Analysis of OSTBC in Cooperative Cognitive Radio Networks using 2-hop DF Relaying Protocol

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ABSTRACT

To achieve cooperative diversity in cognitive radio network, Decode and Forward (DF) protocol is implemented at Cognitive Radios (CRs) using Orthogonal Space Time Block Coding (OSTBC). The 2-hop communication between source and destination is completed with the help of Cognitive Relays (CRs) using Multiple Input Multiple Output (MIMO) technology within the network. To achieve spatial diversity and good code rate Alamouti 2×2 STBC is used for transmission. CR is using the decoding (Decode and Forward (DF)) strategy and without amplifying ability before forwarding data towards destination provide better performance. The main objective of this thesis is to detect Primary User (PU) spectrum availability or non-availability for the use of Secondary Users (SU). The Alamouti STBC encoded data is broadcasted to wireless Rayleigh faded channel through transmitter having two transmitting antennas. The CRs are preferred to place close with PU to detect transmitted signal and because of having decoding capability CRs decode the collected data using Maximum Likelihood (ML) decoding technique then re-encode the decoded data for further transmission towards receiver. The energy of PU signal received at relays is calculated using energy detector used at cognitive controller having authority to make final decision about presence or absence of PU signal within the spectrum by comparing calculated energy of PU received signal with a predefined value. If the calculated signal energy is less than threshold value it is pretended as the absence of PU and in the other case spectrum is assumed as occupied by PU. Decoding PU signal at relays before forwarding towards destination provide better performance in terms of detection probability P_d decreasing probability of false alarming P_f as the Signal to Noise (SNR) increase. The proposed cooperative spectrum sensing using DF protocol at cognitive relays with Alamouti STBC is implemented and results are validated by MATLAB simulation.

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Chapter 1: Introduction To Cognitive Radio and Radio Networks

1.1 Cognitive Radio Networks

The word cognition is the process of knowing, learning and understanding things. Cognitive Radio (CR) [1], [8], [19] is a wireless communication system which is aware of its surrounding environment and use different methodologies to learn from outer environment and also which changes the transmission and receiving parameters to communicate efficiently with licensed or unlicensed users avoiding interference [1], [2], [7]. The basic question which arises here is why CRN are important? [19], [20] .The simplest answer for this question is the shortage of radio spectrum due to overcrowding of different services. According to statistics almost 80-85% of the radio spectrum remains unused for most of the time, only 15-20% of the radio spectrum remains in use all the time [17], [18], [33]. The network in which nodes have the ability of sensing free holes in frequency spectrum of Primary User (PU) or licensed user and take the empty frequency holes without creating any interference with PU, for the communication of Secondary User (SU) or non-licensed users, is known as cognitive radio networks [1], [2], [9].

1.2 Cooperative Networks

The system in which each node is bound to cooperate for a common benefit or purpose is known is cooperative network. It has been found during research that for the detection of very low Signal to Noise Ratio (SNR) of PU, the cooperation between all nodes is necessary [1], [19], [20]. CRs cooperate with each other to achieve a common interest of detecting licensed user's transmission within the spectrum.

1.3 Spectrum Access Policies

Federal Communication Commission (FCC) [1], [7], [11] is an internationally centralized authority to allocate radio spectrum for particular service to the specific companies. When a company wants to start a service, it purchases a frequency band from FCC and in return of it, it

receives a document which shows the ownership of specific frequency band assigned to its service. No two services can have same frequency band. All the users has to pay certain amount to the company (suppose A) for using their service and when they become member of this service they are known as licensed users or Primary Users (PUs) [1], [2], [6], [20] and all others are known as unlicensed users or Secondary Users (SUs). A single user within licensed spectrum is known as Primary User (PU) and in unlicensed user it is known as Secondary User (SU). Now consider if any other company (suppose B) having different services wants to use the frequency spectrum of A for their service when spectrum A is free, will have to take permission first from owner of spectrum A [7], [8], [18]. By mutual agreement between two companies, the users of spectrum B can use spectrum A and vice versa, when it is free, without creating problem for licensed spectrum users. This concept can be well explained by Figure 1.1:

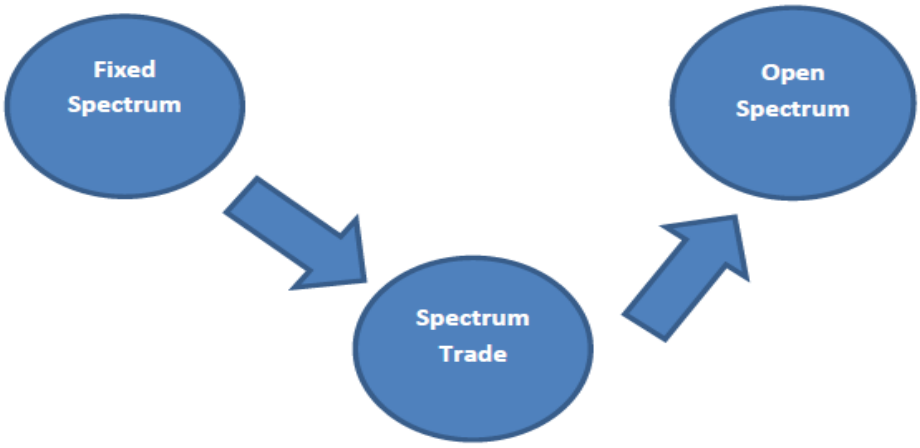

Figure 1.1. Spectrum access policies for Pus and SUs

1.4 Main Functions of Cognitive Radio

There are four main functions of the cognitive radios within cognitive cooperative network [1], [2].

1.4.1 Spectrum Sensing:

The process of detecting unused spectrum is known as spectrum sensing [1].

1.4.2 Spectrum Management:

The process of capturing the best available spectrum is known as spectrum management [1].

1.4.3 Spectrum Mobility:

The process of maintaining communication during spectrum transition is known as spectrum mobility [1].

1.4.4 Spectrum Sharing:

The process of sharing spectrum between PUs and SUs after completing above all functions is known as spectrum sharing. Spectrum sharing is the last step for reliable communication of licensed and unlicensed users to share their spectrum with each other [1], [2].

1.5 Conclusion

Due to congestion in radio spectrum it is observed that for most of time, 85% of spectrum remains free e.g. TV spectrum and some of the services have very congested spectrum e.g. mobile spectrum which remains in use for maximum of the time. The researchers found a way of sharing whole radio spectrum by any of the service after mutual agreement. Hence the concept of cognitive radio was introduced by Mitola III [1], [2], [6] in 1998 by which spectrum sharing between licensed and unlicensed users is done using cognitive radios cooperating with each other. The SUs get access to the PU spectrum when it is free, without creating any interference with PUs transmission. So it is the duty of SU to sense the free holes within PU spectrum and use it until PU transmission start again. It is the responsibility of SU to leave the spectrum before PU arrives at home, so the important function of cognitive radio is to detect PU transmitter through which it decides the presence or absence of PU transmission within spectrum.

Chapter 2: Cooperative MIMO Communication

2.1 Multiple Input Multiple Output (MIMO)

In recent wireless communication systems the major challenges are efficient use of bandwidth and improved link reliability. The radio channel suffers from fading and interference problems due to the presence of other users [1], [2], [19]. At both ends of a wireless network link, the use of multiples antennas plays an important role for the efficient use of bandwidth and link reliability as well as extra spatial degrees of freedom. Different data streams are transmitted simultaneously using multiple-antennas that results in the increased data-rate with no additional bandwidth requirements [1], [4] and also by using space-time coding technique by which the bit error rate (BER) is decreased, while no extra power is required in this case. There are limitations in wireless devices; those are the size problem and hardware-complexity so it is difficult to employ more than one antenna on mobile terminal [1], [5], [6], [7].

