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PhD. THESIS SUMMARY

COOPERATIVE ALGORITHMS FOR COGNITIVE RADIO SYSTEMS

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Chapter 1

Introduction

Since the beginning of wireless communications systems, many components of the personal mobile phone have been developed and adapted to meet the ever-increasing demands and popularity of these technologies [1]. Transitioning from analog to digital communications and shifting focus from speech to data. Especially in the last few decades, there has been an increase in interest in the ability to communicate at any time and in any location. Rising demand for spectrum to support ever-expanding wireless systems and networks has led to a spectrum shortage. Through the cognitive radio network's working plan, main target is to overcome that problem by using creative technologies. Some recent spectral utilization studies have shown that, the current technique of fixed allocation of the spectrum used to manage wireless communication networks is inefficient. By taking advantage of empty channels when they become available, congintive radio (CR) is able to maximize spectrum efficiency.

1.1 Presenting the field of the doctoral thesis

Due to the rapid growth and expansion of wireless networking technologies and how they are used, a lot of time has been spent researching frequency spectrum resources in the past few years. To overcome the constraints of the spectrum and keep up with the increasing demand for bandwidth and data volumes, innovative technologies that can make better use of the available frequency bands need to be developed.

CR is becoming more known as a possible solution to the spectrum congestion problem. It uses opportunistic spectrum utilization as a major development for further wireless communication networks. Spectral sensing is an important part of CR technology because it shows where the gaps in the spectrum are available. Also, new technologies like Dynamic Spectrum Access (DSA) and spectrum sensing are making progress to improve how radio spectrum is used. Even though a lot of research and development has been done into making wireless communication technologies more effective, the small amount of radio spectrum is seen as a major problem for the industry's growth. Spectrum is limited in 5G wireless communication networks, DSA and CR has been suggested as ways to handle this problem in the spectrum [1].

The Federal Communications Commission (FCC) defines a CR as a radio that can sense radio frequency operating environment and confirm radio operating settings dynamically to adjust system performance [2]. CR can reduce interference, increase throughput, and improve interoperability. Wireless Personal Area Networks (WPANs) can make use of commercial Industrial Scientific Medical (ISM) operating settings dynamically [2]. There is a serious problem since users in the same radio spectrum system can have considerable interactions with one another. However, due to the large number of networks operating in the ISM bands, there is no suitable synchronization or radio-resource management methods in place. More recent developments in CR and signal processing have provided answers to these challenges [3]. The main function of the CR is to pinpoint an unobstructed communication link. As a potential future development field and supplementary component in database-depend on CR networks, spectrum sensing-based approaches are especially important for close-range communication. Due to the dynamic access of the channel, reliable and sensitive spectrum sensing requires cooperation and periodic monitoring from more than one user.

1.2 Objectives and scope of the doctoral thesis

In the context of CR networks, the ED-based SS algorithms are very important for increased SU and PU throughput. Also, for the NOMA configurations, the spreading sequences are of paramount importance for increased network capacity.

- Considering this research context, the **main objectives** of the thesis was formulated as following:

    1. To contribute to the SU's detection performance increase by designing new ED-based SS algorithms using cooperative and non-cooperative methods. Among the cooperative scenarios, the distributed relay-based or the amplify and forward (AF) methods should be investigated. Also, centralized or fusion center based cooperative SS algorithms would be important for this investigation. Regarding the non-cooperative (or single SU) SS methods, the threshold value adaptation for optimum detection performance represents a promising research approach.

    2. To contribute to the problem of resource allocation for maximizing the network performance in NOMA architectures. Here, the design of the spreading sequences set is the key issue, and this will be the considered investigation direction.

- Also, for this research the **secondary objectives** will be considered:

    1. To present the current state-of-the-art in the context of cooperative and non-cooperative SS algorithms for CR networks and NOMA architecture.

    2. To design new SS algorithms with enhanced performance as compared with the conventional solutions.

    3. To investigate by analytical methods and by means of simulations in Matlab the detection performance of all considered SS algorithms.

    4. To investigate different solutions for designing the set of spreading sequences in the NOMA schemes and compare their performance.

1.3 The contents and materials of the doctoral thesis

The structure of the thesis is as follows, and its comprised of the following eight chapters:

Chapter 1 will present an introduction, the idea of the doctoral thesis, and the thesis's goals. All the content and listed materials will be introduced.

Chapter 2 will describe the fundamentals of the cognitive radio network environment, as well as the background on CSS techniques. In addition, the problem of spectrum sensing and the related challenges will be presented.

Chapter 3 will introduce a novel cooperative amplify and forward technique that includes of three SUs. In this scheme, two SUs perform sequential relaying for the signal that is transmitted by the third SU using TDMA transmission protocols. Evaluation of the detection probability both analytically and through simulation will be illustrated too.

Chapter 4 will include certain adjustments to a recently proposed technique for double-threshold spectrum sensing using mean energy detection. This aims at reducing the probability of having decision error by implementing an adaptive threshold using the MED test. The simulation results demonstrate that for different duty cycle values, the innovative adaptive spectrum sensing technique provides better performance as compared to the traditional double threshold algorithm.

Chapter 5 will describe a novel cooperative SS method where SU uses the triple-threshold energy detection technique and the fusion center node, which makes a final decision using a simple voting procedure. The effects of the FC voting rule on the performance of cooperative SS detection will be explained too. An adaptive control mechanism for the intermediate detection threshold in each SU will be utilized to reduce the probability of a general error in determining a decision.

Chapter 6 will present the most important code-division multiple-access protocols used in 5G and 6G networks within the context of 3GPP standardization have been explained at a high level. NOMA protocols are allowing several users to share simultaneously the same spectrum resource. That leads to the development of a wireless communication network (5G, 6G).

Chapter 7 will describe several non-cooperative ED algorithms, such as CED, ACED, A3EED, and will propose an improved AAED, with an adaptive sensing threshold, which will be demonstrated as important SS methods for cognitive radio systems. The investigation of the detection performance will be done through theoretical derivation of analytical expressions and by simulations for these algorithms. These results will show that the proposed AAED algorithm reduces decision error probability more than the alternatives.

Chapter 8 includes a summary of the results that were obtained during the PhD research. Also, it will describe the original contributions, and finally a discussion of the potential directions that further development could take is illustrated.

Chapter 2

Opportunistic Spectrum Access System and Networks

Cognitive radio presents the idea of unlicensed utilization of licensed radio frequency bands. Recent spectrum usage studies have shown opportunities in frequency, time, and space, which have inspired the development of cognitive radio. Cognitive radio in primary systems require spectrum sensing to detect primary user communications. To be more accurate, the frequency-planned primary network spectrum has been checked addressing geographical spectrum gaps. The rate achievement of the CR system is considered one of measuring its performance.

2.1 Cognitive Radio System and Networks

2.1.1 Cognitive radio networks principle

The radio spectrum is a governmental resource used by radio transceivers, also known as primary users [4]. Due to the fixed distribution allocation band, some frequency ranges are currently saturated while others are not utilized. Poor signal quality in overcrowded bands and underutilization of the remaining spectrum is consequences of inefficient spectrum utilize, because the radio spectrum is underutilized, there are gaps in coverage known as spectrum holes. However, only a significant percentage of the spectrum is really being used at a certain time. The unlicensed secondary user is allowed to utilize the spectrum at certain time and locations. The cognitive radio is in charge for controlling of performing this type of dynamic assignment.

2.1.2 Operation of cognitive radio

CR is a self-knowledgeable, environment-aware, and determinate wireless communication system. It modifies CR cognition in response to statistical variations in the incoming RF stimuli. This is accomplished by adjusting a number of operating parameters, such as transmit power, carrier frequency, and modulation strategy in real-time. CR has also the ability to adapt and learn from its surroundings [5].

2.1.3 Cognitive radio architecture

The CRN are often divided into two distinct categories: primary users (PU) and secondary users (SU). In the main network design, users are granted access to licensed spectrum bands. The system consists of the primary users and the base stations [6]. Any gaps in the primary network will be filled by the secondary network (cognitive radio). This system consists of a cognitive radio base station and an additional user (a CR user).

2.1.4 Cognitive radio characteristics and functionality

The concept of a cognitive radio cycle refers to the variety of acts carried out by a CR as well as the way in which it interacts with the surrounding radio environment. Another name for a cognitive radio cycle is a cognition cycle, and it describes the process by which a CR identifies possibilities in the spectrum, devises strategies to adapt it, makes a decision, and then takes action in order to access the spectrum [7].

2.1.5 Application of cognitive radio

The utilization of CR as a strategy to solve this problem is gaining more and more support. Following application examples show how CR adds to the environment [8]; the adaptation of the surrounding environment is what has made CR renowned in the field of communications. CR provides several benefits to a variety of industries, including the commercial sector, the military, public administration, and security.

2.1.6 Dynamic spectrum access

They have a lot of spectrum allocation that isn't being used because of the way it's being assigned. White gaps or spectrum holes describe unoccupied frequency ranges [9]. DSA is an innovative method of spectrum sharing. That fills in unused portions of the radio spectrum to increase capacity and reduce scarcity.

2.1.7 Spectrum capturing for wireless networks

Despite rapid development in wireless communication technologies, demand for spectrum is growing faster because of DSA; cognitive radio is a practical option for dealing with spectrum scarcity. A CR must accomplish three steps to communicate opportunistically: spectrum detection, spectrum capturing, and communication. In dynamic spectrum-sharing networks, CRs must perform SS a specialized signal-processing task [5].

2.1.8 Spectrum sensing techniques

There are a few different ways to sense the electromagnetic spectrum, but they can all be classified into three categories: primary transmitter detection method, interference-based detection method, and cooperative sensing detection method. So, cognitive spectrum sensing needs ways to find the gaps in the spectrum quickly and accurately [10],[11].

- **Energy detection:**

The ED strategy is widely used for spectrum sensing, due to its simplicity in computation, implementation and its independence from prior information about the PU signal. In order to evaluate whether or not a PU signal is active, only needs to compare the received energy signal to a predetermined threshold [10].

$$\left\{ \begin{array}{ll} if\ \sum |Y(f)|^2 \geq \lambda \ldots\ldots & H_1 \\ otherwise\ \ldots\ldots\ldots\ldots\ldots & H_0 \end{array} \right\} \tag{2.1}$$

- **Cyclostationary feature detection:**

There are a few aspects of wireless transmissions, like carrier frequency, modulation type, and symbol duration that have cyclostationary properties. At the level of the cognitive user, cyclostationary analysis can be used to determine the distinctive characteristics of a given radio broadcast.

$$R_y^{(\alpha)}(\tau) = \mathbb{E}\left[y(t+\tau)\, y^*(t-\tau)e^{-j2\pi\alpha t}\right] \tag{2.2}$$

- **Matched filter detection:**

Matched filtering is a very useful sensing method because it can increase the SNR of the signal being received. It can be seen how matched filter channels are used for SS. In CR, the matched filter is also known as a coherent detector. If CR is familiar with the PU waveform, this detection method may be superior to all others, because it optimizes the SNR that is obtained, it is quite accurate. Since coherence detection is employed, matching filter detection because needs a small amount of time for sensing to give excellent performance [10].

2.1.9 Cooperative sensing detection

In CSS many SUs work together to increase sensing performance by combining their sensing information. A CSS method can significantly reduce the likelihood of missed detection and false alarm by utilizing multiuser diversity and independent fading channels [12]. In addition, three distinct forms of CSS exist, delineated by the degree of centralization, distribution, or cooperative relay in the dissemination of sensing information amongst participating SUs in a network [13],[14],[15].

- **Centralized cooperative spectrum sensing**

In order to detect the presence of a PU, each SU conducts its own spectral sensing and makes a decision based on its own local sensitivity data. Then, all of the cognitive users transmit their decisions to a central location (fusion center) [12].

- **Distributed cooperative spectrum sensing**

Distributed CSS is cheaper than centralized CSS because it doesn't need a central data center. Even though the distributed algorithm for CSS can be run in a single pass, it may take more than one pass to agree on whether or not PUs exists.

- **Relay-assisted cooperative spectrum sensing**

Researchers have looked into relay-assisted cooperative sensing, which happens when many cognitive users use a detector algorithm to find the licensed primary channel and then report their findings to a central FC. All topologies of cooperative networks are better than non-cooperative at reducing the time it takes to find PU [12].

2.1.10 Data fusion

Another part of CSS is data fusion, which is the process of combining data from different local sensors so that the FC can test hypotheses. Data fusion can be performed in either a soft or hard method, depending on the available bandwidth [1].

- **Soft combining**

Users of CR have the option of sending either all of the local sensing samples or all of the local test statistics in order to make a soft decision. Similarly to soft combining, quantized soft combining allows CR users to quantize the results of local sensing and broadcast. Also the quantized data is used to minimize control channel overheads.

- **Hard combining**

It is very easy and convenient to transmit the one-bit decision for hard combining after binary local decisions have been reported to the fusion center. Standard fusion rules include AND, OR, and majority.

$$Q_f = Prob\,\{\,H_1|H_0\} = \sum_{l=k}^{N} \binom{N}{l} P_f^1 (1 - P_f)^{N-l} \tag{2.4}$$

$$Q_d = Prob\,\{\,H_1|H_1\} = \sum_{l=k}^{N} \binom{N}{l} P_d^1 (1 - P_d)^{N-l} \tag{2.5}$$

That can calculate the false alarm Q_f and detection probabilities Q_d for CSS, as illustrated above.

2.1.11 Spectrum sensing issues and challenges

Dealing with the several sources of uncertainty that might result from things like channel uncertainty, noise uncertainty, and the sensing interference limit, it's one of the challenging aspects of SS for CRN that can be addressed [12],[14].

2.2 Multiple access technology and cognitive radio network

This section focuses on the idea of non-orthogonal multiple access (NOMA) approaches for the impending fifth-generation (5G) wireless networks. All of the existing cellular networks use orthogonal multiple access (OMA) techniques, such as time division multiple access (TDMA), frequency division multiple access (FDMA), or code division multiple access (CDMA), as part of one another. However, none of these methods is capable of satisfying the exacting demands of future radio access systems. NOMA is fundamentally different. Each NOMA user operates in the same band and time, distinguishable by power level. In NOMA, the superposition coding at the transmitter is used to separate users on the uplink and downlink channels [38].

2.2.1 NOMA-based cognitive radio network

In this scenario, secondary user intervention is plainly detrimental to the primary user; therefore, secondary user intervention must be limited. The first solution is CR technology, which can select channels autonomously without user interference (overlay CR) or under specific intervention temperatures (underlay CR). NOMA is a more promising alternative to orthogonal multi-access (OMA) because it permits multiple users to transmit signals using the same time slot and carrier. Both of the technologies mentioned above to enhance spectral efficiency based on spectrum sharing could be an issue of safety to communications.

2.2.2 Concept of non-orthogonal multiple access

The modulation scheme employed in this study is OFDM, while the multiple access scheme utilized is NOMA. In traditional 4G networks, the utilization of OFDMA is employed as a natural extension of orthogonal frequency division multiplexing OFDM. This technique involves the allocation of information for individual users to specific subsets of subcarriers. In contrast, NOMA enables the utilization of all subcarriers by every user. Figure 2.14 depicts the spectrum allocation scheme for OFDMA and NOMA techniques in the context of accommodating two users. The preceding concept is applicable to both uplink and downlink transmission [28].

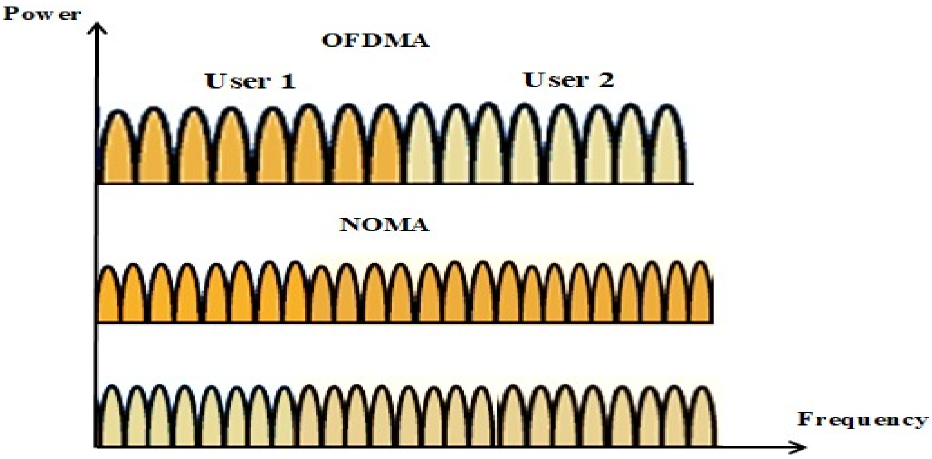

Figure 2.14 Two-user OFDMA and NOMA spectrum sharing.

