum in order to determine whether it is idle or not. This functionality is well known as the *spectrum sensing* and is probably the most essential task of a CR. Through the spectrum sensing the SU is able of examining the PU activity. The challenge of being aware of the PU presence has been adressed through various techniques in [28]-[32]. The spectrum sensing can be categorized in local sensing and cooperative sensing. In the local sensing, each SU individually senses the surrounding environment for an *opportunity* to access the spectrum and then selects an idle segment to transmit its data. The three major techniques for local sensing are:

- Energy Detection

  The energy detection technique, also known as radiometry or periodogram based detector, is one of the commonly used spectrum sensing technique in literature [33]-[40]. This type of spectrum sensing has low complexity and it is quite simple to be implemented either on hardware or software. The Energy Detector (ED) is the only detector that does not require prior information about the PU signal. More specifically, in this spectrum sensing technique the energy of the received signal is evaluated. Then this metric value, as shown in the block diagram for energy-detector in Figure 2.13, is compared to a threshold in order to decide on the activity of the PU.

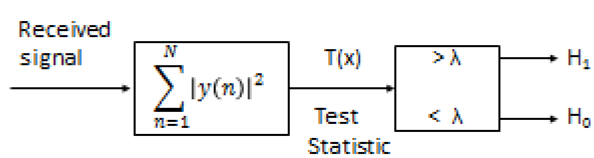


Figure 2.13: Energy Detection technique

  The received signal is expressed by $y(n)$ and the metric value T is defined as the energy of the received signal using N samples. Moreover, λ represents the threshold that will be used to determine whether the PU is present (H_1) or absent (H_0). The energy detector is affected in the cases where the noise is non-stationary and the noise power is not known, [38]. Moreover, the energy detection is sensitive to the noise power, the signal power and the sensing time.

- Matched Filter

  The matched filter method of spectrum sensing is considered an optimal one for signal detection since it maximizes the received signal-to-noise ratio as stated in [41]. Nonetheless, in the matched filter technique it is assumed that there is some prior information about the PU signal. That information could be the modulation scheme and order of the PU signal or the pulse shaping filter used. In line with that, the received signal is correlated with the 'known' PU signal and it is sampled in order to detect the presence of the licensed users in the spectrum. Consequently, the CR requires a dedicated receiver for every primary user class [41].

- Cyclostationary feature

  Similar to the matched filter technique, in the cyclostationary feature one it is taken into account that there is some prior information about the PU signal. Based on that, this method of spectrum sensing uses the periodicity of received signal, to detect the PUs. Modulated signals that have a periodic mean and auto-correlation are characterized as *cyclostationary*. The feature of periodicity is added to the signal structure on purpose, in order to provide to the receiver information for it [41]. Thereupon, this characteristic can be used for the detection of a PU signal in a CR.

The other category of spectrum sensing is the cooperative sensing. As the name indicates, according to this type, the SUs cooperate in order to improve the sensing accuracy. The cooperative sensing can be classified into the centralized and decentralized mode. In the first mode, SUs perform sensing on the band they intend to utilize and send their decisions to a fusion node (i.e a base station) which collects all the outcomes and draws the final decision (PU is active or not). In the decentralized mode, all SUs cooperate among them exchanging sensing results though each SU makes independently his decision on whether the PU is present or not.

2.2.4 Primary User Activity Model

Taking into consideration the previously mentioned aspects of CR, it can become clear that a basic objective of the CR systems is to accurately detect the presence of the PU. Therefore, it is crucial to examine the behaviour of the licensed users over a period of time in a specific channel. Therefore, one needs to define a model that shall represent the activity of the PU. A prevalent approach for the PU activity model is the two state Markovian chain composed by the *ON/OFF states* as illustrated in Figure 2.14. The *ON* state stands for the the PU being active and the *OFF* state accordingly for the PU being absent.

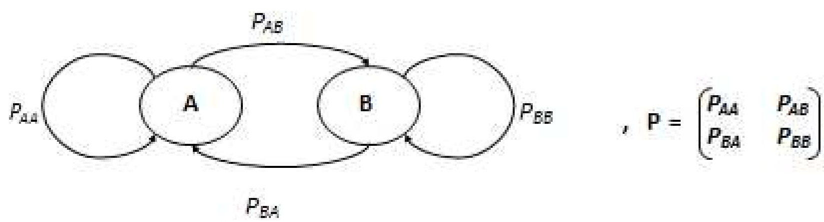


Figure 2.14: Two state Markov chain

A two state Markov chain is characterized by its transition probability matrix (matrix P in Figure 2.14). Such a matrix, corresponds to the probabilities of switching from one state to another as well as the probabilities of remaining in the same state [42]. This model is suitable for the activity of the PU model since we are interested in predicting whether the PU is ON (busy) or OFF (idle) in order to evaluate the probabilities of *detection* and *false alarm*. The estimation of this probabilities is based on results from the spectrum sensing, which can be seen as a binary hypothesis where H_0 is the hypothesis that the PU is not present and H_1 is the hypothesis that the PU is present. Depending on spectrum sensing, there exists a metric value compared to a threshold to indicate the standing hypothesis. Based on the binary hypothesis, we are able to define the probabilities of *detection, false alarm, miss detection and null* as follows:

$$P_D = Prob(T > \lambda|H_1)Prob(H_1) \tag{2.2.1}$$

$$P_{FA} = Prob(T > \lambda|H_0)Prob(H_0) \tag{2.2.2}$$

$$P_{MD} = Prob(T < \lambda|H_1)Prob(H_1) \tag{2.2.3}$$

$$P_N = Prob(T < \lambda|H_0)Prob(H_0) \tag{2.2.4}$$

where T is the metric value for the spectrum sensing, λ is the threshold that our metric value compared with. The $Prob(H_1)$ and $Prob(H_0)$ are the probabilities that the PU is on the ON or the OFF state ($Prob(H_0) = P_{off}, Prob(H_1) = P_{on}$) respectively. The meaning of these probabilities could become more clear if shown graphically as in Figure 2.15 where the Noise PDF represents the case where the received signal contains only noise (idle PU) and the Noise and signal PDF is the PU signal added with noise (PU active).

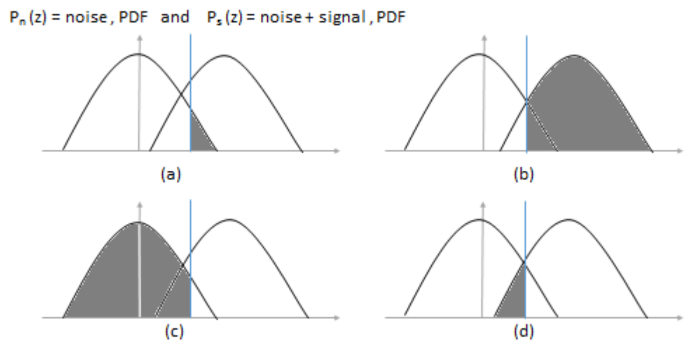


Figure 2.15: (a)False alarm(decide H_1 when actually is H_0), (b)Detection(decide H_1 when is actually H_1),(c)Null(decide H_0 when H_0),(d)Miss-detection(decide H_0 when H_1)

2.3 IEEE 802.22

Due to the ineffective utilization of the spectrum, the exploitation of the TV spectrum has been an intriguing attempt in overcoming this challenge. The structure of the frequency allotment of the analogue TV broadcast services was established many years ago [43]. The transition to the first generation of terrestrial digital television (DTV) (and afterwards to the second generation of DTV [44]), led to the spectrum formerly allocated for TV broadcasting being re-allocated to mobile communication systems (e.x 4G LTE) [45]. Through this action, the TV spectrum is effectively utilized while the development of advanced and innovative unlicensed broadband services are provided to businesses and consumers [46]. Based on the concept of CRs, the IEEE 802.22 standard was introduced in order to make use of the Television White spaces created when the TV signal altered from analogue to digital [47]. The available channels in the TV spectum region are reffered to as TV white spaces. According to the standards specifications in [4], IEEE 802.22 is intended to employ *Wireless Regional Area Networks* in order to provide wireless broadband access while protecting the incumbent licensed users in the TV broadcast bands. The standard is intended to utilize efficiently the sparsely populated DTV spectrum in rural areas [48].

2.3.1 Overview of the Standard

The development of the IEEE 802.22 standard aims at providing broadband internet access to rural and remote areas while maintaining a performance equivalent to that of current fixed broadband access techniques like digital subscriber line (DSL) [2]. A basic reason why the FCC chose the TV bands in order to support the broadband access to rural and remote areas, is that the lower spectrum of TV frequencies will enable far out users to be assisted. Hence, the Wireless Internet Service Providers (WISP) will consider it as a profitable circumstance [2]. Based on that, the IEEE 802.22 employs WRANs in order to service the users in the rural and remote areas. Each WRAN consists of the base station and customer premise equipment entities [4]. In the specifications of the standard provided to public by the IEEE 802.22 working group in 2011 [4], the features of the physical (PHY) and MAC layer were introduced. The PHY layer is designed in order to support systems that will occupy the vacant TV bands while providing wireless communication access up to $100km$ distance. The definition of the PHY is based on an OFDMA for both Upstream access (US) from CPE to BS and Downstream access (DS) from BS to CPE. In the MAC layer, synchronous timing is implemented where frames are grouped into a superframe structure.

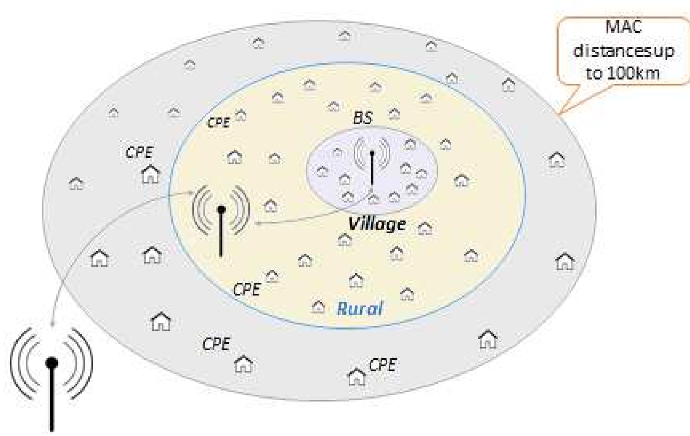


Figure 2.16: Wireless Regional Area Network

2.3.2 Channel Management

The ultimate target of the standard is to provide QoS to the SU while maintaining the incumbent users protected. Taking that into account, channel management is a crucial point in the standard since it will determine the available channels for utilization by the WRANs. While the WRANs operate in an unused band, if an incumbent starts each own operation in that channel, the WRANS has to move the operation to another unused band.

A spectrum is deemed unoccupied by the *Spectrum Manager (SM)* as explained in [4]. The SM combines information by the geographical location of the operating WRAN, database services and of course from sensing of the spectrum. The geographical location of the BS and the CPEs is used to determine the permissible channels at a given location. Database services contain the list of available (unoccupied by licensed users) channels at a specific time instant in a specific area. According to the database service, entering the interested address for the wireless broadband access it will provide a table of all the available channels in that area as well as allowable transmit power. Table 2.1, was obtained by entering an address in the USA as an example of the information that can be provided. Going through the table, there are information about the channel number of channels available. According to [3], in USA there are 10 channels in the VHF band and 37 to the UHF. In addition to the channel number, there is information about the frequency range and the bandwidth that can be 6,7 or 8MHZ (6 MHz in this case) based on the country of operation. Collecting the information by the geographical location, the database service and the spectrum sensing, the channels can be classified as available when there is no PU present or unavailable if an incumbent is currently occupying the channel. Furthermore, the available channels are subdivided in the categories below according to the standards specifications [1]:

(1) The *disallowed* channels that are precluded from use by the operator due to operational or local regulatory constrain

(2) The *operating* channels that are used for communication between a BS and CPEs

(3) The *back up* channels that have been cleared to immediately become the operating channel in case the WRAN needs to switch to another

(4) The *candidate* channels that are candidates to become Back up channels

(5) The *protected* channels in which incumbent or the WRAN operation has been detected through sensing

(6) The *unclassified* channels that have not been sensed yet

2.3.3 Spectrum Sensing

As was mentioned in the former sections, an important part of the channel management in the IEEE 802.22 is the spectrum sensing. A WRAN before occupying a band needs to sense it (according to mentioned sensing techniques) in order to decide whether it will initiate an operation or not. Assuming the sensed band is deemed idle, the WRAN is allowed to transmit information for a maximum period of time of 2seconds [5]. Every 2sec the WRAN has to suspend its operation to sense the currently working channel for the presence of an incumbent user. This procedure is shown in Figure 2.17.

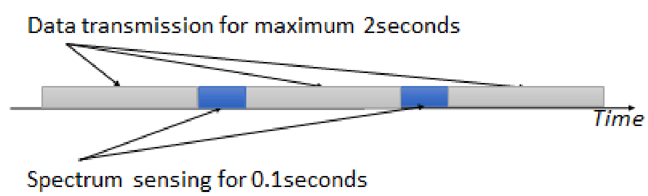


Figure 2.17: Spectrum Sensing in IEEE 802.22

The period of time dedicated for spectrum sensing is called a *Quite Period*. As the name indicates, during a QP the WRAN is not able to send data. As a consequence, the performance of a WRAN is interrupted every 2sec. Such interruptions have an impact on the QoS and the throughput of the SU. For these reasons, it is of great importance to come up with techniques to eliminate this impairment.