The cooperative communication has the characteristic of enabling single antenna mobiles in a multi-user environment to share their antennas and generate a virtual multiple antenna transmitter, hence transmit diversity is achieved [1], [23], [24]. Transmit diversity has been widely acknowledged and easily employed by MIMO system. By virtue and deployment of cooperative communication, single-antenna mobiles gain some of the benefits of MIMO systems. The fundamental concept behind the cooperative communication is that a virtual MIMO scenario is created where single-antenna mobiles in a multi-user environment interact for sharing information with multi-users antennas. In other words, different nodes in the wireless network help assist each other for transmission and relaying information so that a virtual-MIMO system transmission is established [8], [9], [20].

There are many antenna diversity schemes from those MIMO is one of them e.g. Single Input Single Output (SISO), Single Input Multiple output (SIMO), Multiple Input Single Output (MISO), Multiple Input Multiple Output (MIMO) [10], shown in Figure 2.1.

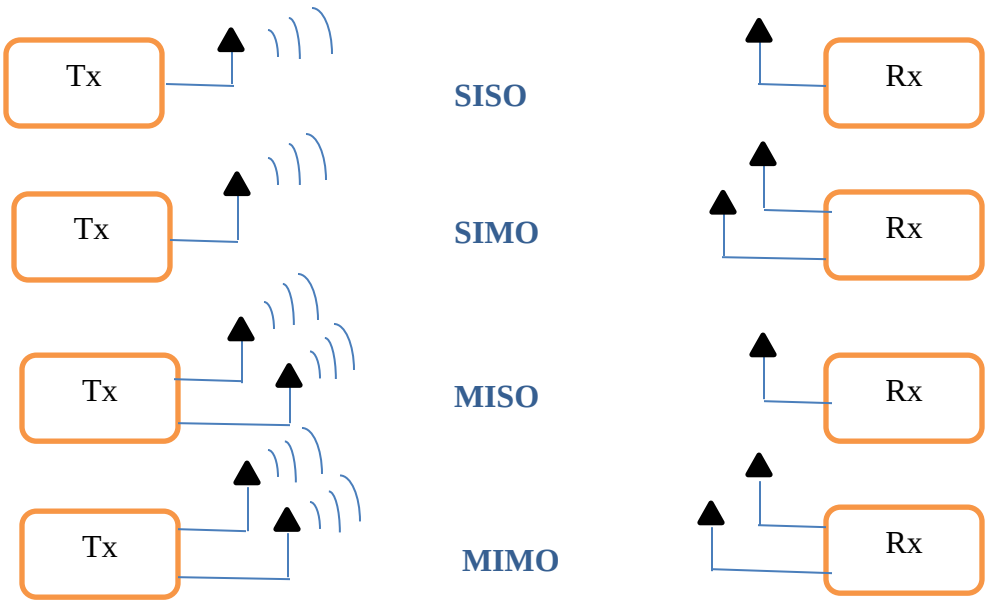

Figure 2.1. A Wireless Communication System having Multiple Antennas as Transmitter and Receiver [10]

2.2 Cooperative MIMO Communication

The coding schemes that are conventionally implemented at MIMO transmitting antennas are known as Space Time Codes (STC) which provides data rate maximization and diversity maximization. There are two types of STC,s : which are Space Time Trellis Code (STTC) [5] and Space Time Block Code (STBC) [5], [11]. The second type has less complexity to decode and have good diversity gain and less coding gain than STTC that is why STBC are used mostly as an encoding scheme for transmitting different streams of data. The benefits of MIMO and STBC can only be realizable only when multiple antennas are used at both transmitter and receiver end [22], [23], [24]. Due to unavailability of direct link between transmitter and receiver fading plays a major anti-role to data streams in wireless communication channel. Spatial diversity was introduced for overcoming fading problem to secure wireless data streams to some extent. To achieve full transmit diversity independent copies of signals are transmitted through multiple antennas placed at transmitter [19], [20], [28]. In cooperative communication source (multiple antennas transmitter) and relays cooperate with each other to transmit data

towards destination that is why this communication is known as cooperative MIMO communication [1], [2], [19], [20].