2.2.3 NOMA for downlink

The base station in the NOMA downlink superimposes the information waveforms on the consumers it serves. successive interference cancellation (SIC) is used by every piece of user equipment (UE) for signal detection. The BS and K UEs, all equipped with SIC receivers. It is assumed throughout the network that UE1 is the closest UE to the BS and that UE K is the furthest. One of the most difficult aspects of implementing SIC is determining how to distribute power among different information waveforms. When using NOMA downlink, the UE that is furthest from the BS receives the most power, while the UE that is closest to the BS receives the least.

2.2.4 NOMA for uplink

The implementation of NOMA for the uplink is a little bit different than the implementation for the downlink. A network that utilizes NOMA to multiplex K user equipment in the uplink. This time, BS makes use of SIC in order to differentiate between the signals coming from the users.

2.2.5 Imperfectness in NOMA

All of the previous material has been based on the assumption that the SIC receiver has perfect cancellation. Subtracting the decoded signal from the received signal without making any mistakes is challenging in practice for SIC. Here, its take a look at the NOMA idea again, this time considering a cancellation mistake in a SIC receiver. Remember that the SIC receiver iteratively decodes the information signals one at a time. After a signal has been decoded using SIC, the individual waveforms can be recreated and subtracted from the received signal. It is possible to finish this process without making a mistake in theory, but in practice, mistakes due to cancellation are to be expected.

Chapter 3

Cooperative Spectrum Sensing with Several Secondary Users

Cooperative spectrum sensing for CR networks involves more opportunistic SUs that help each other to detect the presence of the signal transmitted by a licensed PU. Among cooperative spectrum sensing methods, the Amplify and Forward (AF) technique assumes that SUs relay the received signals without additional processing.

3.1 Cooperative spectrum sensing for CR by utilizing sequential relaying with three SUs

That modify an Amplify and Forward (AF) relay based cooperative detection method that was introduced in [16]. In fact, this work is a continuation of a previous research performed in [17], where that extended the number of SUs from two (in [16]) to three. However, in [17] that simply added an SU, which operates independently to and in parallel with the original SUs. Even in [17] demonstrated that the additional SU increases the detection performance by exploiting the spatial diversity.

3.2 Sequential relaying cooperative detection method

3.2.1 Cooperative detection with sequential relaying for 3 SUs

That is considering a CR environment with three SUs, denoted as S_1, S_2, and S_3, as illustrated in Figure 3.8. The scheme includes also a common CR receiver and the three SUs aim to detect the signal of a PU denoted by P.

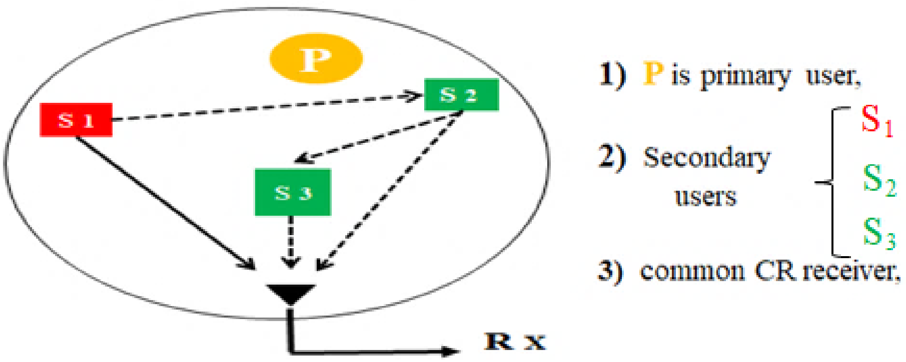

Figure 3.8 *Sequential relaying cooperation in cognitive radio networks.*

Figure 3.9 illustrates a TDMA transmission model that employs an AF protocol to transmit SUs signals in sequential time slots, similar to that used in [16],[17].

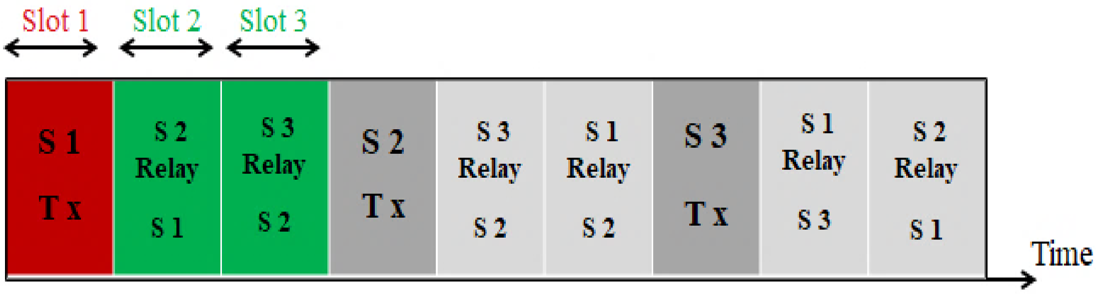

Figure 3.9 *The three-SU sequential relaying techniques TDMA frame.*

Analyze all the signals transmitted by the three SUs and the performance of their cooperative AF spectrum sensing scheme.

$$y_2 = \theta h_{P2} + \alpha h_{12} + w_2 \tag{3.22}$$

$$E\{|ah_{12}|^2\} = PG_{12} \tag{3.23}$$

$$\mathrm{E}\{|y_2|^2\} = \theta^2 P_2 + PG_{12} + 1 \tag{3.24}$$

For the received signal Y, the energy detector computes the statistic $T(Y) = |Y|^2$.

$$T(Y) = |w|^2 \sim exp\,[\sigma_W^2\,(\sigma_W^2)^2] \tag{3.37}$$

Let us take into consideration $F_k(t)$ as the cumulative density function (CDF) for a random variable $T(Y)$, in one of the hypotheses H_k, where k=0 or k=1. Therefore, the CDF of $T(Y)$ for H_0 can be written as follows:

1. First case : For H_0, **(θ= 0),** the CDF of $T(Y)$ is given by:

$$\begin{aligned} F_0(t) &= \int_0^\infty \int_0^\infty P\left(T(Y) > t \middle| H_{0,}\ h_1,h_2\right) pdf\ (h_1)\, pdf\ (h_2)\, dh_1\, dh_2 \\ &= \int_0^\infty \int_0^\infty e\ \frac{1}{2+\tilde{\beta}_3^0 h_1 + \beta_2^0\ f(h_1+h_2) + \tilde{\beta}_2^0 \tilde{\beta}_3^0\ h_1 h_2}\ e^{-(h_1+h_2)}\ dh_1\, dh_2 \\ &= \varphi(t; 2, \tilde{\beta}_3^0, \tilde{\beta}_2^0, \tilde{\beta}_2^0\ \tilde{\beta}_3^0) \end{aligned} \tag{3.39}$$

2. Second case : For H_1 **(θ= 1)**:

$$F_1(t) = \varphi[t; 4P_1{+}2, \tilde{\beta}_3(P_3+1), \beta_2^0\ (P_2+1), \tilde{\beta}_2\tilde{\beta}_3\ (P_2+1) \tag{3.40}$$

Cooperative and Non-cooperative detection: It is possible for S_1 to be detected in combination with S_2 and S_3:

$$P_c^{(1)}(t) = \varphi[\lambda; 4P_1 + 2\,,\ \tilde{\beta}_3(P_3+1), \beta_2^0(P_2+1),\ \ \tilde{\beta}_2\tilde{\beta}_3(P_2+1)\,] \tag{3.41}$$

$$P_n^{(1)}(t) = \alpha^{1/(P_i+1)} \qquad i \in \{1,2,3\} \tag{3.43}$$

3.2.2 Channel model and relation between SUs channel gains

As in [17] that will consider the power-law path loss as the channel model in cooperative CR system. Therefore, the received signal y can be written as:

$$y = hx = \frac{x}{\sqrt{d^n}} \tag{3.44}$$

As introduced in [17], the topology used by the cooperative scheme from Figure 3.8 is entirely specified by the distances between all users (PU and three SUs). This topology and all the configuration parameters are depicted in Figure 3.10. For this environment that makes some simplifying assumptions.

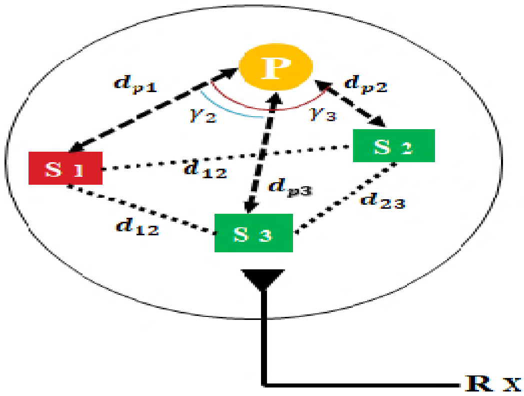

Figure 3.10 *Network topology employed for spectrum sensing by SUs.*

In this case, knowing the values of the distances between the PU, the three SUs and the value of the angles $\gamma 2$ and $\gamma 3$ that can compute by using the generalized Pythagorean theorem [17].

$$d_{pi}^2 + d_{p1}^2 - 2d_{p1}d_{pi}\cos\gamma_2 = d_{1i}^2 \quad i \in \{1,2\} \tag{3.45}$$

$$d_{pi} = P_i^{-1/n}, \qquad i \in \{1, 2, 3\} \tag{3.46}$$

Similarly, the channel gains between users S_i and S_j are:

$$d_{ij} = G_{ij}^{-1/n} \quad \forall i,j \in \{1, 2,3\} \quad i \neq j \tag{3.47}$$

3.3 Cooperative detection performance

That evaluates the detection probability for S_1, which uses the other two SUs (S_2 and S_3) as relays. The detection probability at S_1 through cooperation with S_2 and S_3 is estimated both theoretically using the expression (3.41) and by means of Monte-Carlo simulations. In order to have a fair comparison with the scheme proposed in [17] that use the same values of the system parameters for the performance testing [18]: $P_1 = \tilde{P} = P$ =1W, $\gamma_2 = \pi/6$, $\gamma_3 = \pi/8$, $P_2, P_3 \in [0, 50]$ dB, $\alpha = 0.1$, $n = 3.5$.

3.4 Simulation results

In Figure 3.11, it's noticed in 3D plot, the non-cooperative detection probability does not depend on the received power of the PU signal at S_2 and S_3. However, the cooperative scenario outperforms the non-cooperative one ($P_c^{(1)}, > P_n^{(1)}$). It has to note that the $P_c^{(1)}$determined for the current scheme is asymmetrical (while in [17], the 3D plot is symmetrical) offering a better performance with P_3 (the power of S_3) than with P_2. Hence, for low values of P_3 (S_3 is far from PU, $P_3 < 10$ dB) the cooperative scheme performs worse than the non-cooperative scheme. On the other hand, if P_2 is low ($P_2 <$ 10 dB), the performance of the cooperative scheme is still better than the performance of the non-cooperative. This detection performance asymmetry is explained by the fact that S_3 relays the signal of S_2, while S_2 detects directly the signal from PU. So, the sequential relaying (S_2 followed by S_3) provides a stronger (amplified) replica of the PU signal. The main advantage of the scheme proposed in the current work is that for high values of both P_2 and P_3, it always outperforms the non-cooperative scheme.

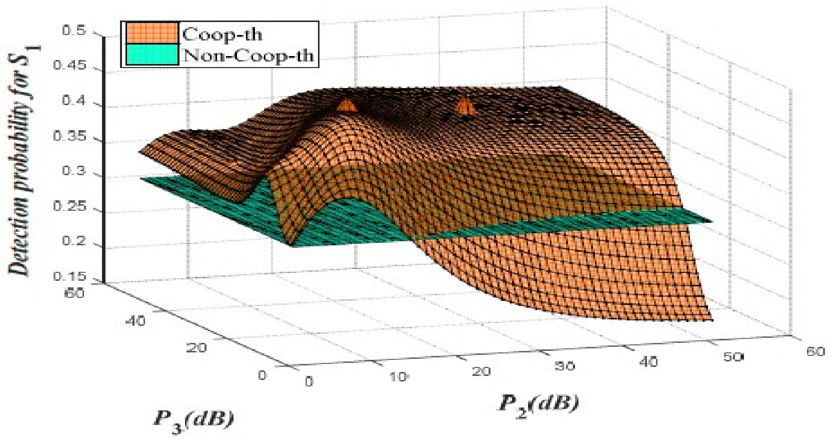

Figure 3.11 *Cooperative and Non-Cooperative theoretical detection probability for S_1 as a function of P_2 and P_3.*

In order to emphasize the asymmetrical features of the cooperative detection performance that illustrated in Figures 3.12-3.15 the values of $P_c^{(1)}$ and $P_n^{(1)}$ for different values of P_2 and P_3. In Figures 3.12 and 3.15 represented $P_c^{(1)}$ as a function of P_2 for two fixed values of P_3, 10 dB and 40 dB, respectively. For a low value of P_3, which denotes a weak received power for the main relaying node S_3, the proposed scheme performs worse than the scheme from [17], as depicted in Figure 3.12. Here, the maximum value of $P_c^{(1)}$ for both schemes (the proposed scheme and the scheme from [17]) is reached for $P_2 = P_3 = 10$ dB. On the other hand, when the value of P_3 is large (see Figure 3.13), the proposed scheme outperforms the scheme from [17]. Besides the fact that the proposed scheme outperforms also the non-cooperative scheme, it also shows a detection probability value that is larger than the maximum value for the scheme in [17], for any value of P_2. Similarly in the Figures 3.14 and 3.15 that plotted $P_c^{(1)}$ as a function of P_3 for $P_2 = 10$ dB and $P_2 = 40$ dB, respectively. In Figure 3.14 the proposed scheme performs almost the same as the scheme from [17]. As explained above, and comparing the results from Figures 3.12 and 3.14 proposed scheme depends more on the relaying node S_3 than on S_2. In Figure 3.15, it is shown that when the value of P_2 is large and also, P_3 >15dB, the proposed scheme clearly outperforms the scheme from [17].

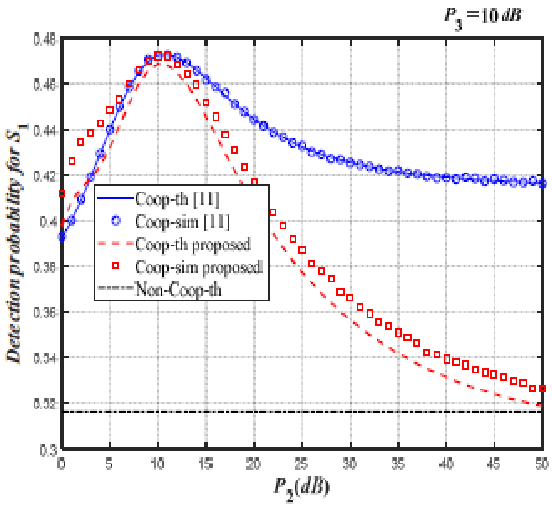

Figure. 3.12 *Cooperative and Non-Cooperative S1 detection versus P_2, P_3=10 dB.*

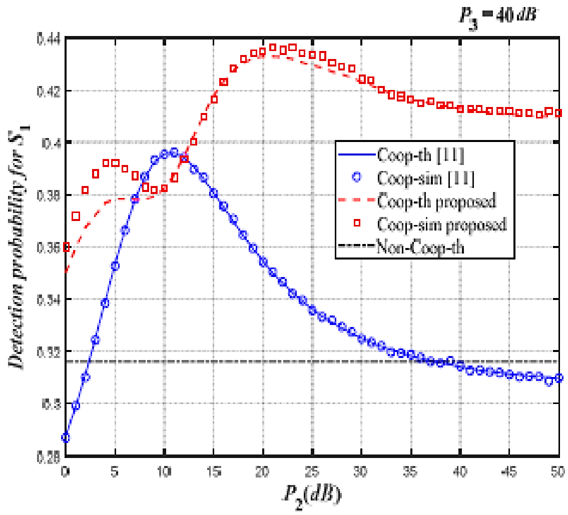

Figure. 3.13 *Cooperative and Non-Cooperative S1 detection versus P_2, P_3=40 dB.*

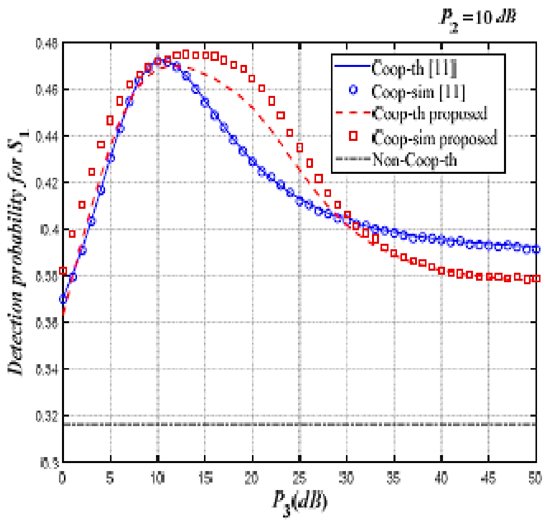

Figure. 3.14 *Cooperative and Non-Cooperative S_1 detection versus P_3, P_2=10 dB.*

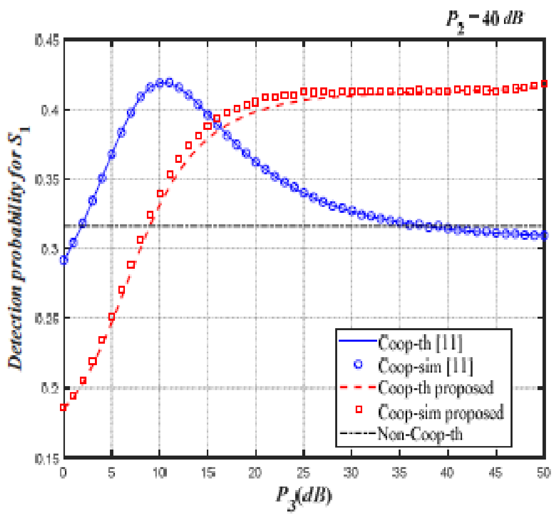

Figure. 3.15 *Cooperative and Non-Cooperative S_1 detection versus P_3, P_2=40 dB.*

Also for the proposed scheme that noticed in Figures 3.12-3.15 a slight difference between the detection probability values estimated theoretically and by simulation, respectively; however, the simulation results are always better than the corresponding theoretical ones. Finally, it's important to mention that obtained similar results for different values of the angles γ_2 and γ_3.