Table 2.1: Database Service results

Channel Number	Frequency Range(MHz)	Allowable T_x Power(mW)	Noise Floor(dBm)
21	512-518	100	**
22	518-524	40	**
24	530-536	40	**
25	536-542	40	**
27	548-554	40	**
28	554-560	100	**
29	560-566	100	**
30	566-572	100	**
31	572-578	40	**
35	596-602	40	**
41	632-638	100	**
42	638-644	40	**
44	650-656	40	**
45	656-662	100	**
46	662-668	100	**
47	668-674	100	**
48	674-680	40	**
50	686-692	40	**
51	692-698	100	**

2.4 Dynamic Frequency Hopping

Based on the challenges of the continuous interruption of the operation of the WRAN, *Dynamic Frequency Hopping* was introduced as a potential solution. In the DFH technique, data transmission and spectrum sensing is performed in parallel with the WRAN hopping over a set of channels [6]. In Figure 2.18, the 'hopping' procedure in the set of channels is demonstrated. A WRAN will initiate an operation on an available channel, for example CH.2 in the figure, for maximum 2 seconds according to the standard [1]. Before the allowable period for data transmission is over, the WRAN will perform *out-of-band sensing* in CH.1,3,4 for 0.1 seconds in order to determine the next working channel. Thus, each WRAN operating in the DFH mode will not have to interrupt the data transmission for spectrum sensing every 2 seconds. Hence, the throughput of the SUs is maintained high, having only a small effect from the channel switching period (it is considered a very small value, not negligible though). Accordingly, a WRAN cell needs two channels for the simultaneous data transmission and spectrum sensing [6]. Consequently, in the case of N_w uncoordinated and mutually interfering WRAN cells, $2N_w$ channels are necessary for their operation in the DFH mode.

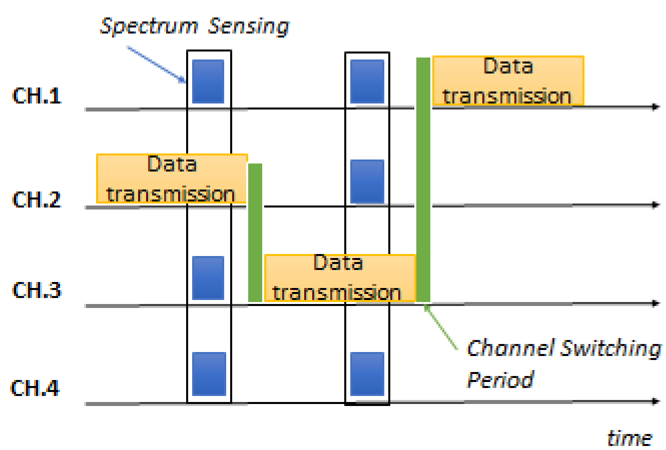


Figure 2.18: Simultaneous data transmission and spectrum sensing(SSDT)

2.4.1 Phase-Shift DFH Operation

Thus far, it has been justified that in order to support N_w WRANs in DFH $2N_w$ channels will be required. Without a doubt this would be a great challenge since it is desired to have as less as possible channels utilized to avoid interfering with the incumbent users. In [6], it has been established that if the WRAN cells decide to cooperate, only $N_w + 1$ channels would be required now for the performance of N_w WRANs. Therefore, the *phase-shift DFH operation* is presented for the coordination of N_w WRANs over $N_w + 1$ channels illustrated in Figure 2.19. In the current scenario, there are 2 WRANs and consequently 3 channels for the DFH operation. According to the phase-shift DFH operation proposed in [6], each WRAN has to shift its DFH operation by one QP over the previous WRAN, as shown in the figure. Initially, the WRANs will begin their operation to the available channels by solving a *Frequency Assignment Problem (FAP)* [49][50]. Afterwards, in the QPs reserved for spectrum sensing according to the phase-shift DFH operation each WRAN cell performes out-of-band sensing to determine which channel is available. Consequently, the WRAN cells are able to cooperate in the $N_w + 1$ channels without causing any collisions. Once more, the ultimate goal of providing reliable performance to the SU is achieved since the data transmission is continuous.

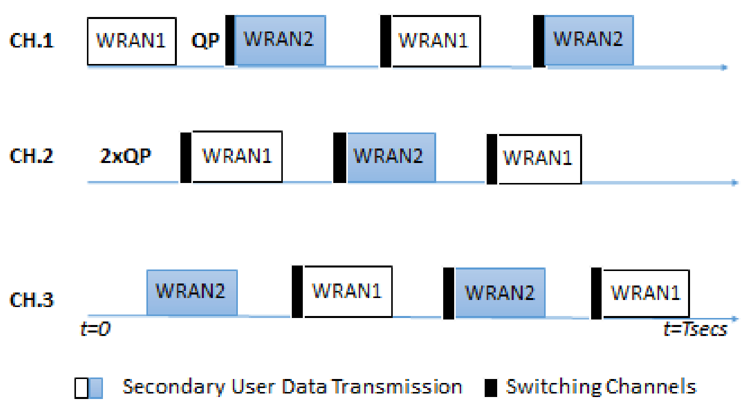


Figure 2.19: Phase-Shift DFH operation

2.4.2 Challenges of DFH Operation

Although, DFH is a considerable candidate in order to overcome the demand for continuous interruption it still could up-rise various challenges. First, the number of required channels for the efficient operation of the DFH is undoubtedly crucial. Such requirement shall increase the probability of an incumbent signal showing up in one of the operating channels in the set. Moreover, the $N_w + 1$ channels can be guaranteed that will be available during the whole time period of the DFH operation. Finally, an essential issue that can affect incumbent users as well as the WRANs is the reappearance of a licensed user during the SU data transmission. Since the WRANs in DFH operate continuously on data transmission and spectrum sensing in the different channel, it is possible that during the $2 seconds$ of the allowable operation period a PU could become active and consequently be harmed by the SU performance. In addition to that, the WRAN efficiency would be decreased, meddling that way with providing reliable data transmission while protecting the licensed users.

Several methods have been provided in [50]-[52], with a network layer approach in order to propose solutions to these challenges. In [50], the *Double Hopping (DH)* is introduced presenting a DFH scheme where the WRANs could hop only between 2 frequencies. Each WRAN then, will have a dedicated channel to perform data transmission and all the cells, will have a common shared channels for spectrum sensing. The aim is to reduce the sensitivity to the PU appearance, simplify the coordination among the cells and decrease the number of blocked frequencies per cell. Moreover, in [52] a technique is proposed for efficient utilization of the QPs created with the phase-shift operation of DFH introduced formerly. Finally, [51] demonstrates a variety of techniques for the coordination of the WRAN cells included in the DFH scenario.

Chapter 3

Performance of Cognitive Radio Systems in AWGN Channels

3.1 Introduction

Thus far, we have presented the basic key aspects of the functionality and the effectiveness of CRs in the introductory chapters. Moreover, the DFH scheme we intend to investigate was introduced as well as the Energy Ratio algorithm we are interested in implementing in our proposed DFH-ER method. Additionally, a theoretical background was given in chapter 2 regarding all the information we need for the development of the DFH-ER scenario.

In order to build up to our proposed DFH-ER algorithm, it is crucial to initially evaluate the performance of the conventional DFH along with the ER technique for spectrum monitoring in the case of a AWGN. At first, the conventional DFH operation is demonstrated. The energy detection for spectrum sensing is presented and the probabilities of detection and false alarm are provided. Additionally, the probability that a channel is blocked and the throughput of the WRAN in DFH are derived. Simulation results illustrate the performance of DFH.

Afterwards, the detailed operation of the ER algorithm is explained. The detection and false alarm probabilities are expressed in order to assist to the constitution of DFH-ER. The efficiency of ER is verified through simulations. The chapter is completed by the presentation of the DFH-ER scheme. The algorithm is defined as well as the system model for AWGN channel. We run simulation in order to illustrate the performance of DFH-ER and compare it to the performance of DFH.

3.2 Performance of Dynamic Frequency Hopping

A scenario of $N_w = 2$ WRANs and $C = N_w + 1 = 3$ channels in the set S_{OP} of operating channels is implemented. The system model for the implementation of DFH will follow the phase-shift operation introduced in section 2.4.1. Initially, a total time range for the duration of the DFH is specified. Thus, in this period the activity of a WRAN 'hopping' over the set of channels is modelled. As stated in the previous chapter, the first step is to define this set of channels according to the database service and assign the WRANs to them for the initiate 'hop'. This could be arranged by solving a *graph coloring* problem according to [50]. Afterwards, a SU will initiate a data transmission for $2seconds$ in the operating channel. The data for the SU is modeled according to an OFDM system. That is the data coming from the source is arranged into blocks and modulated from a QAM constellation mapper. Then the null sub-carriers are added and IDFT is applied to obtain the time-domain OFDM symbols. Thereafter, a number of sub-carriers from the end are copied to the beginning in order to form the cyclic prefix. At the receiver side, the inverse blocks are followed as illustrated in Figure 3.1 . Each WRAN, before switching to the next channel in the set, will sense the channel for $0.1second$. If the outcome of the spectrum sensing is that the channel is not occupied by a PU, data transmission is proceeded in the new channel. Following this procedure, a WRAN repeats its *hopping cycle* over the set of channels. A SU has completed a hopping cycle in DFH when it has passed once over each channel in the set.

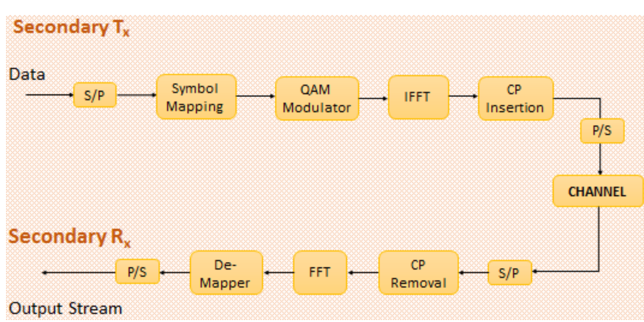


Figure 3.1: Block diagram for OFDM system

3.2.1 Theoretical Results

Energy Detection

For the spectrum sensing on next working channel, the energy detection technique is implemented. According to the Energy Detector, the energy of the received signal is evaluated. Afterwards, the energy is compared to a threshold in order to determine the presence of a PU. The PU activity model is a two state Markov chain represented by the *ON/OFF states*. The metric value compared to the threshold is expressed by:

$$T = \frac{1}{N_s} \sum_{n=1}^{N_s} |y(n)|^2 \tag{3.2.1}$$

where $y(n)$ is the received signal and N_s is the number of samples used for the evaluation of the energy [36]. The power of the received signal $y(n)$ will be σ_s^2 and the noise power σ_w^2. Thus, we can determine the primary-to-noise ratio (PNR) as $\gamma = \frac{\sigma_s^2}{\sigma_w^2}$. Both noise and the PU signal are modelled as zero mean Gaussian random variables. Based on the central limit theorem, the metric value T can be approximated as a real Gaussian variable with mean and variance for each hypothesis test as [36] :

$$T = \begin{cases} N(\sigma_w^2, \sigma_w^4/N_s), & \text{under } H_0. \\ N((1+\gamma)\sigma_w^2, (1+2\gamma)\sigma_w^4/N_s), & \text{under } H_1. \end{cases} \tag{3.2.2}$$

where H_0 representes the case that the PU signal is absent, hence there is only AWGN noise in $y(n)$. Equivalently, H_1 is the event of the PU being present thus; the recieved signal will contain noise added to the primary signal. As stated in [37][53], the key measurement metrics of the performance evaluation of the ED are: the detection probability P_D and false alarm probability P_{FA}. According to the analysis provided in [36], P_D and P_{FA} are given by:

$$P_D = Prob(T > \lambda | H_1) = Q\left(\frac{\lambda - (1+\gamma)\sigma_w^2}{\sqrt{1+2\gamma}\sigma_w^2}\sqrt{N_s}\right) \tag{3.2.3}$$

$$P_{FA} = Prob(T > \lambda | H_0) = Q\left(\frac{\lambda - \sigma_w^2}{\sigma_w^2}\sqrt{N_s}\right) \tag{3.2.4}$$

$$\lambda = (\frac{Q^{-1}(P_{FA})}{N_s} + 1)\sigma_w^2 \tag{3.2.5}$$

where λ is the threshold that will distinguish between the two hypothesis H_0 and H_1. The formulation of these probabilities will assist us to define the probability of channel in the S_{OP} set to be blocked, preventing a WRAN from operating on that channel. As stated in section 2.3.2 for the preliminaries on the standard, a set of back-up channels, C_{BU}, is available in case a WRAN has to switch to a different channel due to the presence of incumbent signal. Nevertheless, it is vital to evaluate the probability of a channel being blocked during the hopping cycle of a WRAN. In order for a channel to be deemed *blocked*, the WRAN has to sense it and decide that the PU has occupied the specific band. Therefore, the first case in which the WRAN draws such a conclusion is when the incumbent signal is present and it gets detected (represented by detection probability). Moreover, the second case in which the WRAN will have to move its operation to a back-up channel is when the PU is inactive and yet the WRAN settles on it being active (represented by the false alarm probability). This analysis will lead to the formation of the probability of channel in the S_{OP} being blocked and hence; having to be replaced by a channel in C_{BU}:

$$\begin{aligned} P_{BL} &= Prob(T > \lambda | H_1 \ \ or \ \ T > \lambda | H_0) \\ &= \frac{P_D + P_{FA}}{2} \end{aligned} \tag{3.2.6}$$

$$P_{NBL} = 1 - P_{BL} \tag{3.2.7}$$

From the above, the blocking probability would be the sum of the detection and false alarm probabilities since in both cases the PU is considered present. According to the PU activity model introduced in section 2.2.4, it is assumed that the probabilities of the PU being ON and OFF are equal. Hence, the evaluation of the blocking probability will follow the same procedure as the detection and false alarm probabilities. The definition of the blocking probability can easily provide us with the probability of the the channel not being blocked which is represented by P_{NBL} in (3.2.7).