When distance between transmitter and receiver is long enough to transmit then wireless relays are used between both ends. The wireless relays act as Access Point (AP) which receives the broadcasted streams from transmitter, process it and forwards toward destination end. Several protocols are implemented at relays such as, Amplify and Forward (AF) [12], [15], [19], Decode and Forward (DF) [1], [2], [9], [10], Compress and Forward (CF) [22], [31], [32], Decode-Amplify and Forward (DAF) [14], [27], [30]. Proposed Decode and Forward (DF) protocol is implemented at wireless cognitive relay which first decodes the received data from transmitter and then forwards to destination. A wireless relay does not possess multiple antennas; hence, it cannot benefit from the advantages offered by the MIMO concept, unless Cooperative MIMO relaying is employed [19], [20]. A MIMO cooperative relay communication system is shown in Figure 2.2. in which $R_1, R_2, R_n, \ldots\ldots, R_n$ are cognitive relays where Source is denoted by *S* node and Destination with *D*.

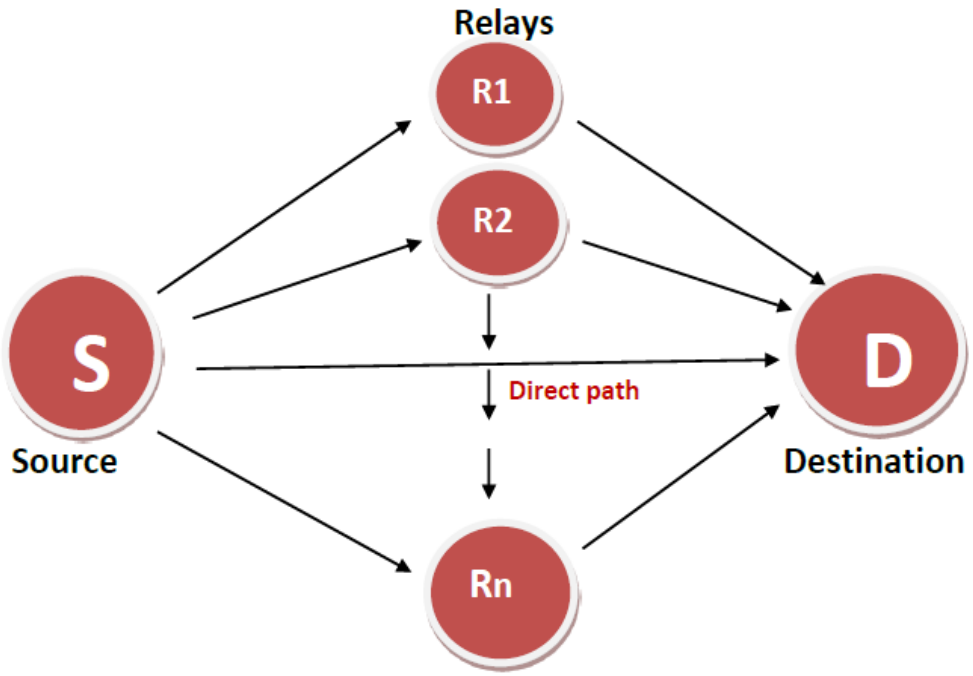

Figure 2.2.Cooperative multi-hop relay communication.