Chapter 4

Threshold Techniques in Cognitive Radio Environments

The mean energy detection (MED) method is modified for double-threshold spectrum sensing. The MED test's adaptive threshold reduces the chance of final decision errors probability (DEP). Simulations show that adaptive spectrum sensing outperforms the double threshold technique at any duty cycle [19].

4.1 Adaptive threshold for double threshold method

According to CED, each SU is responsible for making its own local decisions by comparing its observational value with a predetermined threshold λ value. This is illustrated in Figure 4.2.

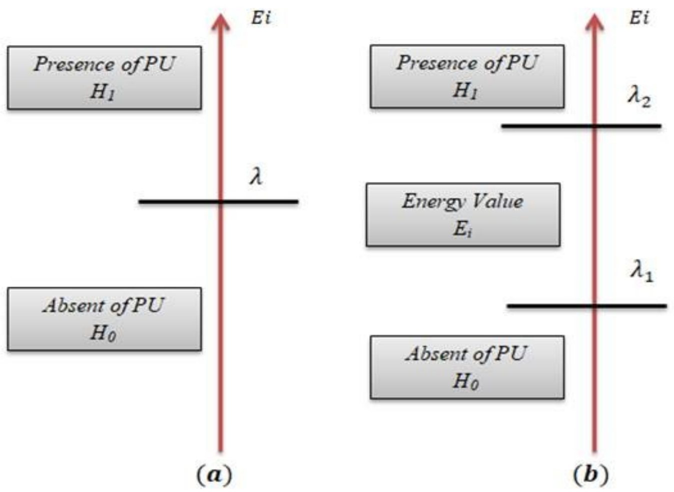

Figure 4.2*(a) CED method and (b) Double threshold energy detection.*

4.2 Threshold approach with alternative adaptive

A single adaptive energy detector and a double threshold energy detector were proposed and discussed. Utilizing a double threshold allows for optimal utilization of the periodicity of the exponentially dispersed activity of the PU in the temporal domain. The amount of time spent sensing has been minimized in the two models that came much later.

4.3 Double-threshold energy detection algorithms

Based on these hypotheses, the ED must choose between two competing scenarios: busy hypothesis H_1 (presence of both PU signal and noise), and idle hypothesis H_0 (presence of only noise) [20]. Under the assumption of a single-threshold CED the a sensing threshold λ of P_d and P_{fa} may be computed with the use of the canonical Q-function, as in [3]:

$$P_{fa}^{CED} = Prob[E_i > \lambda|H_0] = Q\left(\frac{\lambda_H - N\,\sigma_n^2}{\sqrt{2N}\ \sigma_n^2}\right) \quad (4.5)$$

$$P_d^{CED} = Prob\{E > \lambda|H_1\} = Q\left(\frac{\lambda - N(\sigma_s^2 + \sigma_n^2)}{\sqrt{2N}\ (\sigma_s^2 + \sigma_n^2)}\right) \quad (4.6)$$

In the CED algorithm, one of these two probabilities is considered as a target and the threshold is extracted from the corresponding equation, (4.5) or (4.6), and used for the statistic test during each sensing slot i.

$$\begin{aligned} \lambda_H &= \left[\sqrt{2N}\, Q^{-1}\left(P_{fa,target}^{CED}\right) + N\right]\sigma_n^2 \\ \lambda_L &= \left[N - \sqrt{2N}\, Q^{-1}(P_m)\right](\sigma_s^2 + \sigma_n^2) \end{aligned} \quad (4.12)$$

Where the missed detection probability is given by $P_m^{CED} = 1 - P_d^{CED}$, λ_H is the high value threshold, and λ_L is the low value threshold, respectively. Considering these notations, the correct detection of PU signal presence generates $q_i = 1$, if $E_i \geq \lambda_H$, and the correct detection of PU signal absence generates $q_i = 0$, if $E_i < \lambda_L$. In fact, the 2FT-CED algorithm [21] provides no decision at the SU for the confusion region, when $\lambda_L \leq Ei < \lambda_H$.

4.4 Fixed double-threshold algorithm using conventional mean energy detection

In this research work [22], the proposed a double-threshold detection algorithm that uses an extra test for the confusion region. This additional test involves testing the mean energy estimated over L consecutive sensing slots, where the last slot is the current one i. $\overline{E_i} = \frac{1}{L}\sum_{j=1}^{L} E_{i-L+j}$. It must be noted that for the confusion region testing, a new decision threshold is needed, which takes an intermediate value λ_I, such that $\lambda_L \leq \lambda_I \leq \lambda_H$.

4.5 Proposed fixed double-threshold conventional energy detection with an adaptive threshold mean energy detection

Considering that the fixed value of the intermediate threshold λ_I is restrictive, the first consider a linear variation of λ_I between the values λ_L and λ_H, respectively:

$$\lambda_I = (1 - \delta_\lambda)\lambda_L + \delta_\lambda \lambda_H = \lambda_L + \delta_\lambda(\lambda_H - \lambda_L) \tag{4.13}$$

That used DEP as a performance metric to identify the best value for λ_I in (4.13) [23]:

$$P_e(\delta_\lambda, \alpha, \sigma_s^2, \sigma_n^2) = (1 - \alpha)P_{fa}^{2FT-CED-1AT-MED} + \alpha(1 - P_d^{2FT-CED-1AT-MED}) \tag{4.14}$$

That define the optimization problem for the intermediate threshold value λ_I (or for the value of δ_λ) to minimize the DEP [24]:

$$\delta_{\lambda,opt} = arg\, min_{\delta_\lambda} P_e(\delta_\lambda, \alpha, \sigma_s^2, \sigma_n^2) \tag{4.15}$$

It is difficult to derive an exact expression of the optimum decision threshold λ_I for the adaptive 2FT-CED-1AT-MED algorithm. As illustrated previously in [25] that choose to determine the optimum λ_I threshold value by simulation, using a brute force searching algorithm for solving the problem defined in (4.15) [24].

4.6 Simulation result

The proposed 2FT-CED-1AT-MED spectrum sensing method is described. In order to demonstrate the performance of the proposed 2FT-CED- 1AT-MED algorithm, this will compare it with the single threshold CED and the fixed double-threshold 2FT-CMED algorithms, using the same testing scenarios. That determines the fixed values of the two thresholds λ_H and λ_L using (4.12). Also, the fixed value of the number of sensing slots, used to estimate the MED test statistic $\overline{E_\iota}$ to $L = 3$. In [3], it was shown that for $L >$ 3 the detection performance will not improve significantly. First that has to check the convexity of the DEP function for the 2FT-CED-1AT-MED algorithm as a function of δ_λ. For example, in Figure 4.4 represent the DEP value for the three tested ED algorithms with $\alpha = 0.3$ and SNR = −11dB.

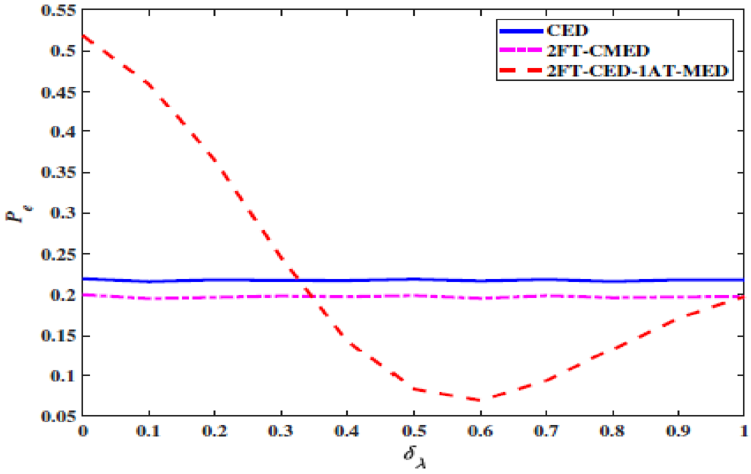

Figure 4.4 *Error probability Pe vs. δ_λ for ED algorithms, α = 0.3, SNR = −11dB.*

In Figure 4.4, the DEP function of the proposed 2FT-CED-1AT-MED algorithm is convex, presenting a minimum value for $\delta_\lambda \approx 0.6$, which is much lower as compared to the DEP determined for CED and 2FT-CMED algorithms. Also that notice the DEP for CED and 2FT-CMED algorithms is constant with δ_λ because these are fixed threshold values algorithms. However, the 2FT-CMED algorithm performs slightly better than CED in terms of DEP. In Figures 4.5- 4.7 plotted these results for $\alpha = 0.3$, $\alpha = 0.5$, and $\alpha = 0.7$, respectively. For low values of the duty cycle, $\alpha \leq 0.5$ that notice all three ED algorithms perform the same for very low and very high SNR values. However, for SNR ∈ [−20, −6] dB notice the proposed 2FT-CED-1AT-MED algorithm outperforms the 2FT-CMED and CED algorithms by at least 3dB [19]. In fact, this detection SNR gain of the proposed algorithm over the conventional ED algorithms increases with α [19]. As a matter of fact that notice in Figure 4.7, for $\alpha = 0.7$, very low DEP values of the proposed algorithm, which are even 2.3 times lower than the DEP for conventional algorithms.

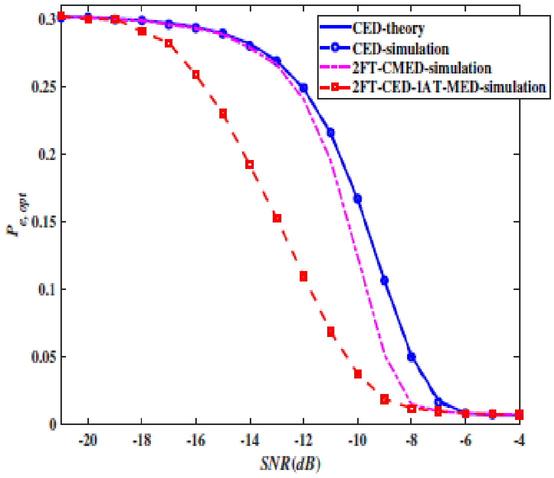

Figure 4.5 *Error probability Pe vs. SNR for ED algorithms, α = 0.3.*

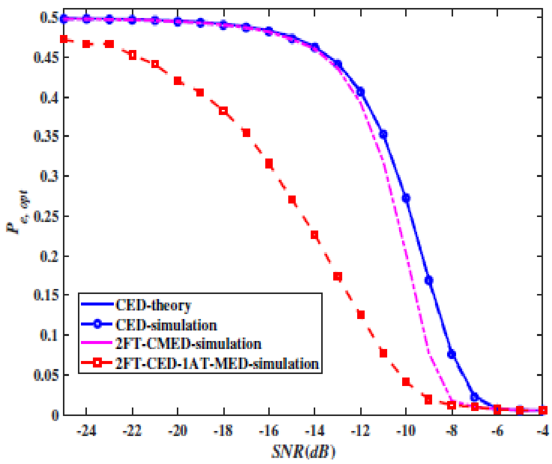

Figure 4.6 *Error probability Pe vs. SNR for ED algorithms, α = 0.5.*

Regarding the results shown in Figures 4.5-4.7 that have notice the proposed ED algorithm performs much better than the conventional algorithms, especially for low SNR values and high α values.

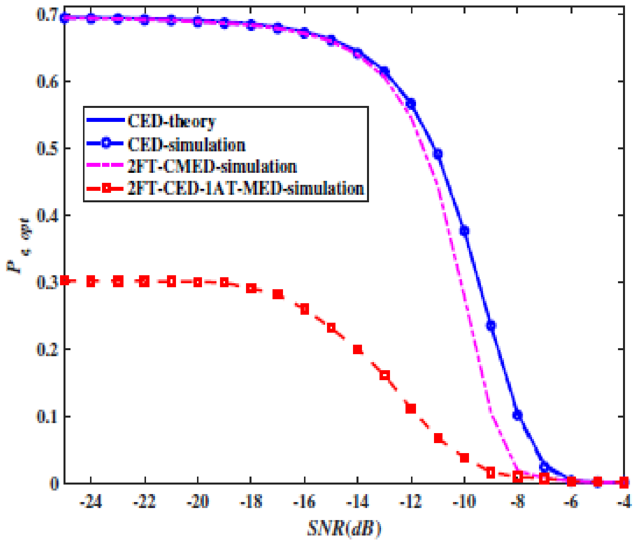

Figure 4.7 *Error probability Pe vs. SNR for ED algorithms, α = 0.7.*

Finally, in Figures 4.8-4.10 presents the values of the correct detection probability P_d estimated for the three ED algorithms. This is using the same simulation scenarios for deriving the previous results from Figures 4.5- 4.7. Similarly, for the proposed ED algorithm that notices a significant increase of P_d with α. In fact, the estimated P_d value for the 2FT-CED-1AT-MED algorithm, used to detect a very busy PU with α = 0.7, reaches almost the maximum theoretical value for any SNR value in the considered range. As it was expected, these P_d plots are in concordance with the P_e results from Figures 4.5-4.7.