ON/OFF Primary User Activity Model

The *ON/OFF Primary User activity model* was introduced already as model for representing the way to examine the incumbent behaviour. In Figure 3.2, it is demonstrated how the spectrum sensing is be performed. Initially, a time range of $t = T_r seconds$ is set. As the figure shows, it is considered that the beginning state is OFF (PU idle) since it is assumed that the DFH operation is initiated once having the list of available channels from the database service. Thus, being at $t = 0$, the SU will initiate the data transmission for $t = 2secs$. Afterwards, when the available time for data transmission is completed the spectrum is sensed for $0.1sec$. The sequence of the states and their duration is generated randomly. Each time the SU will trigger spectrum sensing, the state of the PU will be shown at that specific moment. In the case of the PU being idle (OFF), the received signal will be considered to contain only white Gaussian noise as explained earlier. On the other hand, the ON state will indicate the presence of PU signal and it will be taken under consideration in the received signal. Hence, in the case that the PU is active the probability of detecting the PU is evaluated. Similarly, in the case that the PU is inactive the probability of having a false alarm is calculated.

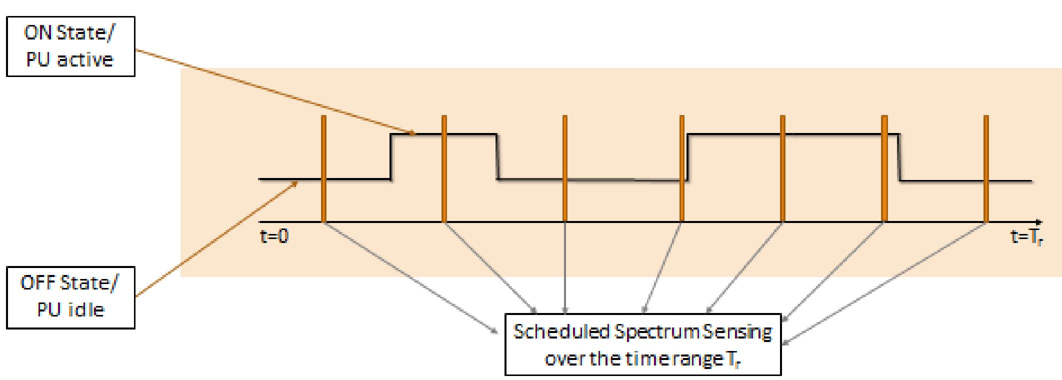


Figure 3.2: Energy Detection with ON/OFF PU activity model

WRAN Data Transmission in DFH

As mentioned previously, the DFH is based on the basic advantage that the data transmission of the WRANs in not interrupted (continuous hopping on channel set). According to [6], the throughput can be expressed with respect to the sensing time and bit rate of the SU as:

$$Throughput(x) = \frac{2 \times b}{2 + x} \tag{3.2.8}$$

where $2seconds$ corresponds to the available time of data transmission allowed for a WRAN, x is the sensing time and b the bit rate. However, since in the DFH there is simultaneous data transmission and sensing time, the throughput does not depend on the sensing time x. Therefore, the throughput is exactly equal to the bit rate b. During a time range T_r, the actions that are performed in an operating channel are the data transmission for $2seconds$, spectrum sensing for $0.1second$ and the switching time for $0.01second$ that is required for the WRAN to 'hop' to the next intended working channel. Therefore, we define how many times these actions can be repeated in the $T_r seconds$ as:

$$h = \frac{T_r}{2.11s} \tag{3.2.9}$$

Thus, if we multiply h with the bit rate, we get the total throughput in this time range in a specific channel in the S_{OP} set. Taking into a consideration a general case of N_w WRANs and $N_w + 1 = C$ channels, we express the minimum and maximum possible throughput achieved in the DFH mode of operation. In order to define the minimum throughput, it is presumed that all WRANs included in the DFH will perform data transmission at least one time. The reason to do so is that according to [4] the WRANs are able to check the availability through the database service. Therefore, the DFH will be initiated as long as there are available $N_w + 1$ channels. Based on that, the first "hopping" pattern would be generated by solving the FAP and the WRANs would perform data transmission for at least $2seconds$. The minimum throughput, can now be evaluated in the worst case scenario where all the C channels in the DFH are blocked for all the time range of T_r seconds right after the WRANs complete their transmission. Thus, we can express the minimum throughput of all the

WRANs included in the DFH scenario as:

$$Throughput_{min} = N \times b \tag{3.2.10}$$

The maximum throughput on the contrary, represents the case where the total C channels are unoccupied by a PU during the whole time range of $T_r seconds$. Hence, each WRAN will "hop" h times in every channel. The case of the maximum throughput, which could be characterized as *ideal*, can be shown graphically in original scenario in Figure 2.19. Thereupon, the maximum throughput is expressed as:

$$Throughput_{max} = h \times b \times C \tag{3.2.11}$$

Nonetheless, all these assumptions were drawn without considering the availability of the channels in the set. A WRAN performs data transmission in a channel in the set, given that the outcome of the spectrum sensing deemed the band available or as defined formerly *not blocked*. Therefore, a modified expression for the total throughput in the original set of C channels in a DFH scenario will be:

$$Throughput = h \times C \times b \times P_{NBL} \tag{3.2.12}$$

3.2.2 Simulation Results

Detection Probability

The probability of detection is simulated for different fixed values of probability of false alarm. Afterwards, the ROC curve is drawn. The number of samples used for the ED is $N_s = 10$. In Figures 3.3,3.4 the results from the simulated DFH scenario are illustrated. Figure 3.3 shows the relation between the probability of detecting an incumbent with respect to the various values of the PNR. As expected, an increase of the PNR provides a more accurate detection probability. The theoretical expression is also drawn according to (3.2.3) in order to verify the efficiency of the simulations. The theoretical analysis and the simulation results match for the three different probabilities of false alarm. Figure 3.4 demonstrates the ROC curve. We can observe that as the PNR becomes larger, the probability of detecting the PU for a small P_{FA} is much higher. Moreover, as it is aimed, the P_D remains high for low P_{FA}.

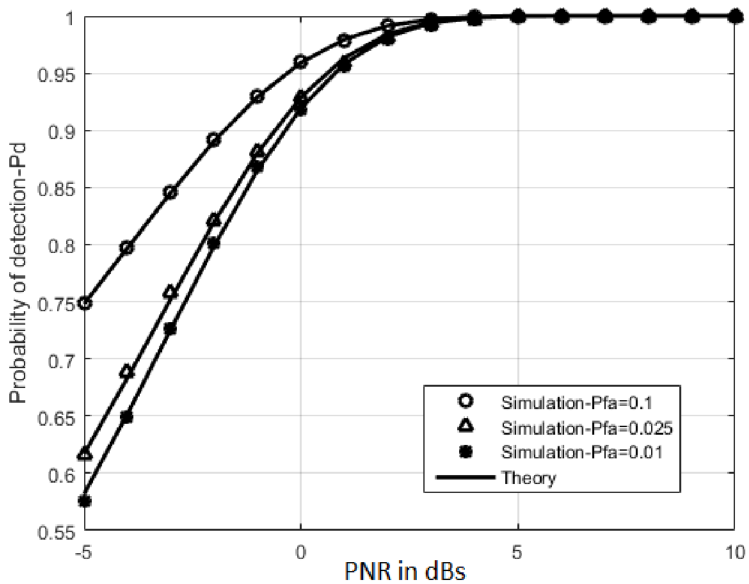


Figure 3.3: Detection Probability with respect to PNR for fixed Probability of False Alarm

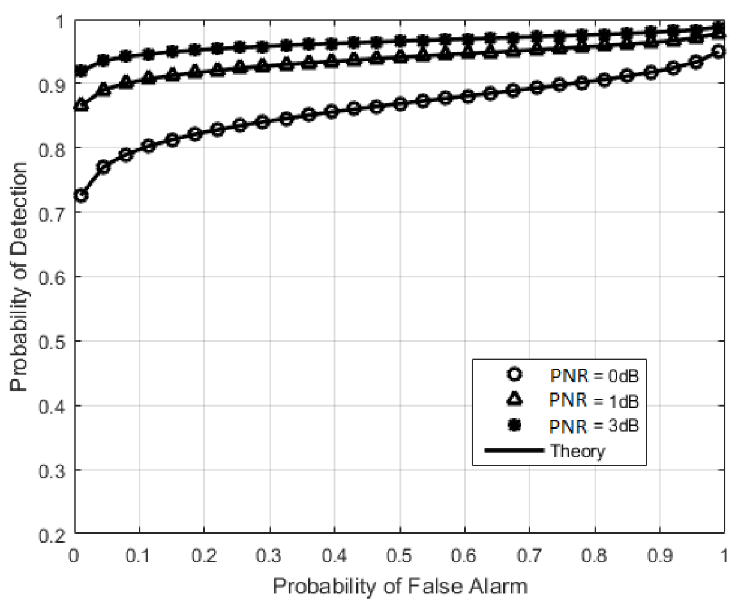


Figure 3.4: Receiver Operating Characteristics curve for fixed values of PNR

Blocking Probability and Throughput

In Figure 3.5 the blocking probability is derived versus the PNR values. The curve drawn in the simulation results shows that as the signal power becomes more intense the probability of the channel being blocked increases. Taking into account that the same performance was displayed in the detection probability, it is plausible for the blocking probability to perform similarly as expected from (3.2.6). The blocking probability reflectes the cases when the WRAN operation on channel originally set in DFH is blocked. In the case that a channel in the set of operating channels of DFH operation is deemed blocked, the WRAN continues the data transmission to a back-up channel [3].

A WRAN performs data transmission only if during the sensing period the PU was decided to be idle. Figure 3.6 illustrates the simulated total throughput in the DFH with 3 channels compared to the theoretical expression derived in (3.2.12). In Figure 3.6a the throughput is evaluated with respect to the PNR values and it is shown that it decreases as the PNR rises. The reason behind that can be seen more clearly in Figure 3.6b where the throughput is compared to the blocking probability. As expected as the blocking probability becomes larger the throughput is reduced. An increase of the blocking probability translates into increase of the probability of detection or false alarm.