2.3 **2-hop Communication**

The transmission between source and destination is completed in 2-hops [19], [20]. In first hop source broadcasts information with the help of multiple antennas towards all neighboring nodes known as relays, and in second hop the relay controller applies some rules on received data for making decision of PU availability or absence then further transmits towards destination which also have multiple antennas to receive [1], [5], [8], [9]. The destination receives different copies of same source from two different paths, one from direct and other from indirect. The destination combines the received signals from source and relays in order to attain maximum reliability and spatial diversity. The logic behind the scene is to use Time Division Duplex (TDD) in cooperative communication for transmission [7], [20]. During time slot one, the source broadcasts and all the nodes receive while in second time slot relay implements defined protocols on data and further retransmits toward data destination. Receiver uses Maximum Ratio Combining (MRC) method [8], [23], [25], [27] to extract original data from combined data reached through different paths. 2-hop communication processes is shown in Figure 2.3. Detailed explanation about 2-hop communication will be in chapter 3.

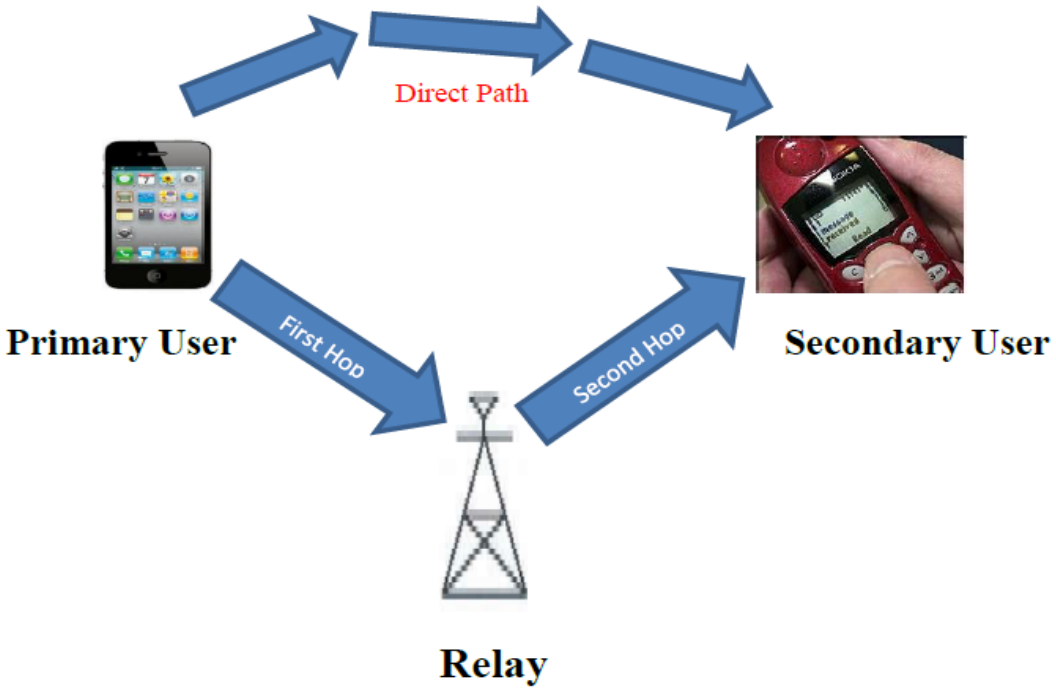

Figure 2.3.2-hop Cooperative Communication System.

2.4 Cooperative Diversity Protocols

The received data at relays, through broadcasting of transmitter, are further processed to make its contribution for enhancing reliability and diversity of signal transmission between source and destination [8], [9], [12], [13]. The relays can be divided into two main categories according to their functionality those are Regenerative and Non-regenerative (Transparent) [15], [19]. There are several protocols which are implemented at relay terminal; some of them are briefly discussed here.

2.4.1 Amplify and Forward (AF) Protocol

In AF strategy, the relay simply amplifies the received data through first hop and forwards it towards destination without regenerating it [13], [20] [31]. The transparent relays just amplify the received signal before re-transmission [19], [20]. Consider a_n is the received signal at relay and y_n is received at destination then relay just amplifies it by multiplying an AF factor β [8], [9], [27]. This process is simply expressed in mathematical Equation 1.1:

$$y_n = \beta * a_n \tag{1.1}$$

The β depends on variance and fading coefficients which is expressed in Equation 1.2:

$$\beta = \sqrt{\frac{SNR_s}{\partial^2 + SNR_r|h|\text{^}2}} \tag{1.2}$$

where *h* is variance and fading coefficient between source and relay [8], [19], [20], [27].