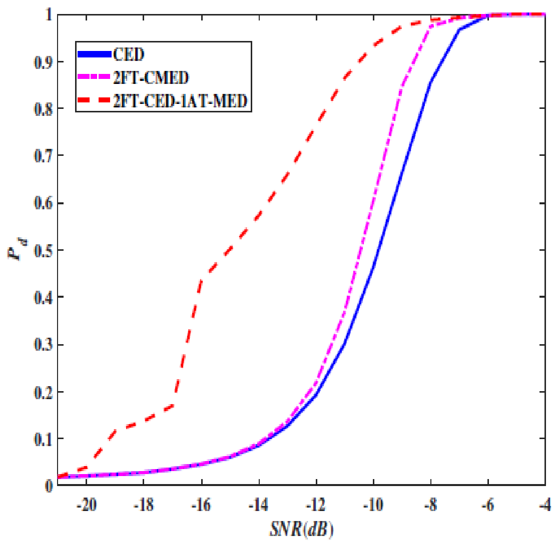

Figure 4.8 *Detection probability Pd vs. SNR for ED algorithms, α = 0.3.*

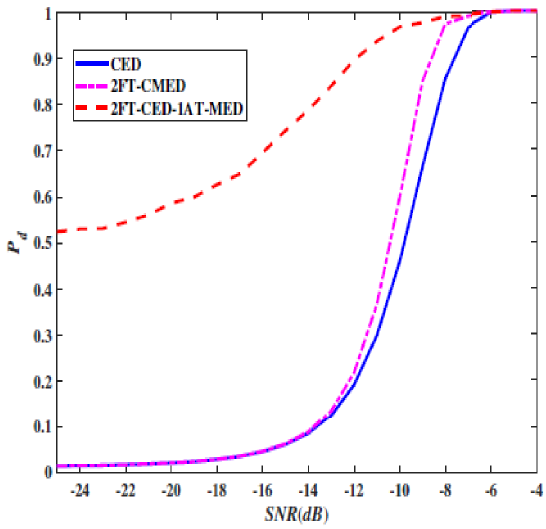

Figure 4.9 *Detection probability Pd vs. SNR for ED algorithms, α = 0.5.*

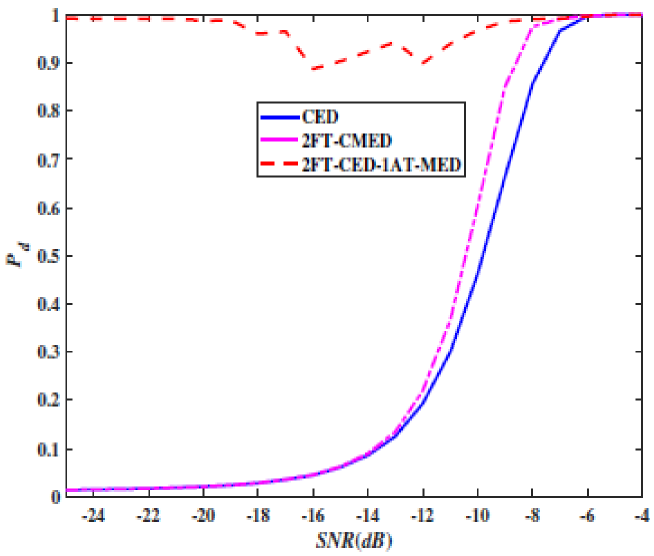

Figure 4.10 *Detection probability Pd vs. SNR for ED algorithms, α = 0.7.*

Chapter 5

Triple-Threshold Energy Detection for Cooperative Spectrum Sensing

Another component of the CR network is the FC that collects the individual detection information from SUs and based on this, it takes the final decision about the presence or absence of the PU signal. That analyzes of the cooperative SS algorithm using triple-threshold ED algorithm in each SU, and a simple voting rule for the final decision at the FC node. This investigates of the cooperative SS detection performance dependence on the FC voting rule, adaptive control mechanism for the intermediate detection threshold in each SU to minimize DEP [26].

5.1 Fixed double-threshold algorithm using conventional energy detection

That are required to highlight a weakness in the 2FT-CED algorithm, which is that doesn't provide a decision for the value of the received signal energy in the region between the 'low' and 'high' thresholds, also known as the 'confusion region', $\lambda_L \leq E_i < \lambda_H$. This is a significant limitation of the algorithm that must be addressed [27],[19] as illustrated in Figure 5.1 [22].

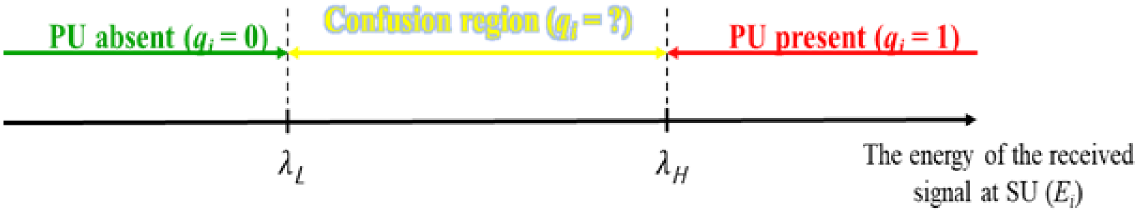

Figure 5.1 *Illustrate the fixed double-threshold detection technique (2FT-CED).*

5.2 Third adaptive threshold mean energy detection

As shown in [19] and [22], the value of the intermediate threshold can be chosen to maximize a number of performance functions as shown in Figure 5.2.

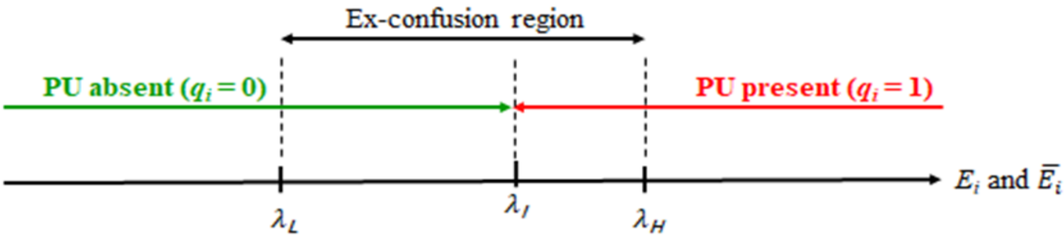

Figure 5.2 *Illustrate the fixed double-threshold CED using the mean energy (2FT-CMED).*

In order to alleviate the confusion region problem, a third (intermediate) λ_I threshold is introduced between λ_L and λ_H [19],[22]. This additional (third) test statistic may use the same simple energy value from the current slot (as CED) or, for even better detection performance, it can use the mean energy (ME) value estimated for L consecutive sensing slots, $\bar{E}_J = \frac{1}{L}\sum_{k=1}^{L} E_{j+k-L}$. As explained in [19],[22], the value of the intermediate threshold can be selected to optimize several performance functions. In [20], the intermediate threshold for testing the ME is set to meet the target FAP, $\lambda_I = \lambda_H$, and thus the algorithm uses two threshold values for three tests and was named as 2FT-CED algorithm using the 2FT-CMED. In [19] that proposed the use of the DEP function for adaptively controlling the value of λ_I.

5.3 Cooperative energy detecting algorithms

Analyze the detection performance of the previously introduced multiple threshold algorithms, including the 2FT-CED-1AT-MED algorithm [19], in a cooperative senairo Thus, consider the presence of N_{SU} SUs in the coverage area of the PU, which are capable to transmit the detection information to a common FC, which takes the final decision on the PU signal presence and sends back to SUs this result.

5.3.1 Voting rules for fusion center

A well-known voting strategy is the logical 'OR' function that is applied onto the decision results transmitted by SUs. Hence, using the 'OR' voting rule in the FC it results into a minimum interference caused to PU.

$$P_{d,FC}^{OR} = 1 - \prod_{i=1}^{N_{su}} (1 - P_d^i) \tag{5.4}$$

$$P_{fa,FC}^{OR} = 1 - \prod_{i=1}^{N_{su}} (1 - P_{fa}^i) \tag{5.5}$$

A different well-known voting strategy is the logical 'AND' function that is applied onto the decision results transmitted by SUs. Using the 'AND' voting rule in the FC, it results into a minimum number of false alarms.

$$P_{d,FC}^{AND} = \prod_{i=1}^{N_{su}} P_d^i \tag{5.6}$$

$$P_{fa,FC}^{AND} = \prod_{i=1}^{N_{su}} P_{fa}^i \tag{5.7}$$

5.3.2 Proposed cooperative triple-threshold energy detection algorithm

In this work that describe a unique cooperative method that takes advantage of the 2FT-CED-1AT-MED algorithm as explained in [19], however, instead of optimizing the local DEP at each SU that propose to estimate and optimize the DEP estimated for all SUs at FC, depending on the voting rule [26].

$$\delta_\lambda = argmin_{\delta_\lambda} P_{e,FC}\left(\delta_\lambda, \alpha, \sigma_x^2, \sigma_\omega^2\right), i \in \overline{1, N_{SU}} \tag{5.8}$$

5.4 Simulation results

Therefore, a number of N_{SU} SUs perform local sensing using either single threshold CED, 2FT-CMED or 2FT-CED-1AT-MED and send the local decisions to FC, which applies the voting rule to take the final decision. As mentioned earlier, in the case of 2FT-CED-1AT-MED the value of the intermediate threshold $\lambda_{I,i}$ is adapted independently at each SU. That models the AWGN and the PU signal generation in Matlab and run Monte Carlo tests to estimate the DEP performance as a function of several system parameters. In order to have a good reference for the proposed cooperative 2FT-CED-1AT-MED algorithm that estimate also the DEP performance for a single SU 2FT-CED-1AT-MED algorithm, where the considered SU is the one having the largest SNR value, the SU placed the closest to the PU and offering the most reliable sensing. The determination of the maximum SNR value among all N_{SU} SUs can be considered as a multiple-SU non CSS method, where the FC node requires additional time and resources to estimate the SNR value for each SU. Another reference algorithm for simulations is the 2FT-CED-1AT-MED algorithm that performs the intermediate threshold optimization in each SU, independently and then, sends the individual decisions to FC. In all plots, this individually optimized decision scenario is denoted as 'Coop. opt. 2FT-CED-1AT-MED'. However, this scenario is not efficient since the decisions taken at the 'weakest' SU (lowest SNR value) will participate equally in the voting rule at FC. Therefore, the individual optimization is not providing any improvement in the cooperative scenarios.

5.4.1 Probability of decision error based on decision threshold value

In Figures 5.3-5.5 that illustrate some typical DEP results for an 'AND' voting rule scenario with N_{SU} = 4 SUs having the $SNRi \in \{-20, -17, -13, -10\}$ dB, a duty cycle value of $\alpha = 0.3$. The only parameter value that differs from one figure to another is the ME window size, L = 3 (Figure 5.3), L = 5 (Figure 5.4), and L = 9 (Figure 5.5), respectively.

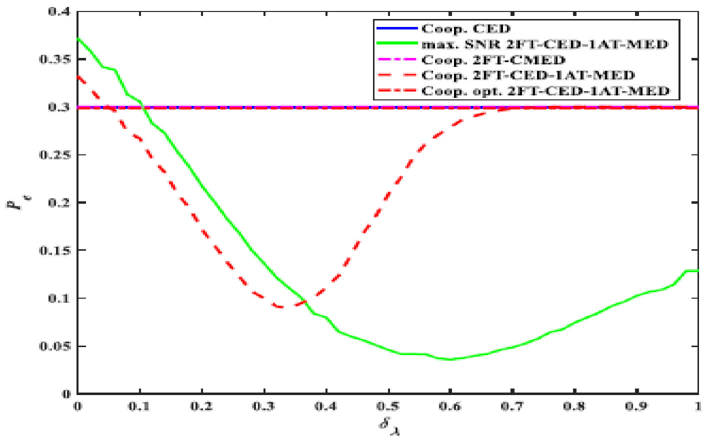

Figure 5.3 *Comparison of Pe and δ_λ for cooperative ED algorithm with four SUs, $\alpha = 0.3$, L =3,SNR =(-20,-17,-13,-10) dB, and the 'AND' fusion center voting rule.*

In Figure 5.3, notice that for small ME windows, the cooperative CED, cooperative SFT-MED and cooperative local optimum 2FT-CED-1AT-MED perform almost the same and show no DEP dependency on δ_λ. On the other hand, for a value of $\delta_\lambda = 0.6$, the maximum SNR single SU 2FT-CED- 1AT-MED offers a minimum DEP $\approx$ 0.04, while the cooperative 2FT-CED-1AT-MED using FC with an 'AND' voting rule at $\delta_\lambda \approx$ 0.34, offers a minimum DEP $\approx$ 0.09. These last two algorithms perform better than the rest for almost any value of δ_λ, but the cooperative 2FT-CED-1AT-MED with 'AND' FC performs better, which alter the best decision provided by the maximum SNR SU.

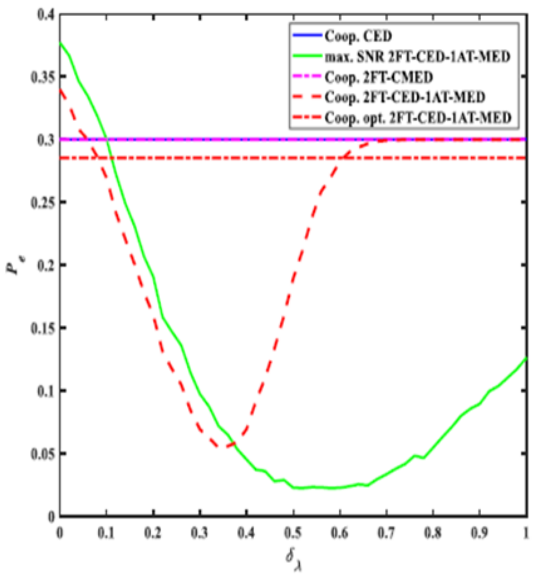

Figure 5.4 *Comparison of Pe and δ_λ for cooperative ED algorithms with four SUs, α = 0.3, L =5, and the 'AND' fusion center voting rule.*

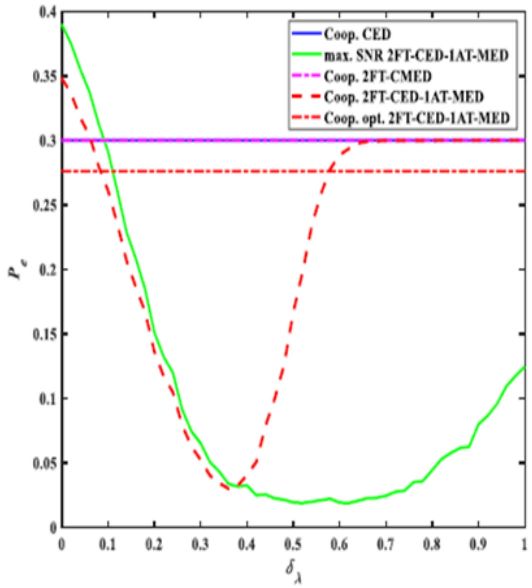

Figure 5.5 *Comparison of Pe and δ_λ for cooperative ED algorithm with four SUs, α = 0.3, L =7, and the 'AND' fusion center voting rule.*

As noticed in Figures 5.4 and 5.5, as compared to Figure 5.3, when L increases the minimum DEP value for the cooperative 2FT-CED-1AT-MED with 'AND' FC gets closer to the minimum DEP of maximum SNR single SU 2FT-CED-1AT-MED. This is explained by the fact that when the mean energy for the received signal is better estimated by all SUs, their individual decisions, which are sent to FC, become more accurate. Also, the individually optimized decision scenario 'Coop. opt. 2FT-CED-1AT-MED' performs slightly better, but still worse than the minimum DEP cooperative 2FT-CED- 1AT-MED. In Figures 5.6-5.9 that illustrate the DEP results for the same scenario as in Figures 5.3-5.5, but for an 'OR' voting rule. Mainly, that observes here the same general dependency of DEP on δ_λ and L. However that considered a new value for L = 20 (Figure 5.5), because the minimum DEP value for the 'OR' rule requires a larger window for the mean energy estimation as compared to the 'AND' rule case presented in Figures 5.3-5.5. Moreover, the DEP for the adaptive threshold algorithms (cooperative 2FT-CED-1AT-MED and maximum SNR single SU 2FT-CED-1AT-MED) perform worse than the other algorithms for more values of δ_λ. This is explained earlier, the 'OR' rules increases considerably the probability of false alarms, which increases the DEP.