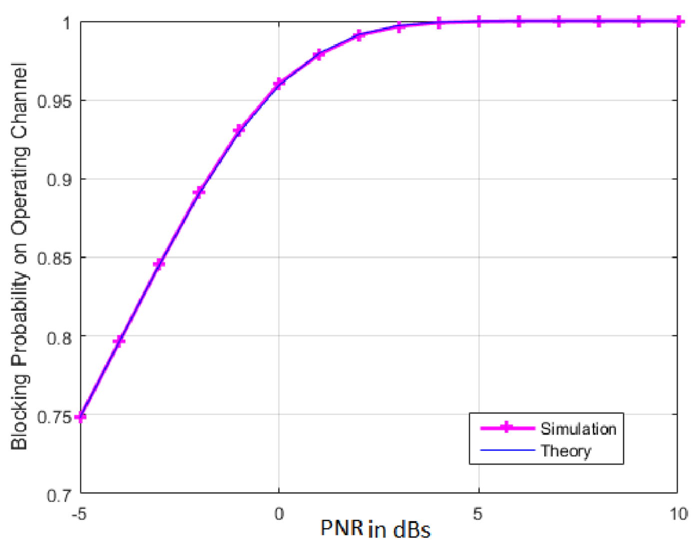
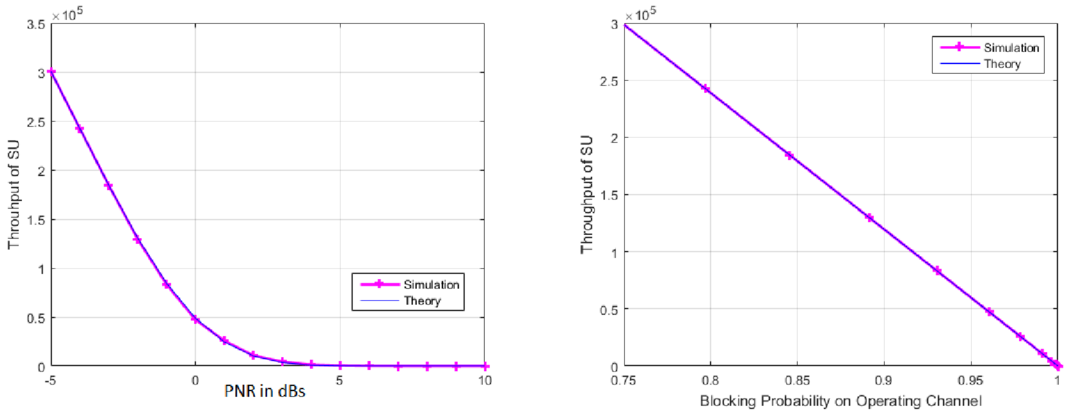


Figure 3.5: Blocking probability for a specific channel in DFH



(a) Throughput vs PNR in DFH

(b) Throughput vs Blocking probability in DFH

Figure 3.6: Total throughput of the SU in the DFH technique

Number of Channels in the DFH Operation

In order to show the effect of the blocking probability on the performance of DFH, the system was simulated for more than 3 channels. The procedure of implementing the DFH with larger number of WRANs/channels, is similar to the case in our system model. In Figure 3.7, the blocking probability is evaluated for 3 different values of PNR with respect to the number of channels. The blocking probability was calculated with respect to the various number of channels for fixed values of PNR $-0.7dBs$, $-0.8dBS$ and $0.9dBs$. The overall blocking probability, observing each PNR fixed value separately has a similar behavior as the number of channel increases. The reason for that, is that the probability of a channel included in the operating set in DFH being blocked does not depend on the number of channels the set consists of.

Equivalent to the blocking probability, the throughput was evaluated for the same range of channel numbers. In Figure 3.8 the throughput is evaluated for 3 different values of PNR with respect to the number of channels. For all the cases, we see that the throughput does not reach its highest value. This is due to the fact that for these PNR values, as demonstrated in Figure 3.7, the blocking probability is high. Hence, the throughput is affected by the blocking probability. Of course, an increase of the number of channels leads to more data transmission on the DFH for the SUs as indicated by (3.2.12).

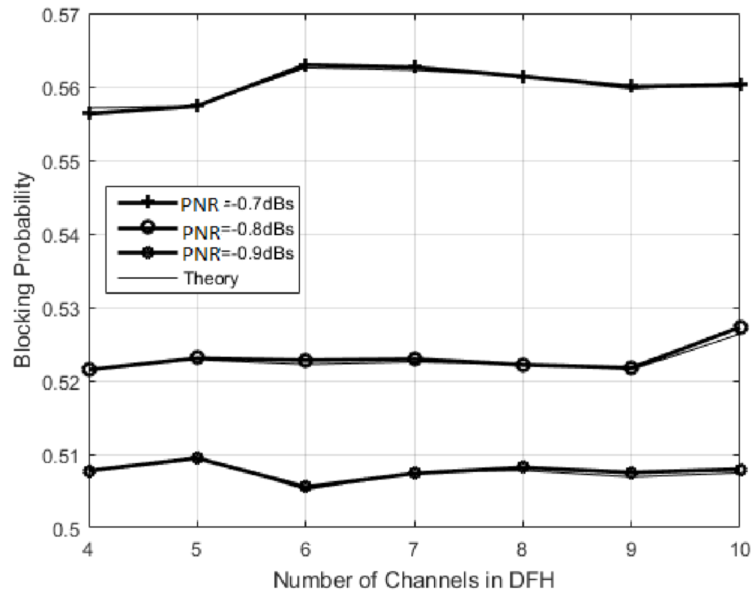


Figure 3.7: Blocking Probability

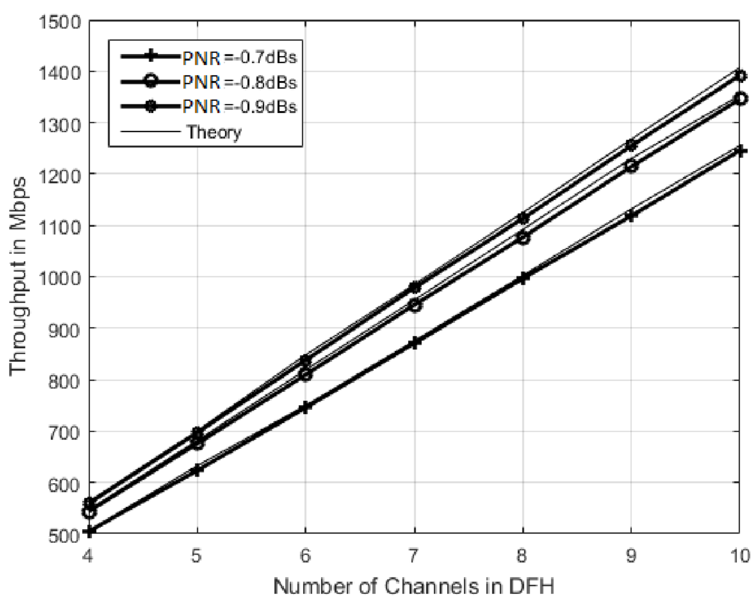


Figure 3.8: Throughput

3.3 Energy Ratio Algorithm

In [7], the Energy Ratio (ER) algorithm is presented for spectrum monitoring in cognitive radio systems. A system model is introduced for CRs where the SU utilizes OFDM as the physical transmission technique. In order to monitor the spectrum, a frequency domain based approach is presented with the addition of an extra feature to the common OFDM signal that would provide the monitoring factor.

3.3.1 Theoretical Results

OFDM Frame in ER

At the transmitter side of the SU, the data inserted is segmented into blocks. Thereupon, the input stream is modulated into complex symbols. Before the IFFT expained in the block diagram of the OFDM system, a number of tones N_{RT}, are reserved for the purpose of spectrum monitoring. The proposed OFDM frame in [7] is demonstrated in Figure 3.9. The reserved tones in the OFDM frame are allocated dynamically in order to span all the band. All the SUs are assumed to know this scheduling in order to be able to extract the reserved tones for monitoring.
Passing through the OFDM symbols, the position of the N_{RT} changes by Δr. The alteration of the

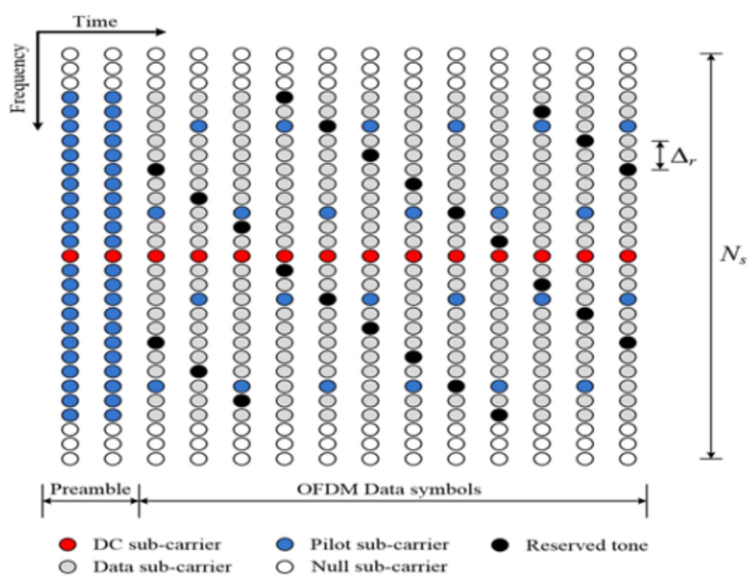


Figure 3.9: OFDM frame as shown in [7]

reserved tones across the OFDM is crucial so the channel is mitigated and the reserved tones do not fall into primary user holes. These PU holes could be an outcome from the PU using also OFDM for the data transmission. Thus, it would not be feasible to apply the ER for the spectrum monitoring. However, if the PU uses a single carrier modulation like QAM or PSK, this effect will not appear since the PU signal would have a flat spectrum through the entire band.

ER Algorithm

Based on this OFDM frame and assuming that the PU appears at some point during the monitoring phase, the metric value for the evaluation of the ER is determined. Afterwards, at the secondary receiver we remove the cyclic prefix and before the DFT the reserved tones from two different OFDM symbols are combined to form a sequence of complex symbols. In order to detect a PU signal, two equally sized windows slide through the sequence. Afterwards, the energy of the symbols in each window is evaluated and the ratio of the two energies is used for PU detection. According to the analysis in [7], the decision making variable is given by (3.3.1) where N represents the number of samples of each window, U_k is the energy of the second window, and V_k is the energy of the first window.

$$X_k = \frac{U_k}{V_k} = \frac{\sum_{i=N+k}^{2N+k-1} |Z_i|^2}{\sum_{i=k}^{N+k-1} |Z_i|^2} \qquad k = 1, 2, 3, ... \tag{3.3.1}$$

In this mathematical expression, N represents the number of the samples in the window. The parameter Z_i is the i^{th} value in the sequence and U_k, V_k are the energy of each window. During the monitoring phase, the SU at the receiver side evaluates this ratio. Once this metric value exceeds a predefined threshold then it is assumed that there has been a change on the energy of the reserved tones in the sequence. Therefore, this change will indicate the presence of the PU.

The performance of the ER algorithm will be evaluated for a AWGN channel. In order to model the PU activity, the ON/OFF model is implemented as presented formerly. The purpose is to express the probabilities of detecting the PU and the false alarm probability. According to [7], the theoretical expressions for the detection and false alarm probabilities are given in (3.3.2),(3.3.3) respectively.

$$P_D = Prob[X > \gamma|H_1] = 1 - I_{\frac{\sigma_v^2\gamma/\sigma_u^2}{1+\sigma_v^2\gamma/\sigma_u^2}}(N, N) \tag{3.3.2}$$

$$P_{FA} = Prob[X > \gamma|H_0] = 1 - I_{\frac{\gamma}{1+\gamma}}(N, N) \tag{3.3.3}$$

$$\gamma = \frac{I_{1-P_{FA}}^{-1}(N, N)}{1 - I_{1-P_{FA}}^{-1}(N, N)} \tag{3.3.4}$$

Using the previously introduced binary hypothesis, H_1 represents the case that the PU is active and H_0 the case where the PU is idle. Thus, the probabilities are drawn comparing the decision metric X with the threshold γ. The $I_b(N, N)$ is the incomplete beta function with parameters b and N. Consequently, $I_b^{-1}(N, N)$ is the inverse incomplete beta function with the same parameters. The samples contained in the second window have a variance σ_u^2 and the samples of the first window have a variance σ_v^2. The term PNR is represented as $\sigma_u^2 = \sigma_v^2 + PNR\sigma_v^2$.

3.3.2 Simulation Results

At this point, we examine the performance of the the energy ratio algorithm using simulation results. The theoretical expression according to (3.3.2), is derived in order to verify the accuracy of our simulations. The OFDM model for the SU data transmission and QAM modulation for the PU data transmission are applied. The window size for the evaluation of the metric value for the detection is set to $N = 32$ and $2RTs$ are reserved for the spectrum monitoring. The energy ratio algorithm is simulated for a fixed secondary to noise power $SNR = 5dB$. Therefore, the Secondary-to-Primary power (SPR) at the secondary receiver and PNR are determined according to the SNR value. In Figures 3.10,3.11, the results for the evaluation of detection probability are included. The ROC curve is demonstrated with respect to fixed SPR values in Figure 3.9 and with respect to SPR for different probabilities of false alarm in Figure 3.10. In both figures, it is illustrated that for lower SPR values the performance of ER is improved. The reason for this outcome is that a high value of SPR leads to a lower value of primary power. Hence, the detection of the PU signal is less effective when the signal power gets weak (the RTs contain only the PU signal).

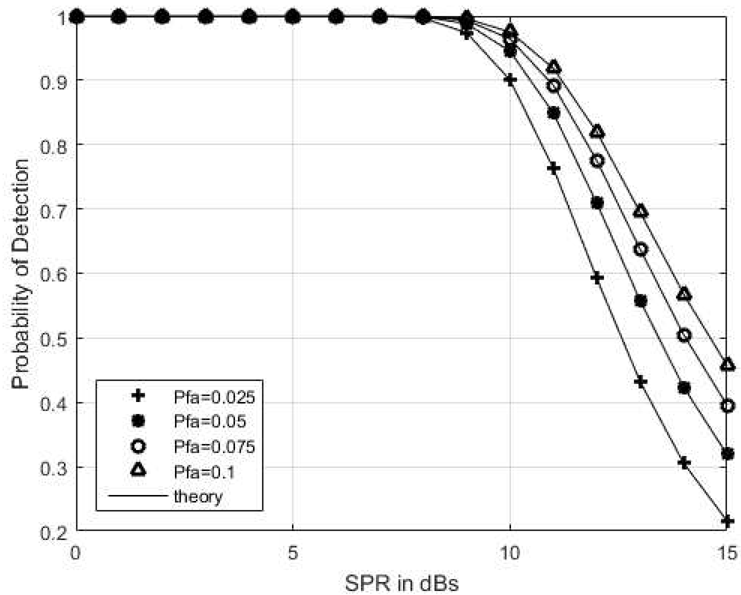


Figure 3.10: Detection Probability with respect to SPR for fixed Probability of False Alarm

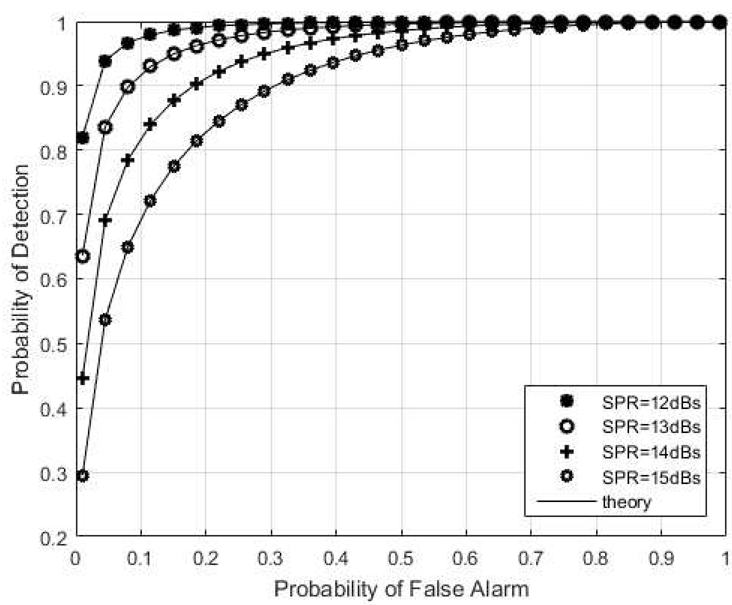


Figure 3.11: ROC for fixed values of SPR

3.4 Performance of Proposed DFH-ER Algorithm

3.4.1 Theoretical Results

Algorithm 1 demonstrates the implementation of the advanced scheme that shall combine the DFH and the ER algorithm. In the enhanced DFH scenario, during the operation of a SU spectrum monitoring will also take place. Before the operation period is terminated, the WRAN performs spectrum sensing in the next intended channel. Therefore, we have a combination of spectrum monitoring in the channel where data transmission takes place and spectrum sensing in the upcoming channel. Initially, information is collected from the database service . Afterwards, the set of operating channels S_{OP} in the DFH is determined. Hence, the remaining available channels are set as back-up channels C_{BU}. It is assumed that the Frequency Assignment Problem and the hopping pattern are known and controlled by a unit. Finally, the enhanced DFH method begins its operation according to Algorithm 1 for a specified time range of $T_r secs$. The DFH-ER operation is illustrated in Figure 3.12.

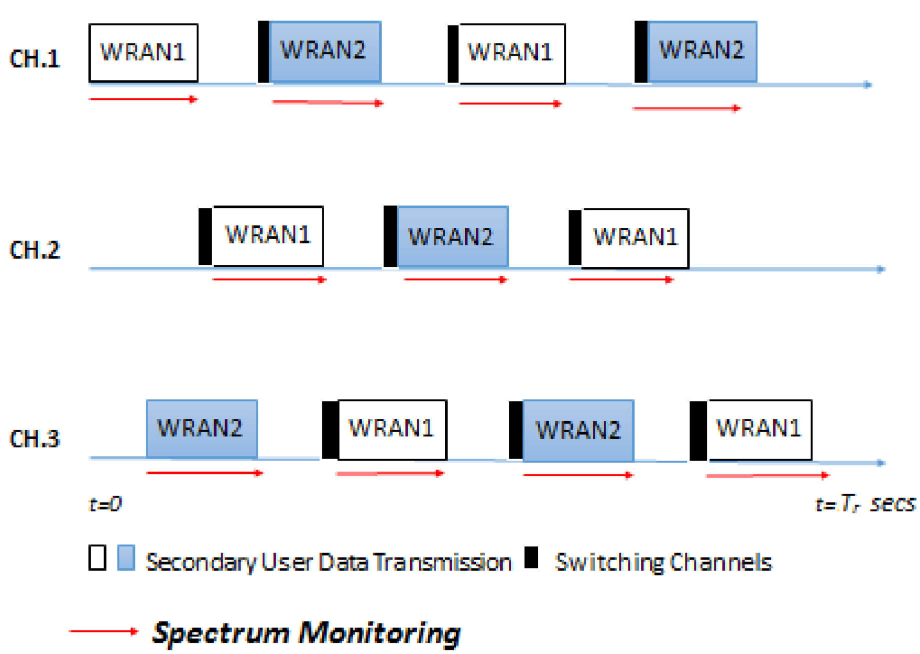


Figure 3.12: Proposed DFH-ER scheme

Algorithm 1 Enhanced DFH operation

```
procedure DFH-ER(N, S_OP)
    S_OP ← Operating Channels
    C_BU ← Back-UP Channels
    N_w ← Number of WRANs
    time ← WRANi initiates data transmission
    while time < T_r do                                          ▷ specified time range
        for <each channel in the set> do
            <Data Transmission in current S_OP>                  ▷ Useful Thoughput of SU
            <Spectrum Monitoring in current S_OP>                ▷ Performance of ER
            if PU = active then
                if detection = accurate then
                    C_BU ← move to                               ▷ Avoid Interference
                else
                    S_OP ← continue to
                end if
                close;
            end if
            close;
            if data = 0.1s until end then
                Next S_OP ← Spectrum Sensing                     ▷ Performance of Spectrum Sensing
                if PU = active then
                    if detection = accurate then
                        C_BU ← move to
                    else
                        Next S_OP ← move to
                    end if
                    close;
                end if
                close;
            end if
            close;
            Increase time by OP, sensing time and switching time
        end for
        Increase Hopping Cycle
    end while
end procedure
```

3.4.2 Simulation Results

The interference caused in the case that the two users coexist in an operating channel is examined when the conventional DFH scenario is implemented along with the proposed DFH-ER scheme. A critical measurement that would provide us a valuable insight on the interference caused is the *useful throughput* of the SU during the data transmission on the operating channel. By the term useful throughput, we refer to the amount of data received at the secondary antennas without error. The PU reappearance is examined at an early, middle, late point of the information transmission. For a fixed SPR of $0dBs$, the useful throughput for both schemes will be evaluated. The results are drawn with respect to the various values of SNR which represents the secondary-to-noise power at the secondary receiver. The useful throughput of the SU data transmission without PU activity is as well evaluated in order to represent the ideal case of no interference. The data transmission follows the OFDM system introduced formerly in both schemes.

To begin with, the performance of the SU data transmission during the DFH operation is illustrated in Figure 3.13. The useful throughput of the SU is affected by the PU activity. As the incumbent user becomes active in an earlier stage, the useful throughput is decreased since the two users interfere for more time. On the contrary, the results from the enhanced DFH-ER scheme in Figure 3.13 demonstrate that the useful throughput is maintained unaffected by the PU appearance. For all the different moments that the incumbent signal is inactive the ER is efficient. Hence, the interference is avoided and the incumbent users are protected as well as reliable data transmission is provided to the WRANs.

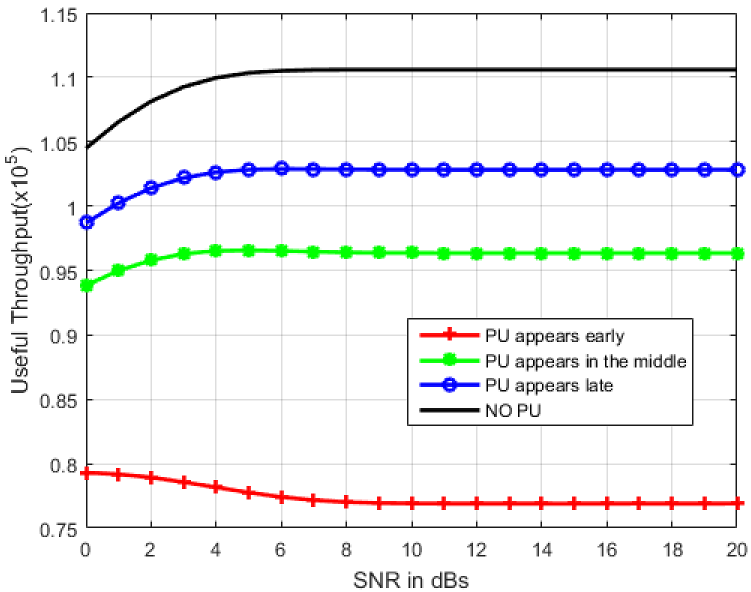


Figure 3.13: Useful Throughput for the conventional DFH scheme

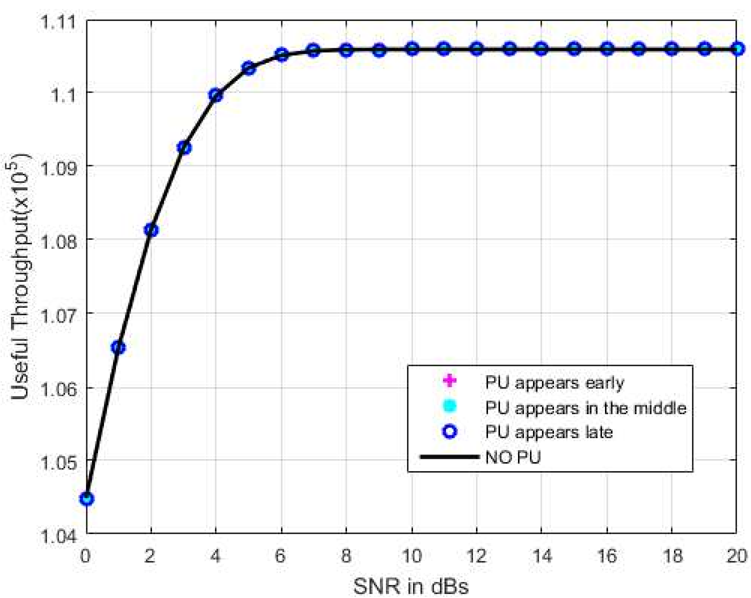


Figure 3.14: Useful Throughput for the proposed DFH-ER scheme

3.5 Conclusions

In this chapter, we introduced our system model over AWGN channel. The operation of DFH was evaluated. The detection and false alarm probabilities were presented for the ED while the blocking probability and throughput were derived. Based on that, simulations were developed demonstrating the performance of DFH. Afterwards, the ER was examined for the spectrum monitoring and the detection probability as well as the ROC were drawn. Finally, the proposed DFH-ER scheme was presented. The detailed algorithm featuring the detailed procedure of the DFH-ER method was shown. The simulation results of the DFH-ER illustrated the efficiency of the introduced method compared to the conventional DFH, as far as the reliability of the WRAN data transmission is concerned.

Chapter 4

Performance of Cognitive Radio Systems over Ricean Fading Channel

4.1 Introduction

The system model is introduced for the case of a fading channel. The modeling of fading channel was presented in chapter 2. In the current theoretical analysis for the implemented techniques, the Ricean fading channel is applied.

Similar to the system model over AWGN, we will provide expressions for the detection probability of ED in DFH over Ricean fading channel. Based on that, the DFH is simulated for the fading environment. Moreover, the analysis presented in [7] for fading channels is provided and is extended for the case of the Ricean channels. Ultimately, the DFH-ER proposed scheme is implemented over a Ricean fading channel demonstrating the effect of the distortion caused by fading on SU useful throughput.