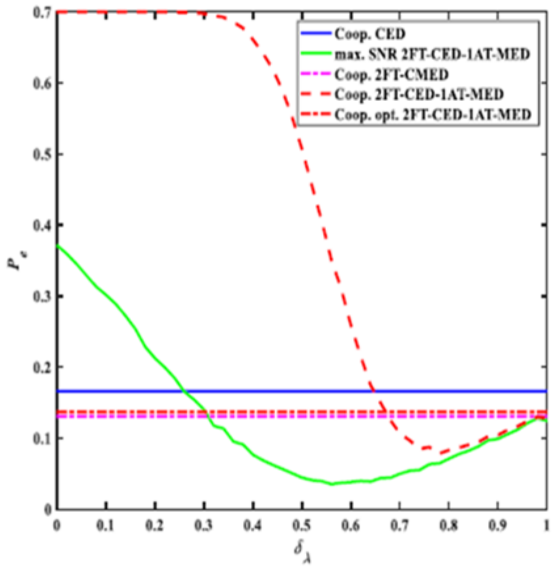

Figure 5.6 *Comparison of Pe and δ_λ for cooperative ED algorithms with four SUs, α = 0.3, L= 3, and the 'OR' fusion center voting rule.*

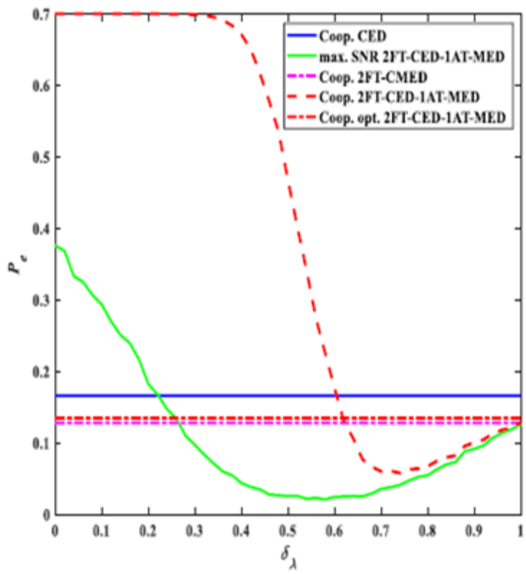

Figure 5.7 *Comparison of Pe and δ_λ for cooperative ED algorithm with four SUs, α = 0.3, L =5, and the 'OR' fusion center voting rule.*

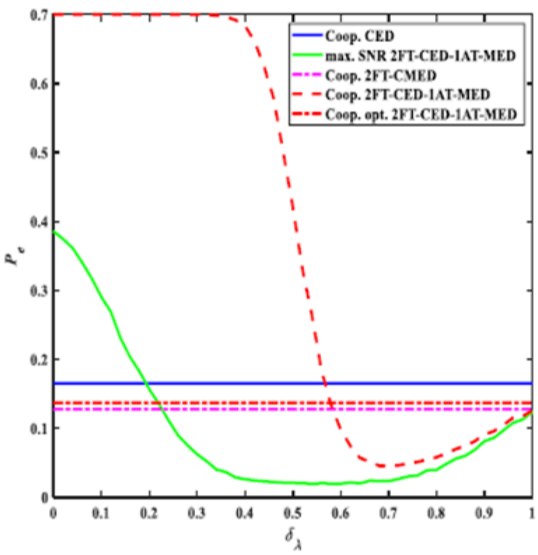

Figure 5.8 *Comparison of Pe and δ_λ for cooperative ED algorithms with four SUs, α = 0.3, L =7, and the 'OR' fusion center voting rule.*

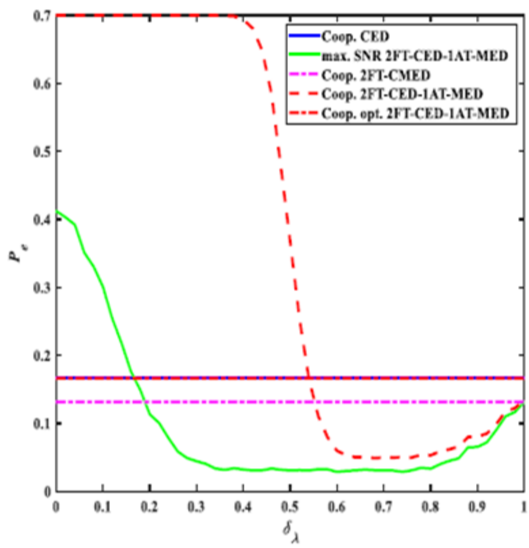

Figure 5.9 *Comparison of Pe and δ_λ for cooperative ED algorithm with four SUs, α = 0.3, L =20, and the 'OR' fusion center voting rule.*

5.4.2 Probability of decision error as function of duty cycle

In Figures 5.10 and 5.11 that consider the DEP analysis for the 'OR' voting rule, under the same simulation scenario as in Figure 5.6 (L = 3), for different values of the duty cycle, α = 0.5 (Figure 5.10) and α = 0.7 (Figure 5.11). Comparing these last two figures with the corresponding plots obtained for α = 0.3 (Figure 5.6). Obviously, the minimum value of DEP for each adaptive algorithm depends on α, but it is important to note that these functions are also convex with the threshold value, for any α.

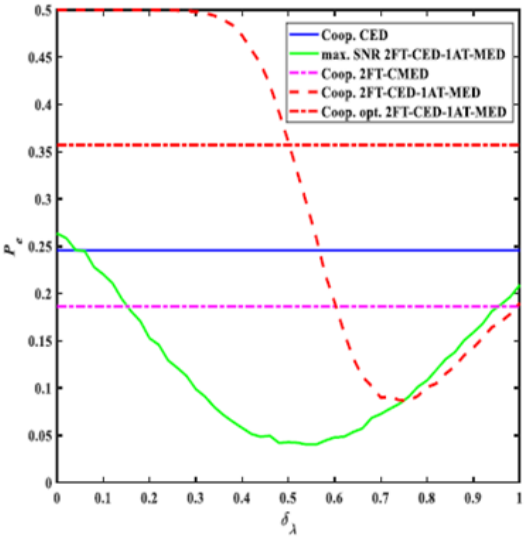

Figure 5.10 *Comparison of Pe and δ_λ for cooperative ED algorithms with four SUs, α = 0.5, L =3, and the 'OR' fusion center voting rule.*

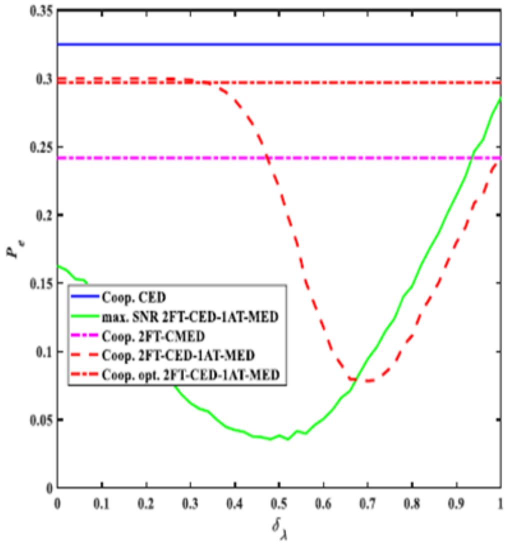

Figure 5.11 *Comparison of Pe and δ_λ for cooperative ED algorithms with four SUs, α = 0.7, L =3, and the 'OR' fusion center voting rule.*

5.4.3 Decision error probability as function of number of sensing slot for mean energy test

In order to have a better representation of the DEP dependency on L, which was noticed in all plots from Figures 5.3-5.9, performed these separate experiments for both voting rules. Hence, the DEP as a function of L is represented in Figure 5.12 for the 'AND' voting rule and in Figure 5.13, for the 'OR' rule, respectively. It was expected, for the adaptive threshold algorithms, the DEP decreases with L. However, the DEP performance of the proposed cooperative 2FT-CED-1AT-MED algorithm depends on the voting rule. For example, in the case of 'AND' rule, when L increases, the DEP of the proposed algorithm decreases and tends to the DEP of the maximum SNR single SU 2FT-CED-1AT-MED algorithm (see Figure 5.12). On the other hand, for the 'OR' rule, even the DEP decreases with L, it converges to a higher value than for maximum SNR single SU 2FT-CED-1AT-MED. As an obvious conclusion, the 'AND' rule is more efficient than 'OR' for this cooperative spectrum sensing method.

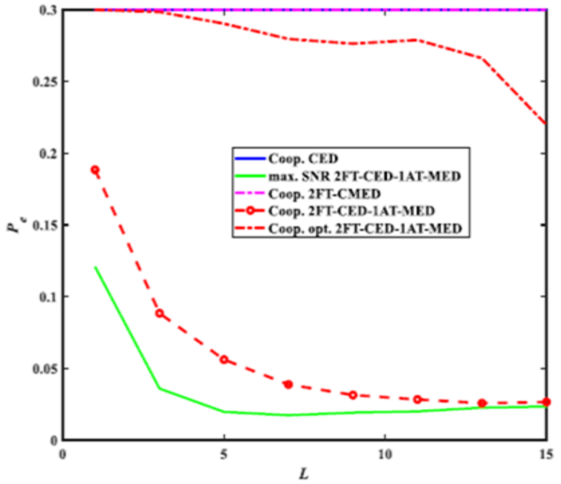

Figure 5.12 *Comparison of Pe and L for cooperative ED algorithms with four SUs, α = 0.3, and the 'AND' fusion center voting rule.*

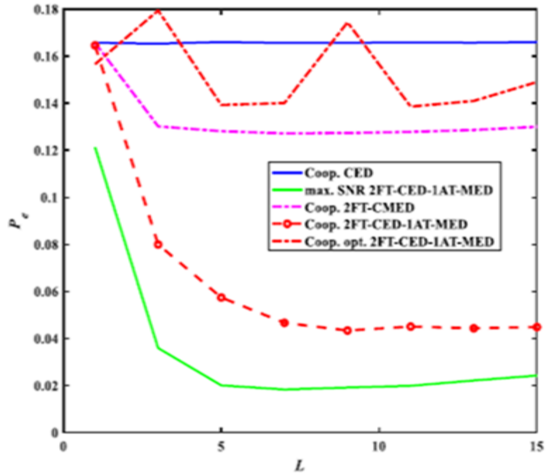

Figure 5.13 *Comparison of Pe and L for cooperative ED algorithms with four SUs, α = 0.3, and the 'OR' fusion center voting rule.*

5.4.4 Probability of decision error as function of the number of SUs

This estimated of the DEP for a different number of SUs, N_{SU}. That considered again a typical scenario: the same parameter values with L = 3, α = 0.3 with ‘AND’ FC voting rule. That assumed for all SUs, their SNR values are equally distributed in the range $SNRi \in [-26, -10]$ dB, always including the maximum SNR value of −10 dB. These results are presented in Figure 5.14. That notices the maximum DEP decrease for the proposed cooperative 2FT-CED-1AT-MED algorithm is obtained when increase the amount of SUs from 1 to 2. When that continue to add more SUs, the DEP improvement is not significant anymore, because the additional SUs will also have smaller SNR values, and thus, they alter the FC voting. Due to the same reason, the performance of the proposed cooperative 2FT-CED-1AT-MED algorithm will never reach the performance level of the maximum SNR single SU 2FT-CED-1AT-MED, no matter how many SUs that add.

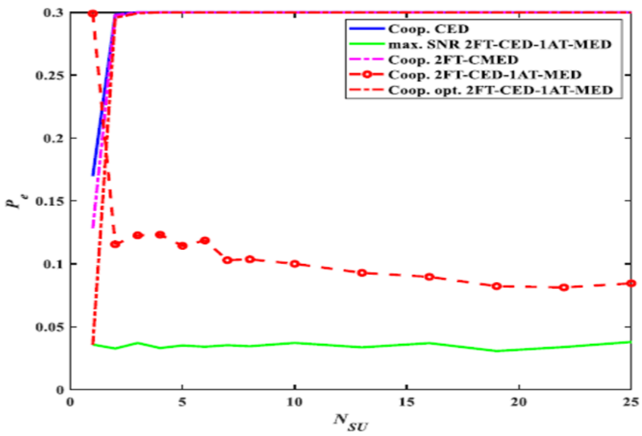

Figure 5.14 *Comparison of Pe and N_{SU} for cooperative ED algorithms, with equally distributed an $SNR \in [-26, -10]$ dB, L=3, α = 0.3, and the ‘AND’ FC voting rule.*

Chapter 6

Strategy for Non-Orthogonal Multiple Access and Performance in 5G and 6G Networks

The purpose of this chapter is to provide a high-level overview of the most important non-orthogonal multiple access (NOMA) protocols in 5G and 6G networks that incorporate code division within the context of 3GPP standardization. The chapter objective is also to look into and compare the various strategies that have been proposed as a solution to the issue of resource distribution to achieve high performance. Many different NOMA plans for 5G and 6G systems have been suggested by a multitude of businesses. NOMA is currently developing in two primary directions: one is with power division, and the other is with code division. During the process of standardization carried out by the 3GPP, the attention of the developers was concentrated in the second direction for the application of NOMA schemes in 5G and 6G systems.

6.1 Objective of the NOMA conception

NOMA is a technology that can increase the effectiveness of orthogonal access systems due to its compatibility with other multiple access methods, its adaptability in the use of system resources, and the simplicity. It can connect and operate a large number of subscriber devices. TDMA and FDMA are two well-established orthogonal signal separation technologies employed in modern multichannel communication systems [28]. When using orthogonal access, each user is given exclusive use of a separate signal or frequency range. Multiple users can share the same frequency or specific time in a network that employs NOMA.

6.2 NOMA code-separated techniques

Based on subscriber signal code division, 3GPP described various NOMA systems. The proposed schemes for existing 5G scenarios did not show a significant advantage over the used 5G technologies; hence, NOMA was not included in 5G standards but was further studied for new scenarios [29].

6.2.1 Development of NOMA technology

Power division (power domain NOMA) and code division (code domain NOMA) are the two basic kinds of NOMA schemes. In the first case, channel users may broadcast at different decibel levels. Code division NOMA does not use orthogonal code sequences to partition subscriber signals, unlike traditional CDMA systems, which have a capacity proportionate to the number of code sequences [30].

6.2.2 Low-density spreading by CDMA technology

LDS sequences with CDMA and OFDMA were used to make the first code division NOMA schemes. LDS–CDMA, an enhancement of CDMA employing low-density codes was introduced over ten years ago [31]. Due to LDS sequences, LDS–CDMA technology can use a multi-user reception algorithm that is comparable to the algorithm that maximizes the probability of users. Consider an LDS–CDMA system with K = 6 users using sequences of length N = 4. Information symbols reflect into code sequences using the following formula:

$$S = \underset{M^k M^w}{\begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 \end{bmatrix}} \tag{6.1}$$

In this case, the signal base is represented by the number of rows in the matrix S, and the number of subscribers who access these sequences is represented by the number of columns. A loading ratio of 150%, the system can support far more users than standard CDMA networks. A graphical representation of this system is provided in Figure 6.2; user 1 (x_i) represents subscriber information symbols and y_1 represents elements in received code sequences.

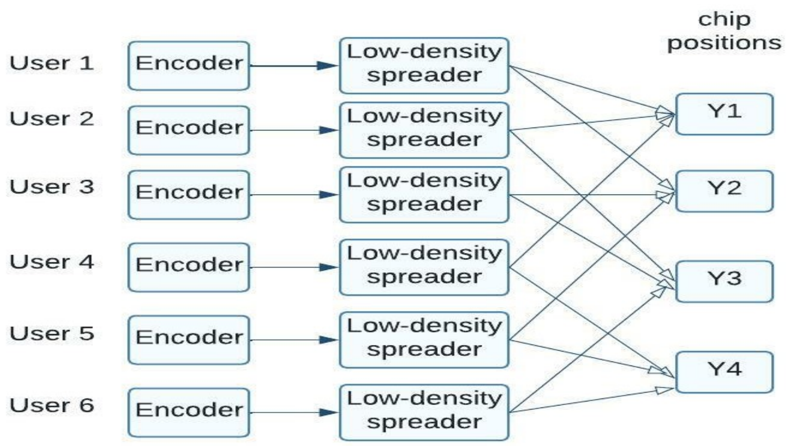

Figure 6.2 *Illustration of an LDS–CDMA systems and basic architecture.*

6.3 Code division with processing

In the development of 3GPP standardization, two primary groups of schemas were presented for the development of the NOMA direction with code division. These groups are distinguished by the type of processing they perform: either at the bit level (before the modulator) or at the symbol level (after the modulator). In Figure 6.3 illustrate a block schematic of a bit-level processing NOMA system.

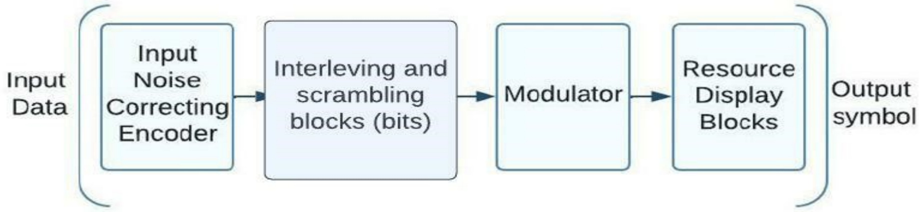

Figure 6. 3 *A schematic of the sending side of a NOMA system that shows processing at the bit level.*

6.4 MA with code separation

The 3GPP document also suggests NOMA circuits with processing at the symbol level (after the modulator), which include numerous variations that differ in the way NOMA group signals are produced. These NOMA circuits feature processing at the symbol level. When processed at the symbol level group signals that are compliant with the 5G requirements can be generated using a number of different methods [32], such as individual interleaving for each subscriber with the addition of invalid characters or the use of individual code sequences for diverse subscribers using modulation types that are already specified in the 5G standards.

6.4.1 Individual code sequences for traditional 5G modulation subscribers

Code sequences with a high number of zero elements and a low level of cross-correlation between the signals of various subscribers are frequently used for this method of group signal formation [33]. The building blocks of these sequences can be derived from the 3GPP-defined BPSK, QPSK, or QAM signal structure standards. Figure 6.4 shows the transmitting side structure of a NOMA system using the 5G modulation that has been in use up to this point.

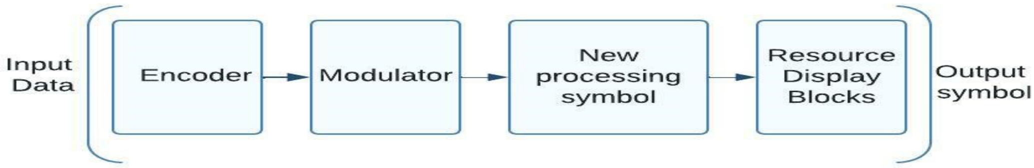

Figure 6.4 *A schematic of a 5G-modulated NOMA transmission system.*

6.4.2 Implementing belch sequences in NOMA models

Two examples of Welch sequence (Welch bound equality)-based NOMA variants are Qualcomm's RSMA and Ericsson's WSMA. Welch boundary equality is an equality used to make WBE sequences.

$$B_{Welch} = {K^2}/{N} \tag{6.2}$$

The block diagram of the WSMA system's subscriber station's transmitter is depicted in Figure 6.5. It is optional to scramble the bits after they have been subjected to noise-correcting coding (bit-level processing). The data are then subjected to quadrature amplitude modulation (QAM), spread, and interleaved with code sequences. The WSMA system employs short WBE sequences with a low cross-correlation coefficient. [34].

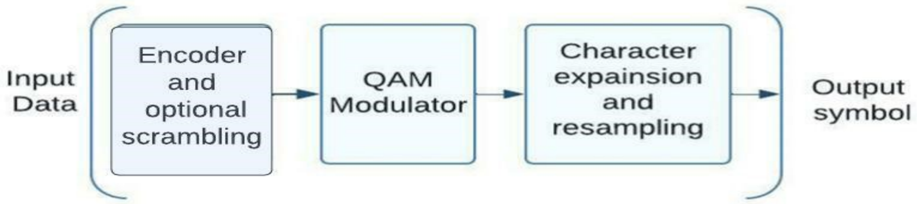

Figure 6.5 *Aspect of the WSMA scheme concerned with structural transmission.*

Depending on the required characteristics of the sequence matrix S, the efficiency indicator is selected, for the WSMA scheme, total square correlation (TSC) coefficient, which is bounded by equality (6.2) and specified by the relation,

$$TSC = \sum_{i=1}^{K}\sum_{j=1}^{K}|S_i \quad 'S_j|^2 \geq K^2/L \tag{6.3}$$

6.4.3 Grassmannian-sequence-based NOMA protocols founded on the generalized welch equality

Grassmannian sequences provide the foundation for LG Electronics' NCMA proposal; this is made use of these sequences. When making these kinds of sequences, a more severe optimization strategy is applied in comparison to the WSMA scheme. This strategy involves minimizing the greatest level of mutual correlation that can exist between any two WBE sequences.

$$\sum\nolimits_{I=1}^{K}\sum\nolimits_{J=1}^{K} P_I P_J \left|S_i S_j\right|^2 \geq \left(\sum\nolimits_{k=1}^{K} P_k\right)^2 /N. \tag{6.5}$$

$$R_s = \|S'PS\|^2 = \sum\nolimits_{i=1}^{k}\sum\nolimits_{j=1}^{k} P_i P_j \left|S_i{}'S_j\right|^2 \tag{6.6}$$

The matrix is $G = [S_1 \ldots . S_K]$, which consists of vectors of sequential values and $G \subset C^{N \times K}$ where $C^{N \times K}$ is the set of complex matrices with the dimensions $N \times K$, N is the length of the sequences, and K is the total number of sequences.

6.4.4 Sequence-based NOMA schemes with reconfigured modulation based on sparse templates

Figure 6.6 illustrate a block diagram of a NOMA system with sparse patterns and modified 5G modulation on the transmitting side of subscriber stations.

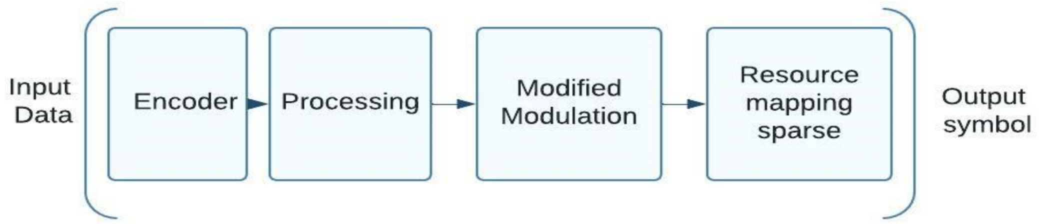

Figure 6.6 *Sparse pattern and modified 5G modulation NOMA system structure.*

In this scenario, SCMA employs codes where the number of leading zeros is constant across all templates. The purpose of subscribers below is a sample sequence template with four elements:

$$S = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 \end{bmatrix} \tag{6.7}$$

In this configuration, each column of the matrix S corresponds to a different subscriber, and the number of rows is equal to the total number of elements in each sequence.

6.4.5 A Character-level extension and scrambling implementation of a NOMA system

Figure 6.7 illustrates that the process for scrambling can also be used at the symbol level. This is shown in the diagram [35].

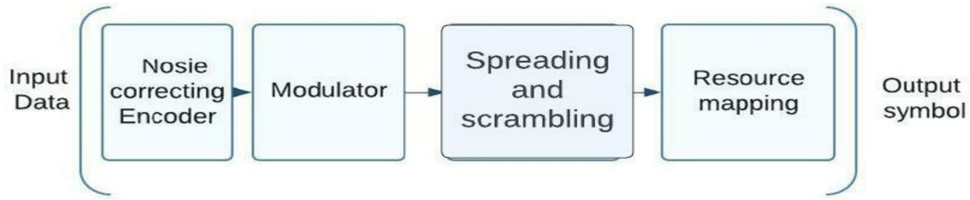

Figure 6.7 *Design of a NOMA system's character-level hybrid processing.*

In the RSMA technique introduced by Qualcomm, each modulated symbol has its own brief expanding sequence that is employed during symbol expansion.

6.4.6 Character-level NOMA scheme with zero-adding interleaving

Figure 6.8 illustrates a block diagram of a NOMA system that includes interleaving and zero element addition at the symbol level (from the perspective of the subscriber station). After the interference code has been processed, the bit level is entered. The Samsung IGMA (interleaved grid multiple access) system employs a similar transmitting side arrangement [36].

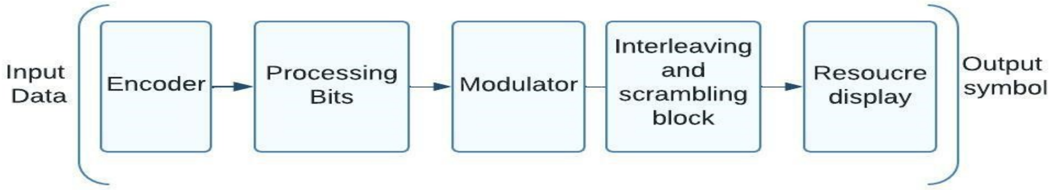

Figure 6.8 *NOMA system structure with interleaving and zero elements.*

6.5 Characteristics of the methodology of implementing NOMA schemes

Since NOMA systems use complicated code sequences, sophisticated methods of modulation and coding, and complex algorithms for multi-user reception of such signals, their processing is inherently difficult. The widely used SCMA method, for instance, requires both sophisticated transmitting code and elaborate receiving signal processing algorithms. Complicated algorithms for the multi-user receipt of such signals are necessary for the MUSA system due to its usage of complex sequences. Trellis coding techniques are the most difficult to implement in an LPMA setting. Research into efficient algorithms for making code and coding, innovative methods of modulation and mapping, and combinations with orthogonal access schemes and MIMO technology are all areas that 3GPP standardization members have identified as requiring further investigation. The 3GPP paper emphasizes the significance of developing low-computability algorithms for multi-user receipt of NOMA signals [37],[38].

6.6 Conclusions

It was suggested NOMA technology be used to address these issues. Many different types of non-orthogonal access have been proposed as part of the 3GPP standardization process, but no final decision has been taken on the regulation of the usage of any particular NOMA schemes. The 3GPP technical analysis demonstrates that the high complexity of implementing algorithms for the generation and processing of signals. This technology would be useful for a variety of uplink and downlink application scenarios in both current and future 5G and 6G systems.

Chapter 7

Average Energy Detection with Adaptive Threshold for Spectrum Sensing in Cognitive Radio Systems

In this chapter, introduce non-adaptive CED, ACED, A3EED, and AAED algorithms with an adaptive sensing threshold, which are some of the most popular approaches for spectrum sensing in CR systems. The algorithm described in this study is analyzed and demonstrated with numerical results from simulations. The simulation results show that the AAED algorithm is significantly more effective than the alternatives in terms of reducing the decision error probability. For spectrum sensing, its performance is demonstrated to be superior to that of the CED, ACED, and A3EED algorithms [41].

7.1 Average energy detection algorithm

In the CR network, each SU estimates the energy of the sampled received signal$y(n)$, where *n* denotes the *n*-th sample from a sensing slot of *N* samples. Hence, the energy of the received signal estimated for the *i-th* sensing slot is given by $E_i = \sum_{n=(i-n)\cdot N+1}^{i.N} |y(n)|^2$. Its assume that the received signal at each SU during the *i*-the sensing slot is given by

$$y(n) = \beta_i . S(n) + \omega(n) \tag{7.1}$$

One method to enhance the detection performance of the CED algorithm, the energy can be estimated in *L* consecutive sensing slots and a new test statistic can be generated by computing the average energy (AE) value, for the last *L* slots with the *i-th* slot being the last, as [3],[19],[26]:

$$\overline{E_{\iota,L}} = \frac{1}{L}\sum_{k=1}^{L} E_{i+k-L} \tag{7.2}$$

If its use the AE from (7.2) as a test statistic with a given sensing threshold *λ*, then the probabilities of correct detection and false alarm for this average energy detection (AED) algorithm are given by [3]:

$$P_d^{AED} = Prob(\overline{E_L} > |H_1) \tag{7.3}$$

And

$$P_{fa}^{AED} = Prob(\overline{E_L} > |H_0) \tag{7.4}$$

In low SNR regimes, the number of samples N is very large, and thus, the tail part of the probability density function of the received signal average energy $\overline{E_L}$ for values higher than the sensing threshold is approximated by a normal distribution [39],[40], for each hypothesis, such as:

$$\overline{E_L} \sim \begin{Bmatrix} N\left(\mu_{AE,0,}\sigma_{AE,0}^2\right), for\ H_0 \\ N\left(\mu_{AE,1,}\sigma_{AE,1}^2\right), for\ H_1 \end{Bmatrix} \tag{7.5}$$

Where $\mu_{AE,j}$ and $\sigma_{AE,j}^2$ represent, respectively, the mean value and the variance of the average energy $\overline{E_L}$, estimated for the H_j hypothesis, with $j \in \{0,\ 1\}$. Using the assumption made and the notations introduced in (7.5), the probabilities of correct detection and false alarm from (7.3) and (7.4), respectively, can be written as:

$$P_d^{AED} = Q\left(\frac{\lambda - \mu_{AE,1}}{\sigma_{AE,1}^2}\right) \tag{7.6}$$

$$P_{fa}^{AED} = Q\left(\frac{\lambda - \mu_{AE,0}}{\sigma_{AE,0}^2}\right) \tag{7.7}$$

7.2 Adaptation of the AED sensing threshold for minimum decision error probability

In this section, it will use the sensing threshold optimization method, which minimizes the DEP for the AED algorithm [23],[24]:

$$P_e = (1 - \alpha).P_{fa} + \alpha \cdot (1 - P_d) \tag{7.15}$$

The DEP is a metric that addresses both sources of decision errors in a SS, the false alarm and misdetection events [23]. Hence, a performance optimization may consider the minimization of the DEP function from (7.15) with the decision threshold value as an argument [24]:

$$\lambda_{opt} = \underset{\lambda}{argmin}\ P_e \tag{7.16}$$

Next, it will apply the optimization from (7.16) to the AED algorithm presented in Section 7.2. Hence, using in (7.15) the expressions of P_{fa}^{AED} and P_d^{AED} from (7.7) and (7.6), respectively, its write the optimization equation as.

$$\begin{aligned} \frac{d\ P_e^{AED}}{d\lambda} = 0 \leftrightarrow \left(\sigma_{AE,0}^2 - \sigma_{AE,1}^2\right) \cdot \lambda^2 - 2 \cdot \left(\mu_{AE,1,} \cdot \sigma_{AE,0,}^2 - \mu_{AE,0,} \cdot \sigma_{AE,1,}^2\right) \cdot \lambda \\ +\mu_{\ AE,1,}^{\ 2} \cdot \sigma_{AE,0,}^2 - \mu_{\ AE,0,}^{\ 2} \cdot \sigma_{AE,1,}^2 - 2 \cdot ln\left(\frac{\alpha}{1-\alpha} \cdot \sqrt{\frac{\sigma_{AE,0}^2}{\sigma_{AE,1}^2}}\right) \cdot \sigma_{AE,0}^2 \cdot \sigma_{AE,1}^2 = 0 \end{aligned} \tag{7.17}$$

Where the expression of the first derivative of the Q-function was used:

$$\frac{dQ(x)}{dx} = -\frac{1}{\sqrt{2\pi}}e^{\frac{-x^2}{2}} \tag{7.18}$$

The discriminant of the quadratic equation in (7.17) is given by

$$\Delta = 4 \cdot \sigma_{AE,0,}^2 \cdot \sigma_{AE,1,}^2 \cdot \left\{ \left(\mu_{AE,1} - \mu_{AE,0}\right)^2 + \left(\sigma_{AE,0}^2 - \sigma_{AE,1}^2\right) \cdot ln\left[\frac{\alpha^2}{(1-\alpha)^2} \cdot \frac{\sigma_{AE,0}^2}{\sigma_{AE,1}^2}\right] \right\} \tag{7.19}$$

That takes positive values for the regular system parameters' values.

$$\Delta > 0, \forall \alpha \in [0,1], \rho = \frac{\sigma_s^2}{\sigma_\omega^2} \leq 0\ dB, T > B \gg L - 1. \tag{7.20}$$

It results in the optimum decision threshold values, which minimize the DEP for the AED algorithm are given by:

$$\lambda_{opt,1,2} = \frac{\mu_{AE,1} \cdot \sigma_{AE,0}^2 - \mu_{AE,0} \cdot \sigma_{AE,1}^2 \pm \sqrt{\frac{\Delta}{4}}}{\sigma_{AE,0}^2 - \sigma_{AE,1}^2} \tag{7.21}$$

There is a need for an additional condition to select the optimum decision threshold value out of the pair specified in (7.21). Here, its propose the condition of the "confusion region", which is defined as the interval between the threshold values that minimize individually the target performance meters, $P_{fa,target}^{AED}$ and 1–$P_{Pd,target}^{AED}$, the false alarm and misdetection probabilities, respectively [19],[26]:

$$\lambda_H = \left[\sqrt{2N} \cdot Q^{-1}\left(P_{fa,target}^{AED}\right) + N\right] \cdot \sigma_\omega^2, \tag{7.22}$$

$$\lambda_L = \left[N - \sqrt{2N} \cdot Q^{-1}\left(1 - P_{Pd,target}^{AED}\right) + N\right] \cdot (\sigma_s^2 + \sigma_\omega^2), \tag{7.23}$$

Hence, the additional "confusion region" condition for the optimum AED decision threshold is

$$\lambda_L < \lambda_{opt} < \lambda_H \tag{7.24}$$

Checking the threshold values obtained in (7.21) using the condition from (7.24), it results that the optimum decision threshold for the AED algorithm is the following:

$$\lambda_{opt,1,2} = \frac{\mu_{AE,1} \cdot \sigma_{AE,0}^2 - \mu_{AE,0} \cdot \sigma_{AE,1}^2 - \sqrt{\frac{\Delta}{4}}}{\sigma_{AE,0}^2 - \sigma_{AE,1}^2} \tag{7.25}$$

7.3 Numerical result

In this section, it will present the theoretical and simulation performance results of the AAED algorithm in comparison with other ED algorithms such as non-adaptive CED, ACED and A3EED, respectively. Actually, the DEP performance will be estimated as a function of SNR, α and L. As will be shown next, in all these scenarios the AAED outperforms all the other ED algorithms. In all simulation scenarios, the considered values of system parameters are: the number of samples in a sensing slot is N = 65,537, the modulation used for the PU transmitted signal *s(n)* is Binary Phase-Shift Keying (BPSK), the total duration of the PU transmission cycle is T = 500 sensing slots, the total number of hypotheses made in a trial is 2,500 slots (which corresponds to 5 PU transmission cycles), and the number of simulation trials (iterations) used to average the DEP values is 10.