4.2 Dynamic Frequency Hopping Performance

4.2.1 Theoretical Results

The alteration on the DFH operation with the addition of a fading channel would be initially on the performance of the energy detection for spectrum sensing. In order to verify the efficiency of the energy detector under Ricean fading, the probability of detection has to be derived. Initially, the PDF of the PNR γ in a Rician distribution would be according to [33] :

$$f(\gamma) = \frac{\kappa+1}{\overline{\gamma}} e^{-\kappa - \frac{(\kappa+1)\gamma}{\overline{\gamma}}} I_o\left(2\sqrt{\frac{\kappa(\kappa+1)\gamma}{\overline{\gamma}}}\right), \qquad \gamma \geq 0 \tag{4.2.1}$$

where I_o represents the modified Bessel function of the first kind of order zero. Parameter $\overline{\gamma}$ represents the average PNR of the received signal which is equal to the expected value of the channel gains multiplied by the PNR γ: $\overline{\gamma} = E[\sigma_H^2 \gamma]$. Therefore, the detection probability of the incumbent user after comparing the metric value representing the energy of the received signal with the threshold λ , in the case that the channel is modeled as Ricean is:

$$\overline{P}_{dRic} = Q\left(\sqrt{\frac{2\kappa\overline{\gamma}}{\kappa+1+\overline{\gamma}}}, \sqrt{\frac{\lambda(\kappa+1)}{\kappa+1+\overline{\gamma}}}\right) \tag{4.2.2}$$

In chapter 2, the Rayleigh fading channel was present as a special case of the Ricean channel when the $\kappa-factor$ is equal zero. Therefore, the theoretical analysis for ED over Rayleigh is additionally provided in order to be able to verify through simulations the aforementioned statement. Following the analysis introduced in [33], in the case of a Rayleigh fading channel the PNR PDF will be expressed according to (4.2.3). Therefore, the theoretical expression for detection probability in a Rayleigh fading is determined in (4.2.4). The threshold used for the metric value is represented by λ, the average PNR by $\overline{\gamma}$ and $u = TB$ stands for the time-bandwidth product.

$$f(\gamma) = \frac{1}{\overline{\gamma}} e^{-\frac{\gamma}{\overline{\gamma}}} \tag{4.2.3}$$

$$P_{dRay} = e^{-\frac{\lambda}{2}} \sum_{n=0}^{u-2} \frac{1}{n!}\left(\frac{\lambda}{2}\right)^n + \left(\frac{1+\overline{\gamma}}{\overline{\gamma}}\right)^{u-1}\left[e^{-\frac{\lambda}{2(1+\overline{\gamma})}} - e^{-\frac{\lambda}{2}} \sum_{n=0}^{u-2} \frac{1}{n!} \frac{\lambda\overline{\gamma}}{2(1+\overline{\gamma})}\right] \tag{4.2.4}$$

Simulation Results

Based on the DFH scenario implemented thus far, its performance will be evaluated under the presence of Ricean fading channel. Initially, the probability of detection is derived with respect to the various values of primary-to-noise ratio in Figure 4.1. The theoretical expression in (4.2.2) is drawn in order to verify the accuracy of our simulations. In the background information in the section on fading channels, it was stated that if the $\kappa - factor$ is reduced to zero then we have a Rayleigh fading channel. In order to confirm this conclusion, in Figure 4.1 the special cases of Rayleigh and AWGN are simulated. The curves in Figure 4.1, illustrate the performance improvement as κ increases since the presence of LOS provides a more reliable system. Furthermore, as expected, the detection probability has the optimal performance over AWGN channel which is also derived to stand as an upper bound. Figure 4.2 demonstrates the ROC curve for the energy detection. The same conclusion can be seen from these results.

In addition to the detection probability and the ROC curve, similar to the system model for AWGN, the blocking probability and the throughput are derived. According to the improved probability of detection over higher κ values, the blocking probability will be increased. Consequently, the throughput of a WRAN in the specific channel that is sensed would be decreased since higher blocking probability would lead to the SU having to switch to a back-up channel. In Figure 4.3 the blocking probability results are shown where in Figure 4.4 the results for the throughput evaluation are shown. As we can observe from these results for the throughput, the theory and simulation curves are closely matched. The difference between these results is due to the number of hopping cycles that are performed in the simulations, compared to the fixed number used in theory(eq.(3.2.12)).

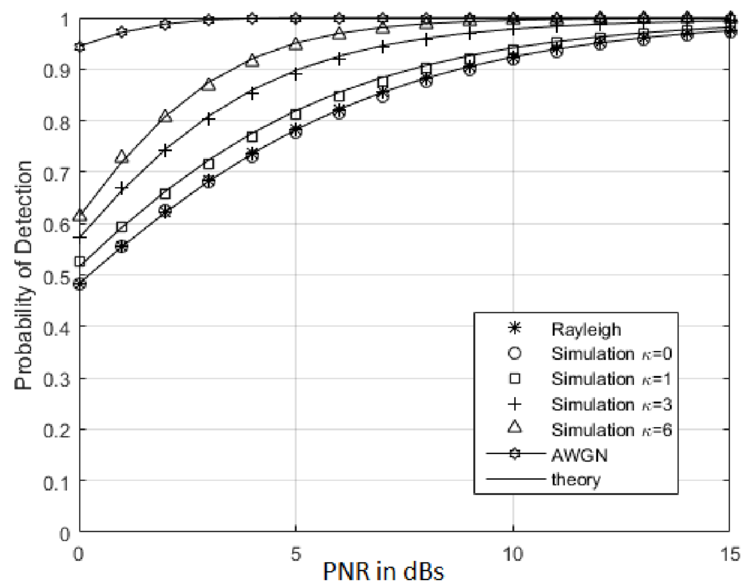


Figure 4.1: Detection Probability in DFH over Ricean fading channel

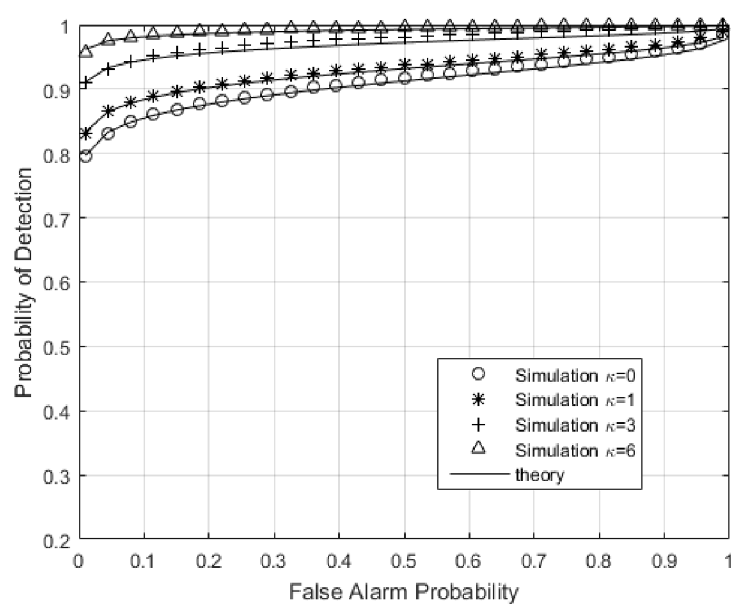


Figure 4.2: Receiver Operating Characteristics in DFH over Ricean fading channel

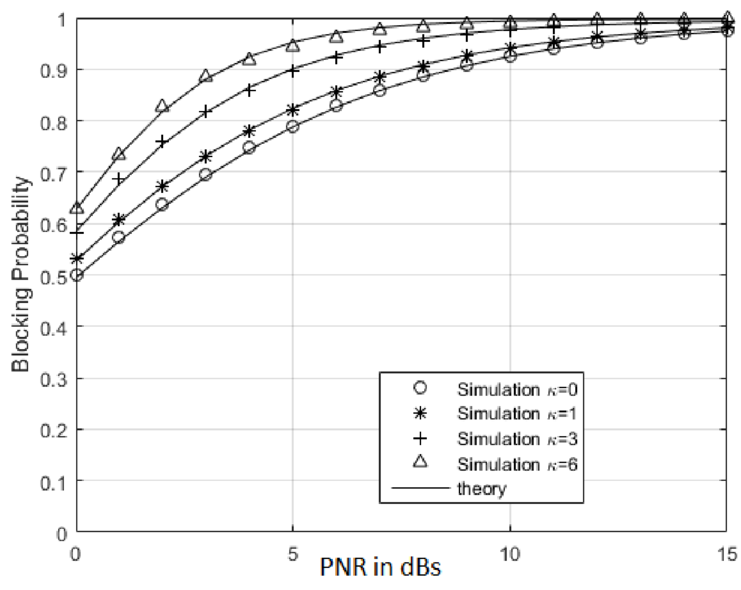


Figure 4.3: Blocking Probability in DFH over Ricean fading channel

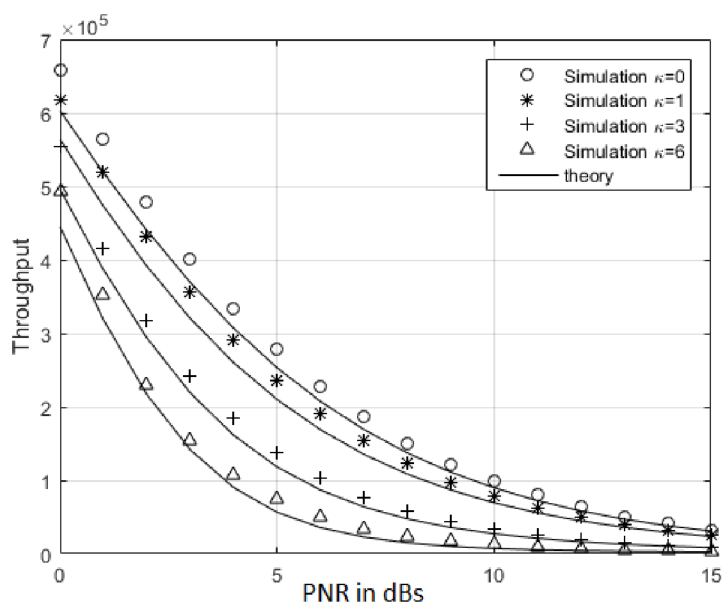


Figure 4.4: Throughput of SU in DFH over Ricean fading channel

4.3 Energy Ration Algorithm

4.3.1 Theoretical Results

As indicated in [7], the secondary and primary signals are combined at the receiver antenna and then processed as one received stream. In the case that r_i^k, $i = 0, 1, ..., N_{RT} - 1$ are the reserved tone indices for the k^{th} OFDM symbol then the j^{th} reserved tone is represented according to:

$$\begin{aligned} Y(r_j^k) &= H_{ps}(r_j^k)X_p(r_j^k) + H_{ss}(r_j^k)X_s(r_j^k) + n(r_j^k) \\ &= H_{ps}(r_j^k)X_p(r_j^k) + n(r_j^k) \end{aligned} \tag{4.3.1}$$

where $H_{ps}(r_j^k)$, $H_{ss}(r_j^k)$ are the frequency domain responses of the channels from PU transmitter antenna to SU receiver antenna and from SU transmitter antenna to SU receiver antenna, respectively. Moreover, $X_p(r_j^k)$, $X_s(r_j^k)$ are the PU and SU transmitted symbols. The PU to SU channel impulse response h_{ps} is modeled as a Finite Impulse Response (FIR) filter. The FIR filter has N_g taps and the channel gain of each tap is $h_{ps}(l)$ for $l = 0, 1, ..., N_g - 1$. Thereupon, the sum of the channel tap powers for the general case of a Ricean fading channel where the mean is a non zero constant parameter is expressed as:

$$\sigma_{HRic}^2 = \sum_{l=0}^{N_g-1} E[|h_{Ric}(l)|^2] \tag{4.3.2}$$

$$h_{Ric} = h_k + h_{ps}(l) \tag{4.3.3}$$

In [7], it is stated that the analysis presented thus far for the ER algorithm in a fading channel can behave as well as the one for a AWGN channel. However, the detection of the PU will now depend also on the channel profile and is defined as:

$$\begin{aligned} P_D &= Prob[X > \gamma | H_1] = 1 - I_{\frac{\sigma_v^2 \gamma/\sigma_u^2}{1+\sigma_v^2\gamma/\sigma_u^2}}(N, N) \\ &= 1 - I_{\frac{\gamma/(1+\sigma_H^2 PNR)}{1+\gamma/(1+\sigma_H^2 PNR)}}(N, N) \end{aligned} \tag{4.3.4}$$

Simulation Results

The detection probability with respect to the SPR values and equivalently for the ROC curve with respect to the false alarm probability values, is evaluated for the system model under Ricean fading. Our initial goal in these simulation results, would be to verify the relation among the AWGN, Rayleigh and Ricean channels as demonstrated for the DFH scheme. For the Ricean fading channel, the channel profile is expressed by (4.3.2), (4.3.3) and we can provide the channel profile for the Rayleigh channel by setting h_k in (4.3.3) equal to zero.

In Figure 4.5, the detection probability is simulated for four different values of κ. In the curves included in the figure it is demonstrated that the special case of $\kappa = 0$ matches the one for Rayleigh. In addition, the AWGN case is added. In these simulation results we are able to verify the conclusion provided in [7] that the performance of ER in not degraded severely due to the fading effect. At last, the ROC is derived and shown in Figure 4.6 only for the cases of $\kappa = 1, 3, 10$. As desired, the requirement for high values of detection probability in low false alarm, in addition to the performance improvement due to the increase of κ are observed.

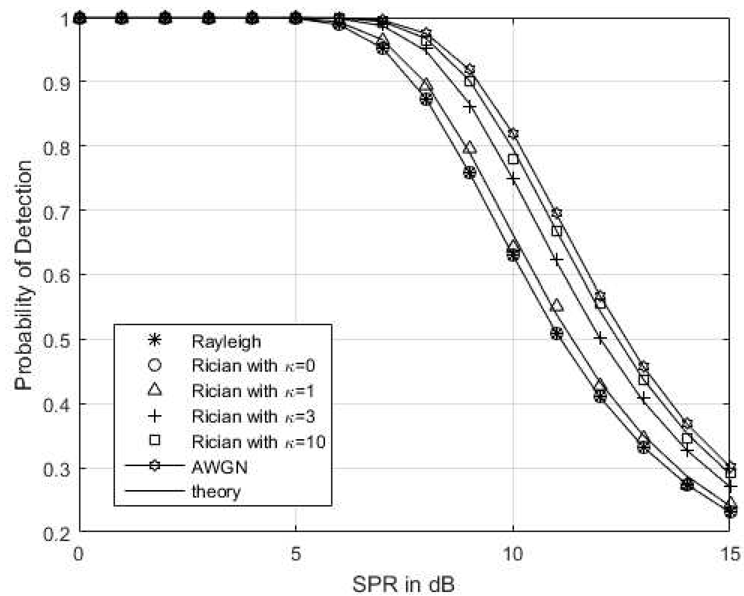


Figure 4.5: Detection probability for ER algorithm

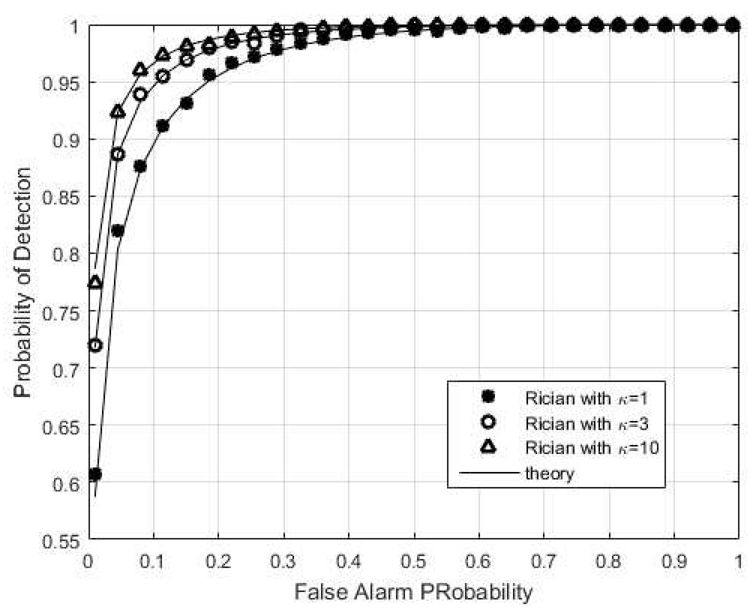


Figure 4.6: Receiver Operating Characteristics for ER algorithm

4.4 Proposed DFH-ER Scheme

Simulation Results

According to algorithm 1 introduced formerly, the DFH-ER scheme is now implemented for a Ricean fading channel. Similar to the system model for AWGN and having the results for DFH and ER algorithm on Ricean fading channel we shall evaluate the useful throughput of a WRAN when the DFH-ER is employed.

To begin with, the performance of the SU data transmission during the DFH operation is illustrated in Figure 4.7. The useful throughput of the SU is affected by the PU activity similar to the AWGN case. The moment of the PU appearance once more seems to have a great impact on the reliability of the data transmission. On the contrary, the performance of the DFH-ER algorithm in Figure 4.8 maintains the useful throughput unaffected by the PU appearance at any time instant. Even though the useful throughput is degraded due to the effect of fading (compared to Figure 3.14 for AWGN), the DFH-ER outperforms the conventional DFH.

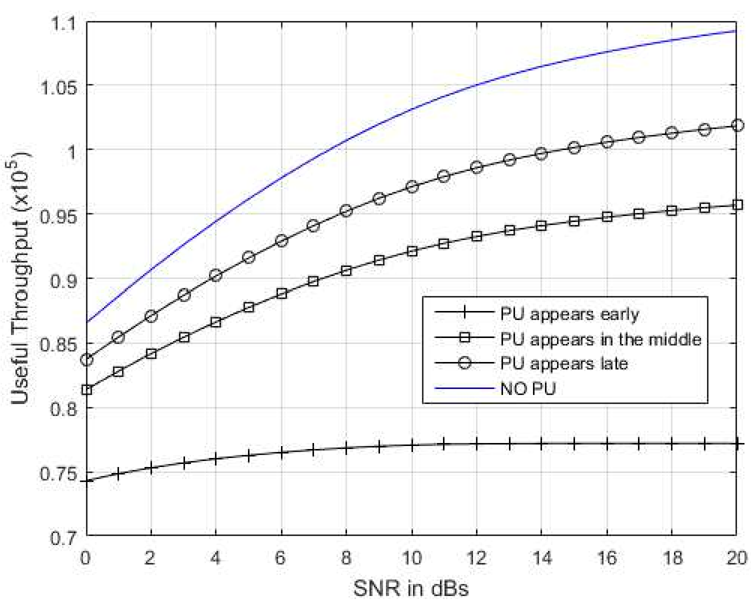


Figure 4.7: Useful Throughput for the conventional DFH scheme over Rician fading channel

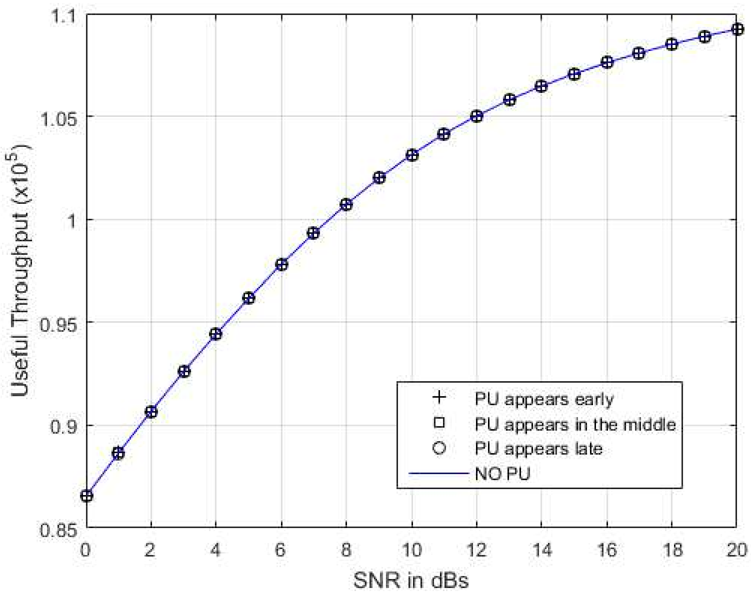


Figure 4.8: Useful Throughput for the proposed DFH-ER scheme over Rician fading channel

4.5 Conclusions

The influence of fading was investigated thoroughly in this chapter. Initially, the DFH was analyzed and simulated under the effect of a Ricean fading channel. In the derivation of the detection probability, we demonstrated the behavior of ED over various types of channels. Afterwards, the ER algorithm was reviewed for the same case. The extended simulation results on the three types of channels showcased the performance of the algorithm in each case. In the final step, we implemented our proposed DFH-ER scheme for a system model over Ricean fading channel. In conclusion, the DFH-ER was proven to operate more efficiently than DFH.

Chapter 5

Performance of Cognitive Radio Systems in MIMO Fading Channels

5.1 Introduction

The implementation of multiple antennas in CRs has been extensively researched in literature [34][54]-[58], as an efficient way of optimizing the operation of the CR. Therefore, multiple antenna SUs can be used for reliable data transmission and spectrum sensing [59]. Hence, in order to overcome the distortion due to the effect of fading on the performance of the proposed DFH-ER the implementation of a MIMO system is analyzed (MIMO introduced for IEEE standard 802.22 in 2015 amendement [60]). The DFH-ER scheme is simulated as developed thus far. For the SU data

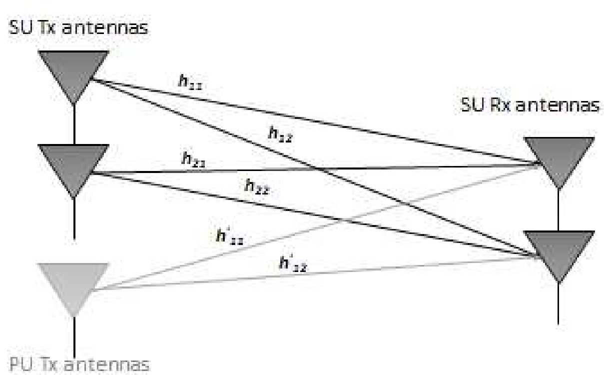


Figure 5.1: 2x2 MIMO extension for the roposed DFH-ER scheme

transmission a $2x2$ and a $4x4$ antenna configurations will be applied according to the MIMO system model described in chapter 2. On the contrary, for the PU a SIMO scheme will be maintained for simplicity, following the structure of SIMO schemes introduced in the background information. The $2x2$ MIMO system for the SU and the $1x2$ SIMO for the PU are illustrated in Figure 5.1. In the presented figure, h_{sj} represents the channel gain between SU transmit antenna *s* and receive antenna *j*. Accordingly, $\grave{h}_{pj}$ represents the channel gain between PU transmit antenna *p* and secondary receive antenna *j*. It is critical to examine the way the spectrum sensing and monitoring are applied for the MIMO case and evaluate the operation of DFH, ER, proposed DFH-ER algorithm. The performance of the ED and ER will be evaluated over a Ricean channel for MxM MIMO with M secondary antennas and a single primary transmit antenna.

5.2 Performance of Dynamic Frequency Hopping

5.2.1 Theoretical Results

The ED for spectrum sensing is used for a SIMO system, since the band under inspection is not utilized for SU data transmission. Therefore, only the presence of PU is examined. According to [54], the maximum ratio processing is applied for ED in systems with receive diversity (SIMO). The received signal at the secondary receive antenna has the accumulated transmitted primary signals through the M Ricean channels [54] and according to that the metric value is determined [35]:

$$T_M = \sum_{n=1}^{N_s} |y_M(t)^2| = \sum_{n=1}^{N_s} \sum_{i=1}^{M} |y(t)|^2 \tag{5.2.1}$$

Consequently, the metric value for the SIMO case is the accumulated energy of each received signal at the secondary receive antennas. Hence, for the M receive antennas we define the total PNR in (5.2.1) that will assist in determining the probability of detecting the PU signal.

$$\gamma_M = \sum_{i=1}^{M} \overline{\gamma} = M\overline{\gamma} \tag{5.2.2}$$

Thus, having formed the decision metric we apply the energy detection in order to detect the PU signal. The evaluation of the detection probability will be altered by the increase of the $\overline{\gamma}$ to γ_M [54]. Consequently, (4.2.2) can be modified to incorporate the SIMO implementation as:

$$\overline{P}_{dRicM} = Q\left(\sqrt{\frac{2\kappa\gamma_M}{\kappa+1+\gamma_M}}, \sqrt{\frac{\lambda(\kappa+1)}{\kappa+1+\gamma_M}}\right) \tag{5.2.3}$$

5.2.2 Simulation Results

In the evaluation of the DFH scheme, the efficiency of the ED is examined. The overall DFH scenario is simulated for the SISO, $2x2$ MIMO and $4x4$ MIMO system. The probability of detection is simulated for the three cases in order to showcase the performance improvement from the SIMO implementation compared to the SISO over Ricean fading channel. In the results introduced in chapter 4 on the SISO system model implementation over Ricean fading model, the detection probability was analyzed for various values of $\kappa - factor$. In the current results, we define a fixed value to $\kappa = 3$ as a middle case in order to demonstrate the impact of the MIMO implementation. Moreover, an *optimal detector* is assumed for the simulations. According to [59], an ED is optimal when the SU receiver knows the channel gains, noise variance and PU signal variance.

Figure 5.2 illustrates the detection probability for fixed $P_{FA} = 0.1$ with respect to the PNR variation. The values of P_D are improved significantly as the number of secondary receive antennas grows, since such an increase provides receive diversity. Consequently, the information sent from the PU transmit antenna is passed through more channels. Equivalently, the ROC curve is presented in Figure 5.3 in order to verify the augmentation provided by the SIMO implementation. In both figures as a bench mark, we plot the analytical performance of the system using (5.2.3).