7.3.1 Decision error probability as a function of SNR

The first test considers the DEP variation as a function of SNR for all ED algorithms under investigation. The SNR range is set between [-25 dB and 15dB] with a step of 1 dB. In order to emphasize the dependency on SNR, it's consider a constant value for the spectrum utilization ratio, α = 0.3, which is a typical value for the current mobile communication systems.

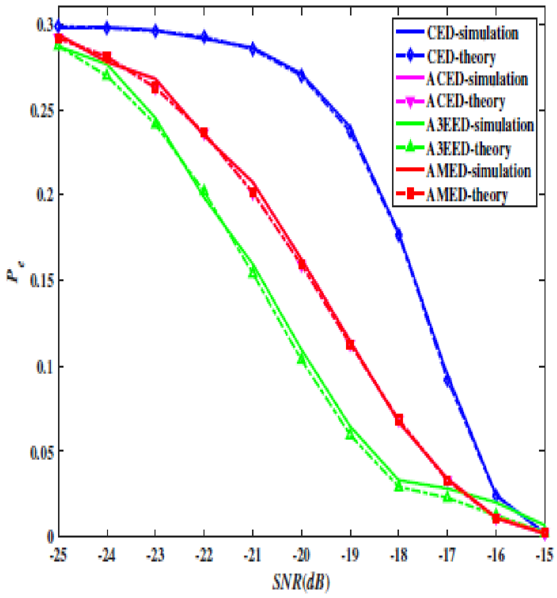

Figure 7.1 *DEP for adaptive algorithms as a function of SNR, α=0.3, L=1.*

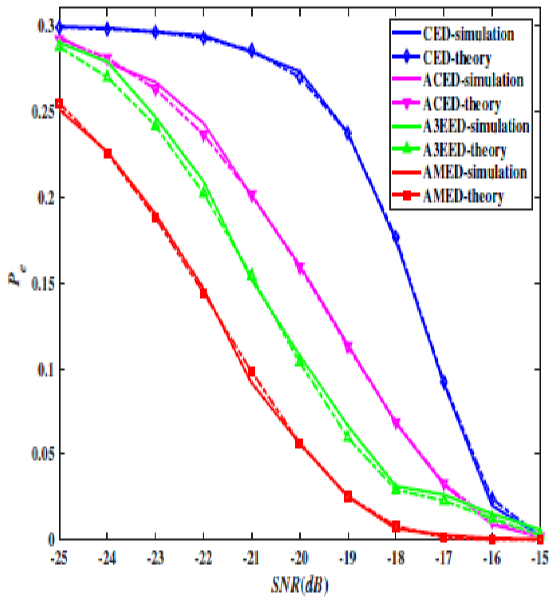

Figure 7.2 *DEP for adaptive algorithms as a function of SNR, α=0.3, L=3.*

In Figure 7.1, the DEP of AAED algorithm is estimated for a single sensing slot ED, L=1. In fact, for L=1, the average energy used as a test statistic by the AAED algorithm is equal with the energy of the received signal estimated single sensing slot. Therefore, the AAED algorithm with L=1 is equivalent with the ACED algorithm, as demonstrated by equations (7.2). This equivalency is easily noticed in Figure 7.1. Also, this plot confirms the results obtained in the previous works [23],[24], where the ACED (and AAED, with L=1) outperform the non-adaptive CED with a SNR gain up to more than 3 dB. However, the A3EED provides an additional gain of more than 1dB, which is explained by the fact that this ED method operates over 3 sensing slot, while all the other algorithms operate over a single slot. Therefore, in the next step it's decided to increase the number of sensing slots used for AE estimation to L=3 (see Figure 7.2). Surprisingly, the AAED with L=3 outperforms A3EED by more than 1 dB at all considered SNR values. Moreover, the AAED eliminates the additional decision delay of up to one sensing slot introduced by A3EED as mention it in [24]. Figure 7.3 shows the DEP for AAED with L=7, where a SNR gain of more than 3 dB is obtained over A3EED.

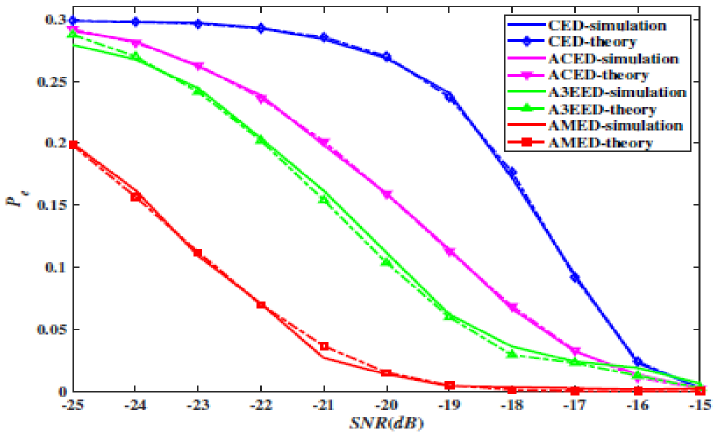

Figure 7.3 *DEP for adaptive algorithms as a function of SNR,* $\alpha = 0.3$, *L=7.*

In Figures 7.4 and 7.5, for L=13 and L=17, showing SNR gains over A3EED of more than 4 dB and 4.5 dB, respectively.

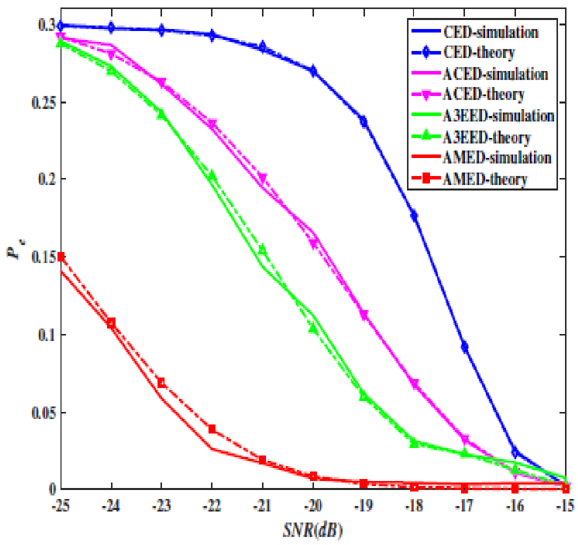

Figure 7.4 *DEP for adaptive algorithms as a function of SNR, α=0.3, L=13.*

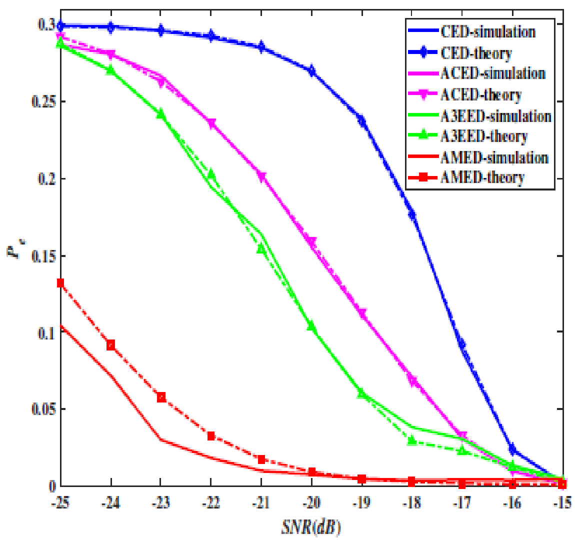

Figure 7.5 *DEP for adaptive algorithms as a function of SNR, α=0.3,L=17.*

7.3.2 Decision error probability as a function of *L*

In Figures 7.6 and 7.7, it's depict the DEP variation with L for the AAED and the other ED algorithms for two different SNR values, SNR = −22 dB and SNR = −20 dB, respectively. As notice in both figures, the only ED algorithm that depends on the number of sensing slots is AAED and that is why the DEP performance of this algorithm improves with L. In Figure 7.6, it notices that starting from L = 3 up to L = 13, the DEP decreases by a factor of more than 3. Also, increasing the number of energy averaging sensing slots above L = 13 brings no performance gain and limits upwards the complexity of the AAED algorithm. For a higher SNR value (SNR = −20 dB), as depicted in Figure 7.7, the DEP decrease with L is also noticed, but it reaches a flat region for a lower value of the number of slots, around L = 10. Moreover, as expected, for higher SNR values, the DEP takes lower values. In all cases, the DEP for AAED takes lower values that all the other considered ED algorithms.

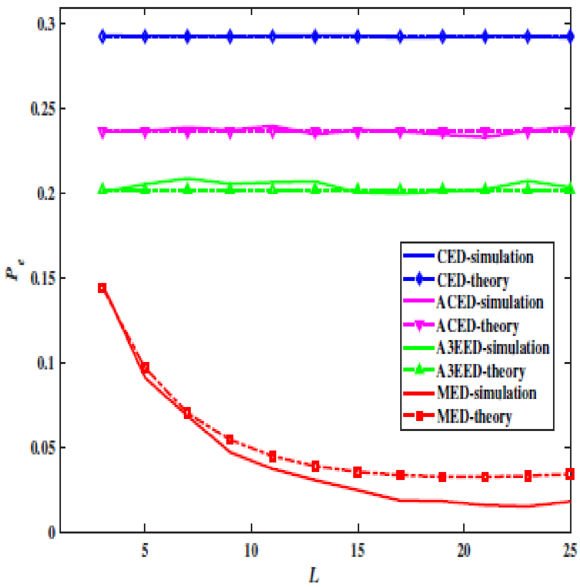

Figure 7.6 *DEP for adaptive algorithms as a function of SNR, α=0.3,SNR = - 22dB.*

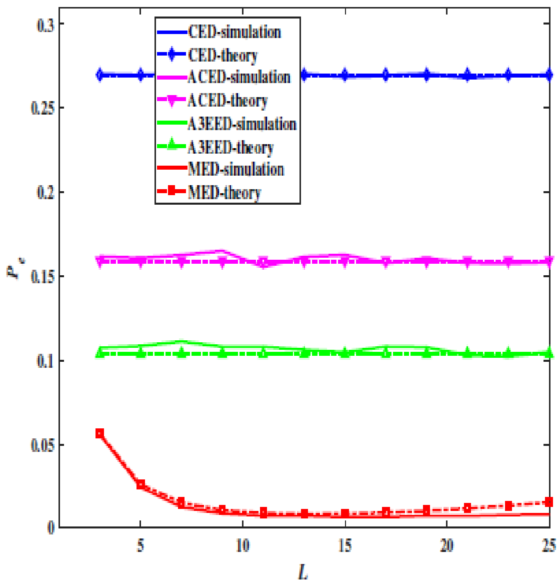

Figure 7.7 *DEP for adaptive algorithms as a function of SNR, α=0.3,SNR =- 20dB.*

7.3.3 Decision error probability as a function of α

In this test, it's set the value of the number of sensing slots used for AE estimation to L = 7, which is a good compromise between the performance and complexity levels. In Figures 7.8 and 7.9, it can be seen that the DEP for AAED reaches the minimum values among all considered ED algorithms. For the non-adaptive CED, it notices a linear increase of DEP with α, which is explained by the fact that the decision threshold is not adjusted at all. For all the other ED algorithms, which adaptively adjust the decision threshold for reaching a minimum DEP for any α value, also notice a concave shape of the DEP plot with α, with the maximum value for α = 0.5. Also, the larger the SNR, the smaller the DEP, as it observes the DEP decrease in Figure 7.9 as compared to Figure 7.8.

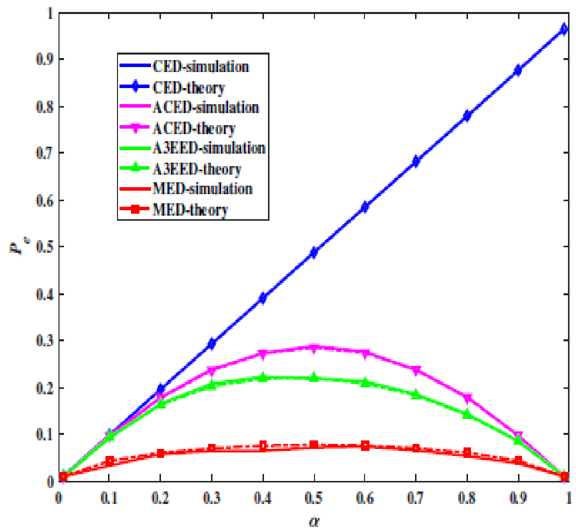

Figure 7.8 *DEP for adaptive algorithms as a function of α,L=7. SNR = - 22 dB.*

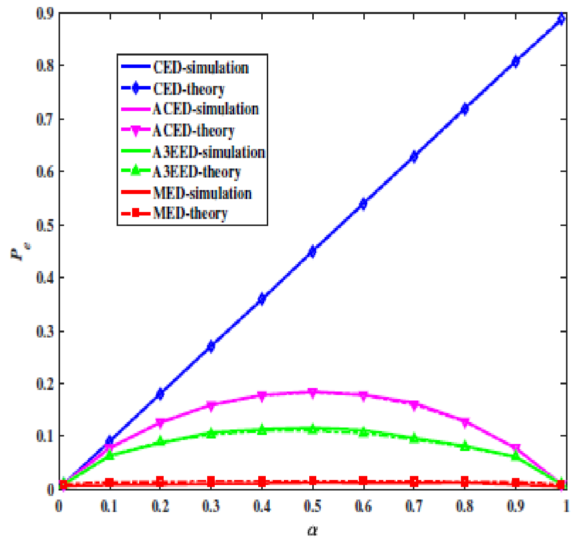

Figure 7.9 *DEP for adaptive algorithms as a function of α,L=7. SNR = - 20 dB.*

Chapter 8

Conclusion

By designing efficient SS strategies, the aim is to maximize the potential benefit of PU signal detection while minimizing sensing errors in CR networks. Therefore, the focus of this thesis is on designing efficient algorithms that conform to specified levels of sensing reliability. Both centralized and distributed sequential hypothesis testing form the basis of those systems. The suggested cooperative decentralized SS methods find their major usage in slotted primary user transmission systems, while centralized cooperative SS schemes use SU individual sensing to send this information to FC that takes the final decision. Other solutions for improved sensing performance include the use of multiple decision thresholds and the threshold value adaptation in accordance to an optimum performance meter. All these CR sensing solutions were investigated with a single purpose to identify unoccupied spectrum and empty frequency bands quickly and accurately. A secondary main research goal was to develop resource distribution and spreading solutions for multiple accesses in mobile networks. Considering the success of the NOMA proposals for 5G and 6G networks, the present thesis considered some of its development strategies for both power and code division versions.

8.1 Obtained results

The thesis is structured into eight chapters that present in an intuitive manner the general context and the scope of the research, the conventional solutions for the raised problems, the usual research methods and analytical approaches, and some proposed solutions with their performance analysis, as follows:

Chapter 1 presented the general research field of the doctoral thesis, describing the concept of CR systems and networks and DSA, with the accent on spectrum sensing function. Also, as a second research scope, the NOMA technology was presented. In this context, the scope of the thesis and the main research objectives were described.

Chapter 2 the principle and the architecture of CR networks were thoroughly explained and analyzed. Here, the most used SS algorithms were reviewed, including the non-cooperative and cooperative solutions. Moreover, the concept of NOMA technology and the possible combination with CR networks were investigated.

Chapter 3 presented a cooperative SS scheme for CR, which uses a distributed amplify and forward (AF) configuration with more SUs. First, the AF CSS scheme with two SUs from the seminal work was presented and second, the modified and improved scheme with three SUs was proposed and analyzed. A simplified channel model was proposed and used for estimating analytically the channel gains and received and relayed PU signal. The detection performance of the novel three SUs AF scheme using the ED for spectrum sensing was investigated, both theoretically and by simulation, and significant detection gains were noticed as compared to the reference scheme.

Chapter 4 was dedicated to the presentation of single-SU or non-cooperative SS algorithms using ED for which the detection performance is controlled by setting the decision threshold value with respect to a specific meter. Hence, the conventional ED SS algorithms using one or two decision thresholds were analyzed analytically and by simulation. The test statistic can be enhanced by gathering information from adjacent sensing time slots. It was considered time averaging over several consecutive sensing slots for the received signal energy as a test statistic modification function. Also, the adaptation of decision threshold values for minimizing the detection error was investigated. This adaptive threshold approach was demonstrated to improve the detection performance considerably as compared to fixed threshold value approach.