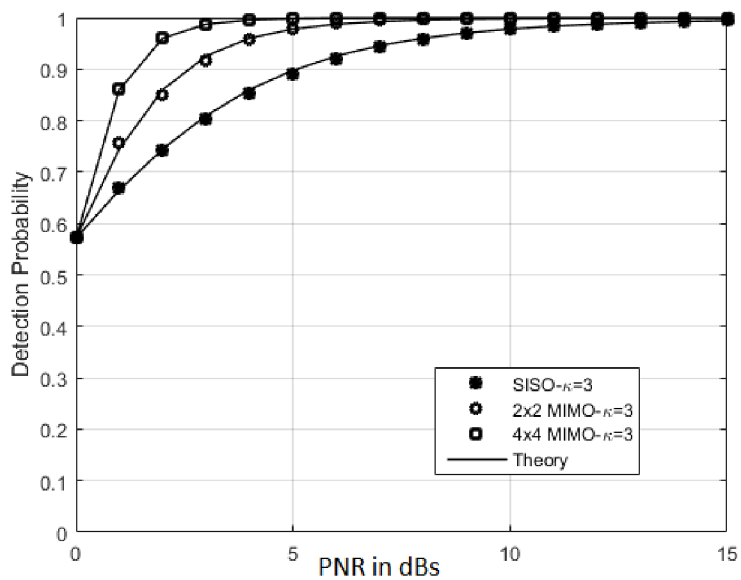


Figure 5.2: Detection Probability with respect to PNR for fixed Probability of False Alarm

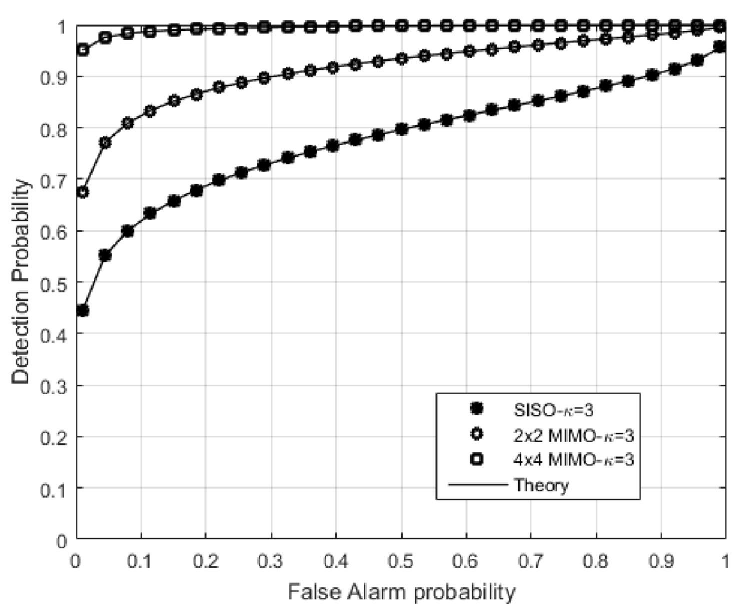


Figure 5.3: ROC for fixed value of PNR

5.3 Performance of Energy Ratio

5.3.1 Theoretical Results

In addition to the ED, the energy ratio algorithm shall be adjusted to the MIMO system. As introduced in [7] and discussed thus far, the spectrum monitoring is performed during the SU data transmission. Therefore, the MIMO MxM is implemented. Specifically, for each OFDM symbol now there will be M sets of reserved tones providing a total of $M * N_{RT}$. Thereupon, the decision metric value and theoretical expression for detection probability need to be evaluated for the MIMO scheme. Both expressions are represented as (3.3.1) and (4.3.4) accordingly, where now the number of samples in each window will be $N_M = M * N$ resulting in:

$$X_k = \frac{U_k}{V_k} = \frac{\sum_{i=N_M+k}^{2N_M+k-1} |Z_i|^2}{\sum_{i=k}^{N_M+k-1} |Z_i|^2} \qquad k = 1, 2, 3 \tag{5.3.1}$$

$$\begin{aligned} P_D &= Prob[X > \gamma|H_1] = 1 - I_{\frac{\sigma_v^2\gamma/\sigma_u^2}{1+\sigma_v^2\gamma/\sigma_u^2}}(N_M, N_M) \\ &= 1 - I_{\frac{\gamma/(1+\sigma_H^2 PNR)}{1+\gamma/(1+\sigma_H^2 PNR)}}(N_M, N_M) \end{aligned} \tag{5.3.2}$$

5.3.2 Simulation Results

After the evaluation of the conventional DFH scheme with the MIMO implementation, the ER algorithm is as well simulated for this case. Equal to the results generated for DFH, the detection probability of the ER for spectrum monitoring is presented for the MIMO scheme. In Figure 5.4, P_D is derived for fixed probability of false alarm 0.1, SNR $5dBs$ for various values of SPR. As shown, the performance of the spectrum monitoring technique is enhanced by the increase of transmit and receive antennas. The implementation of the MIMO scheme provides more reliable detection compared to the SISO. Moreover, Figure 5.5 includes the results for the ROC evaluation for $SPR = 12dBs$. Similarly, this figure verifies the efficiency of the MIMO system operation.

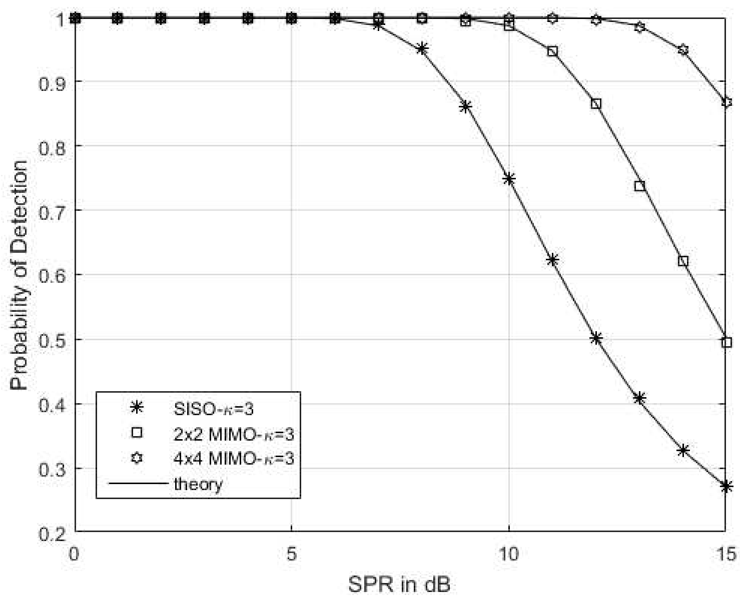


Figure 5.4: Detection Probability with respect to SPR for fixed Probability of False Alarm

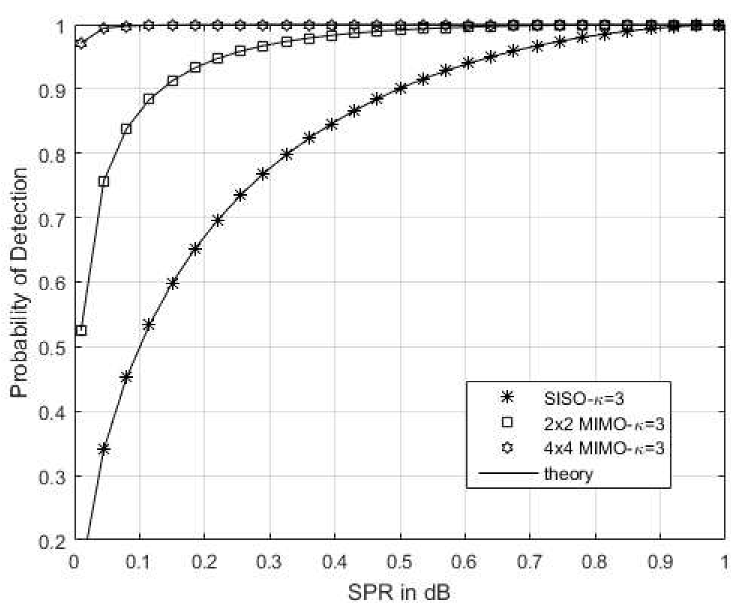


Figure 5.5: ROC for fixed value of SPR

5.4 Performance of Proposed DFH-ER Scheme

In order now to examine the performance of the proposed scheme for the MIMO case, the useful throughput of the SU is evaluated. To recover the transmitted symbols at the secondary receiver side, an MMSE detection is used for the MIMO system that was introduced in chapter 2. In both examined schemes, the results are shown with respect to the SNR and for fixed SPR. As a bench mark, the ideal case where no PU appears during the SU data transmission is also plotted. Therefore, following the activity model, the PU is assumed to reappear right after the SU data transmission is initiated on the currently working channel.

5.4.1 Simulation Results

Figure 5.6 illustrates the performance of the SU in DFH scheme. The inclusion of the MIMO has improved the SU performance compared to the SISO system. However, the reappearance of the PU signal during the SU data transmission significantly reduces the useful throughput for each system developed. Furthermore, the DFH-ER is simulated for the same cases in order to evaluate the useful throughput while the spectrum is being monitored. Figure 5.7 shows the elevated SU performance due to the increase of the number of antennas. Once more, reliable data transmission for the WRANs is provided while meeting the requirements of the standard for incumbent protection.

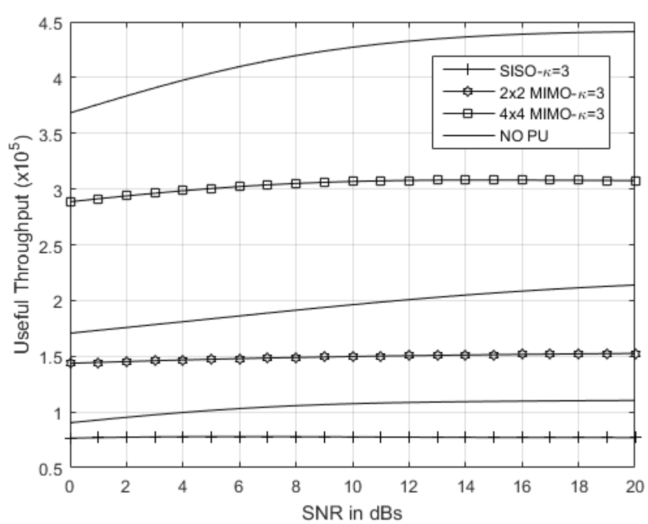


Figure 5.6: Useful Throughput for DFH over Rician fading channel with MIMO implementation

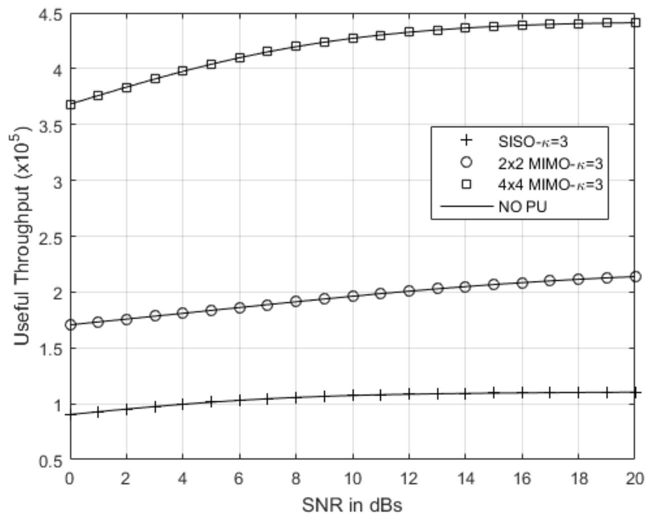


Figure 5.7: Useful Throughput for DFH-ER scheme over Rician fading channel with MIMO implementation

5.5 Conclusions

In this chapter, we investigated the performance of all methods given a MIMO system model. The intention was to provide a performance improvement due to multiple antennas at the secondary receiver and transmitter. Analytical expressions were provide in order to support the extension of the methods under investigation to the MIMO system. Initially, the DFH operation was upgraded to a MIMO system for the SU and a SIMO for the PU. Efficient simulation results demonstrated the enhanced performance due to the MIMO compared to the SISO system model introduced in chapter 3. Afterwards, the ER algorithm was developed for the MIMO system model presenting as well an improved performance. Conclusively, the proposed DFH-ER algorithm was implemented for the MIMO case establishing its ability to protect the incumbent users while providing reliable data transmission to the SUs.

Chapter 6

Conclusions and Future Work

In this chapter, we summarize the basic points on the contributions of the thesis. Moreover, we will present some potential ideas for implementation in the future in order to extend the current research.

6.1 Conclusions

- In chapter 1, an introduction was provided on the research topic of the thesis. The motivation that led to the development of this research is reviewed as well as the outline of the thesis.
- In chapter 2, background information was presented for the theory covered in the thesis. The concepts of fading channels in wireless communication system, OFDM system model of operation as well as communication with multiple antenna application were examined. Moreover, the IEEE 802.22 for WRANs was introduced along with the DFH technique.
- In chapter 3, we introduced our system model for the simple case of AWGN. The operation of the DFH was analyzed and simulation results are provided evaluating its performance. The probability of detection as well as the SU throughput are derived and simulated. Furthermore, the ER algorithm for spectrum monitoring was demonstrated through analysis and simulations. Finally, the completed proposed DFH-ER algorithm was introduced. Based on the theory, DFH-ER was simulated and compared to the conventional DFH verifying its

efficiency.

- In chapter 4, an overview of the system model was provided over fading channel. The basic type of fading channel utilized was the Ricean fading channel, presenting theoretical analysis and simulation results. However, the special case for Rayleigh fading channel was implemented in order to present a thorough comparison for AWGN, Rayleigh and Ricean fading channels. Hence, we used the DFH, ER and the proposed DFH-ER technique over fading channel providing the corresponding analysis and verifying their performance through simulations.

- In chapter 5, we presented an extension of our system model to a MIMO case. Analytical expressions were provided for the ED and the ER. Simulation results demonstrated the performance improvement due to the MIMO implementation compared to the SISO case.

6.2 Future Work

- In our work we utilized the system model provided for the Energy Ratio algorithm without considering any impairments for the OFDM utilization. The research could be extended in order to examine OFDM impairments such us the power leakage, the Narrow Band Interference (NBI) as well as the ICI in the ER, DFH and the proposed DFH-ER.

- In our extension to MIMO system models we considered a SIMO scheme for the PU activity. In a future work, the PU could be also investigated for a MIMO system.

- The spectrum sensing technique we examined in our work was the energy detection. One can extend our research using other detection techniques.

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