Chapter 5 integrated the adaptive threshold techniques from the previous chapter in cooperative spectrum sensing configurations. Several cooperative schemes were considered with variable number of decision thresholds and simple voting rules at the FC node. It was also explored the impact of the FC voting decision rule on the performance of cooperative SS algorithm. As in Chapter 4, it was developed an adaptive control mechanism for the intermediate detection threshold in each SU to reduce the decision error probability. The simulation results confirmed the effectiveness of the suggested algorithm.

Chapter 6 investigated the NOMA solution for the development of performant 5G and 6G wireless communication networks. Several spreading techniques for NOMA were investigated, such as low-density spreading, code division with bit-level processing and code separation, and character-level spreading. The chapter concluded on the methodology of implementing the NOMA schemes using these spreading solutions.

Chapter 7 the single-SU average ED with adaptive threshold was investigated theoretically and by simulation experiments. In fact, this AAED algorithm was used in Chapters 4 and 5, in cooperative configurations and there it was demonstrated its impact on the overall SS performance. Analytical expressions were derived for the DEP meter as a function on the SS parameters, such as: SNR, number or averaging sensing slots, and PU's duty cycle. The simulations confirmed all the theoretical assumptions made. It was showed that spectrum sensing solutions with AAED outperforms CED, ACED, and A3EED algorithms.

Chapter 8 presented the obtained results, original contributions with the accent on the author's publications, and the perspectives and future works of the current PhD research.

8.2 Original contributions

Several SS algorithms, either cooperative or single-SU methods, based on ED have been analyzed and improved as part of this thesis. These proposed SS techniques have enhanced the CR system's detection performance when compared to previous strategies. Also, some NOMA novel spreading techniques were investigated. The following part is a summary of the main contributions of the thesis:

1. I studied the principle and the functions of the CR networks and systems. In this context, I wrote a survey on CR and dynamic spectrum access solutions that is part of the first two chapters of this thesis. In context of a CR environment, a number of technologies were compared and evaluated in terms of their sensing sensitivity, the complexity of implementation, and computational requirements. I mainly focused on SS methods and algorithms and presented several perspectives on these issues. Some of these study results were published in a SCOPUS and IEEE Xplore indexed conference paper [12] and in another open-access MDPI conference paper [43]. As another possible solution for efficient spectrum management, I studied the NOMA principle and concepts, which were included in Chapter 6. In this context, I wrote, as a first author, an ISI-WOS Q2 journal paper on possible strategy for the efficient use of NOMA in 5G and 6G networks [38]. On the same matter, I published a SCOPUS and IEEE Xplore indexed conference paper [44].

2. In continuation of previous research [16], [17], I developed a novel amplify and forward cooperative detection scheme that employs 3 SUs with two secondary users SUs performing a sequential relaying strategy. Using a modified fading channel model for the channel gains between SUs, I derived analytical expressions for the statistical moments of the test variable and finally, expressions for the detection probability. I performed simulations that confirmed the accuracy of these theoretical results. Both theoretical and simulations results confirmed that adding more SUs in the cooperative AF configuration increases the detection performance with the price of an increased detection time. These results were introduced in Chapter 3 of the thesis and published in an ISI conference proceeding paper [18] and an open-access journal paper [42].
3. As another set of contributions, I mention the evaluation and modification of some double-threshold ED algorithms. Therefore, different performance meters were considered for fixing adaptively the decision threshold value and even the modification of the test variable by an additional processing function. For example, the introduction of the average energy test variable, by averaging the received signal energy over several consecutive sensing slots in conjunction with the adaptive setting of the decision threshold to minimize the decision error probability, proved to increase the detection performance of the ED algorithm. The simulation results showed that for any duty cycle, the innovative adaptive spectrum sensing technique outperforms the classic double threshold algorithm. For low duty cycles values (i.e., 30%), SNR gains of 3 dB were noticed. At high duty cycles and low SNR values, the proposed approach provides even better results. These solutions and their performance analysis were included Chapter 4 and published in a SCOPUS and IEEE Xplore indexed conference paper [19].
4. The adaptive threshold solutions presented in Chapter 4 and [19] were used to develop an efficient cooperative spectrum sensing algorithm. Therefore, in Chapter 5, I included another contribution consisting in the cooperative spectrum sensing investigation of the adaptive threshold ED with average energy test statistic introduced to each SU in the configuration and finally, the decision taken at the fusion center. Several multiple threshold ED algorithms and simple FC voting rules were compared. Also, the decision error probability was investigated considering several system parameters, such as the PU's duty cycle value, number of sensing slots used for energy averaging, and the number of SUs in the cooperative configuration. This novel cooperative SS algorithm and its simulated performance analysis were published in another SCOPUS and IEEE Xplore indexed conference paper [26].
5. Another contribution of the thesis is the theoretical investigation of the adaptive ED SS algorithm with average energy test statistic, i.e., AAED, which was analyzed only by simulations in Chapters 4 and 5. Hence, in Chapter 7 the single SU AAED algorithm was investigated thoroughly and an exact analytical expression of the decision threshold value, which minimizes the DEP value, was derived. It is important to mention that the theoretical results confirmed the simulation results

obtained previously. Also, the DEP performance results showed that AAED outperforms other known and related adaptive threshold SS algorithms. The proposed AAED algorithm and the entire theoretical analysis together with the simulation confirmation were submitted for publication in an IEEE journal [41].

6. I participated in a research investigation on the development of equipment with flexible RF front ends for effective use of the limited radio spectrum resources. The spectrum sensing performance of four different SDR platforms was analyzed and compared in an ISI conference proceeding paper [24].

8.3 List of original publications

8.3.1 Papers related to the PhD topic

1. A. Marțian, Florin L. Chiper, Omer M. Kh. Al-Dulaimi, Mahmood J. A. Al Sammarraie, C. Vlădeanu, and Ion Marghescu, "Comparative Analysis of Software Defined Radio Platforms for Spectrum Sensing Applications," in International Conference on Communications (COMM), Bucharest, Romania, pp. 369-374, June 2020, WOS:000612723900065. [ISI Proceeding]
2. Omer M. Kh. Al-Dulaimi, Mahmood J. A. Al Sammarraie, C. Vlădeanu, A. Marțian, and Dimitrie C. Popescu, "Cooperative Spectrum Sensing for Three Secondary Users with Sequential Relaying for Cognitive Radio," in International Conference on Communications (COMM), Bucharest, Romania, pp. 221-226, June 2020, WOS:000612723900040. [ISI Proceeding]
3. C. Vlădeanu, O. M. K. Al-Dulaimi and A. Marţian, "A Modified Double-Threshold Spectrum Sensing Algorithm Based on Adaptive-Threshold Mean Energy Detection", 2021 International Symposium on Signals, Circuits and Systems (ISSCS), pp. 1-4, 15-16 July Bucharest, Romania, 2021.DOI: 10.1109/ISSCS52333.2021.9497419. [Scopus, IEEE Xplore]
4. Omer. M. K. Al-Dulaimi, C. Vlâdeanu, A. Martia, Aymen. Mohammed. K. Al-Dulaimi,and Mohammed K. H. Al-Dulaim, *“Cognitive radio using spectrum sensing by cooperative two secondary users,” in* IOP conference series: Materials science and engineering, 2021, vol. 1094, no. 1, p. 12031, DOI 10.1088/1757-899X/1094/1/012031. [Open Access]
5. Omer M. K. Al-Dulaimi, Florin L. Chiper, C. Vlădeanu, and A. Marţian " Triple-Threshold Energy Detection with Adaptive Intermediate Threshold for Cooperative Spectrum Sensing," 14th International Conference on Communications (COMM), Bucharest, Romania, pp. 1-6 June, 2022, DOI: 10.1109/COMM54429.2022.9817328. [Scopus, IEEE Xplore]

6. Omer M. K. Al-Dulaimi, Aymen M. K.Al-Dulaimi, and Mohammed K.H "*Cognitive Radio Technologies and Applications in Dynamic Spectrum Access Method*" 9th International Conference on Problems of Info communications. Science and Technology, Kharkov, Ukraine, IEEE, 2022. [Accepted under publication]
7. Omer M. K. Al-Dulaimi, Mohammed K.H, Maiduc Osiceanu Alexandra and Aymen M. K.Al-Dulaimi *"Performing Strategic Spectrum Sensing Study for the Cognitive Radio Networks"* International Conference on Communications, Information, Electronic and Energy Systems (CIEES 2022), Veliko Tarnovo, Bulgaria, IEEE, 2022, DOI: 10.1109/CIEES55704.2022.9990635.[Scopus, IEEEXplore]
8. A. M. K. Al-Dulaimi, O. M. K. Al-Dulaimi and M. K. H. Al-Dulaimi, "*Implementing 3GPP Code Division for Non-Orthogonal Multiple Access in 5G*," 2022 International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT), Ankara, Turkey, 2022, pp. 998-1006, doi: 10.1109/ISMSIT56059.2022.9932803. [Scopus, IEEEXplore]
9. Omer M. K. Al-Dulaimi, Mohammed K.H, Maiduc Osiceanu Alexandra and Aymen M. K.Al-Dulaimi, *"Strategy for Non-Orthogonal Multiple Access and Performance in 5G and 6G Networks"* in MDPI sensor journal, Vol. 23, Issue 3, Article Number 1705, DOI: 10.3390/s23031705, Published FEB 2023, WOS:000930017200001. [ISI-Q1, IF 3.847]
10. Omer Mohammed. K. Al-Dulaimi, Mohammed Khodayer Hassan, Aymen Mohammed Khodayer Al-Dulaimi and Maiduc Osiceanu Alexandra "*Cognitive Radio Network Technology for IoT-Enabled Devices*" International Conference on Electronics, Engineering Physics and Earth Science (EEPES 2023). Eng. Proc. 2023, 41(1), 7, Kavala, Greece, June 21-23, 2023; https://doi.org/10.3390/engproc2023041007, [MDPI Engineering Proceedings, vol. 41]
11. Omer M. K. Al-Dulaimi, C. Vlădeanu, A. Marțian, and Dimitrie C. Popescu, "Average Energy Detection with Adaptive Threshold for Spectrum Sensing in Cognitive Radio Systems" *Submitted in IEEE journal*, August 2023. [Under publication]

8.3.2 Relevant conference and journal publications

1. Mohammed. K. Hassana, A. Hassanb, Aymen. M. Khodayerc, and Omer. M. Khodayerd, *"Internet Security Impact on E-Banking Users."* Workshop on Emerging Technology Trends on the Smart Industry and the Internet of Things, TTSIIT 2022Virtual, Kyiv, pp. 118–123, 2022. [Scopus]
2. Omer. M. K. Al-Dulaimi, Mohammed. K. H. Al-Dulaimi, and Aymen. M. K. Al-Dulaimi, "*Resource blocks for real-time and data elastic traffic in IMS/LTE networks are developed and studied"* International Middle Eastern Simulation and Modeling Conference (MESM), pp. 159–164, 2022. [Scopus]

3. Mohammed K.H, Aymen M. K.Al-Dulaimi, and Omer M. K. Al-Dulaimi " *Security Measures of Protection for Banking Systems*" 9th International Conference on Problems of Infocommunications. Science and Technology, Kharkov, Ukraine, IEEE, 2022. [ISI Proceedings pending]
4. Mohammed K.H, Aymen M. K.Al-Dulaimi, and Omer M. K. Al-Dulaimi "*Bandwidth Allocation Linear Unit with Resource Allocation Level 1 Design and Evaluation in LTE Downlink*" The second international conference on scientific research and innovation ,USA 2023.[Accepted under publication]
5. Aymen. M. K. Al-Dulaimi, Omer. M. K. Al-Dulaimi, Mohammed. K. H. Al-Dulaimi, and M. O. Alexandra, "*Design and Development of Free-Space Optical Transmission Systems and Applications*," in 2022 International Conference on Communications, Information, Electronic and Energy Systems (CIEES), 2022, pp. 1–6, DOI: 10.1109/CIEES55704.2022.9990826 . [Scopus, IEEEXplore]
6. Omer. M. K. Al-Dulaimi, Mohammed. K. H. Al-Dulaimi, and Aymen M. K. Al-Dulaimi, "*Analysis of Low Power Wireless Technologies used in the Internet of Things (IoT)*," in 2022 2nd International Conference on Computing and Machine Intelligence (ICMI), Istanbul, Turkey, 2022, pp. 1–6, doi: 10.1109/ICMI55296.2022.9873714. [Scopus, IEEEXplore]
7. Mohammed K. H, Aymen M. K, Ali Hassan, Omer M. K and Maryem M , "*Security Issues for Banking Systems*." International Conference on Computing, Intelligence and Data Analytics, ICCIDA 2022 Kocaeli 16 September 2022, Volume 643 LNNS, Pages 117 – 131, Turkey, Sept, 2022. [Springer, Scopus]
8. Mohammed. K. Hassana, Aymen. M. Khodayer, and Omer. M. Khodayer, "*Security Enhancement in Cloud Computing system (CCS)*." second international conference on emerging technology trends on the smart industry and the internet of things (TTSIIT2023), Baghdad, Iraq, January, 2023. [ISI Proceedings pending]
9. Omer Mohammed. K. Al-Dulaimi, Mohammed Khodayer Hassan, Aymen Mohammed Khodayer Al-Dulaimi and Maiduc Osiceanu Alexandra "*Deep Learning For Wireless Network Distribution (5G/LTE)*." in Electrical Engineering and computer science, International journal of University POLITEHNICA of Bucharest, 2023 . [Under publication]
10. Mohammed. K. Al-Dulaimi, Aymen M. Khodayer Al-Dulaimi, Omer M. K Al-Dulaimi and Maiduc Osiceanu Alexandra "*Aspects of Artificial Intelligent Applications in Cyber Security to Decrease Threats and Restrict Cyber Attacks for Smart Grids*" International Conference on Electronics, Engineering Physics and Earth Science (EEPES 2023), Kavala, Greece, June 21-23, 2023. [Scopus conference accepted]
11. Aymen Mohammed Khodayer Al-Dulaimi, Mohammed Khodayer Hassan Al-Dulaimi and Omer Mohammed Khodayer Al-Dulaimi, "*Construction and Analysis of Dynamic Distribution for Resource Blocks of Real-Time and Data Elastic Traffic in IMS/LTE networks*," 2021 International Congress of Advanced Technology and Engineering (ICOTEN), Taiz, Yemen, 2021, pp. 1-7, doi: 10.1109/ICOTEN52080.2021.9493500. [Scopus, IEEEXplore]

12. Omer. M. K. Al-Dulaimi, Aymen M. K. Al-Dulaimi, M. O. Alexandra and Mohammed K. H. Al-Dulaimi,"*Implementation Of Bayesian Approaches In 5G/6G For Cellular Communication Using Multiple Time Series Models*" in Electrical Engineering and computer science, UPB Scientific Bulletin, Series C, vol. 85, no. 1, pp. 209 – 226, 2023, ISSN 2286-3540, WOS:001032564800003. [ISI Journal, IF 0.3]

8.4 Perspectives for further developments and future work

As a future trend for the research, this topic can be looked into more and expanded to include cooperative quick-spectrum sensing. The spectrum-sharing algorithms and multiple-access protocols that were made for multi-user cognitive radio networks should work with this extension.

The following aspects can be explored in more detail:

- Sequential spectrum sensing and spectrum sharing could be studies in more details.
- Software-Defined Radio (SDR) hardware platforms have problems with how to implement the proposed algorithms and how hard they are to understand.
- Continued investigation of the decentralized multi-hypothesis sequential problem.

Another interesting idea for future work is to develop the user-group assignment algorithm proposed in Chapter 3 so that it takes the effect of correlation into account. Selecting users with the least amount of correlation to sense in each group can make the proposed group-based cooperative spectrum sensing scheme work even better. But more research needs to be accomplished before that can reach substantial conclusions. The first step in making a more reliable fusion scheme for multiband cooperative sensing was to look at how the time offset affected the performance of the multiband cooperative detection framework. This was done in Chapter 5. Assuming that different cooperating users have different time offsets is an easy assumption to work into that analysis. That topic can be looked into more and expanded so that reducing the effects of sensing errors caused by time offset can be thought of as a future direction for research. It can conclude that need to do more analysis of the proposed algorithm by using other voting rules, like the majority rule, or even other optimization metrics than DEP. As a future research goal, its mention the insertion of the AAED into cooperative spectrum sensing schemes, where the superior single-user decisions would contribute to even higher global decision performance.

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