2.4.2 Decode and Forward (DF) Protocol

The relays which have capability of regeneration of the data use DF protocol for modeling of a wireless system to combat with fading environment. In DF protocol [7], [12], [14], [29] relay first decodes the received data then it re-encodes using specific encoding scheme and then re-transmits toward destination. Due to decoding at relay, it is observed that data takes more time to reach towards destination through indirect path [19], [20], [32]. Beside this it is also the possibility for any relay not to decode well because of having more fading environments at its

end which further affect the overall performance of system [9], [10]. The DF protocol can further be classified into two types; Fixed DF protocol (FDF) and Adaptive DF (ADF) protocol [19], [20], [30], [32]. The FDF relaying protocol relay is bound to forward information either it is decoded well or not, which creates performance degradation due to propagation of errors which leads to wrong decision at destination, on the other hand in ADF protocol [3], [25], [32] source does not transmit to relay if the link between source and relay is busy. In such case where link is busy, source transmits directly to destination in second time slot where relay forwards the copy of previous data or remains silent during second time slot towards destination [13], [20], [19], [26]. This is shown in Equation 1.3:

$$y_r = a_{est} * h_{sr} + n_{sr} \quad where \ a_{est} \approx a_{i/p} \tag{1.3}$$

In above equation y_r is the resulted data before retransmission towards destination and a_{est} is the estimation of input signal, h_{sr} is the channel between source and relay, $n_{sr}$is the noise added in the signal due to Additive White Gaussian Noise (AWGN) wireless channel. DF protocol is implemented on relays to detect empty spectrum available in PU spectrum which will further play their role in resulting better performance in terms of detection probability [19], [20], [32]. Detail explanation about this protocol will be in further chapters.

2.4.3 Compress and Forward (CF) Protocol

Compress and Forward (CF) [19], [33] relaying protocol is almost the inverse of AF relaying protocol. In AF protocol relay have duty to amplify received data before transmitting towards destination but in CF protocol relay plays his duty to compress data before retransmission during second hop [3], [7], [32]. Decoding of received signal is not necessary in CF protocol so relay only compresses the data and forwards which helps in bandwidth saving and transferring higher data rate through channel.

2.4.4 Decode-Amplify and Forward (DAF) Protocol

To model such a system in which relay have both capabilities of decoding and amplifying before re-transmission, DAF [8], [11], [18] protocol is implemented at relay. This technique helps to combat with faded signal because of using Hybrid Decode-Amplify and Forward (HDAF) which

have the ability to regenerate signal using ADF protocol and amplify the regenerated signal that helps in performance improvement by removing noise and fading from signal [21], [22]. It has been seen by research that by increasing number of relays between source and destination the diversity gain also increases through high SNR links [14], [25], [26], [30].

2.5 Conclusion

The information between Source and Destination is transmitted in two ways; one through direct link and other through indirect or multipath link. Cooperative diversity technique is used which helps in increasing channel capacities in specific bandwidth with the help of cooperation between multiple antennas at transmitter and receiver end. To complete cooperation diversity relays are used between source and destination which are placed at different distances from PU, mostly these are placed close to PU. The transfer of information from one end to another with the help of relays is a 2-hop communication process using TDD technique. Cooperative diversity can be performed based on different strategies implemented on relays e.g. AF, DF, CF, DAF. Implementation of DF protocol at relay, to design a cooperative communication MIMO system with the help of CRs, is the proposed method. Using DF protocol at relays, among all above mentioned protocols, provides better detection performance for PU signal and diversity is achieved. Increasing number of relays between source and destination using DF protocol, diversity gain is improved while noise and fading decreases, which results improvement in performance of overall cooperative MIMO communication system.

Chapter 3: Cognitive Spectrum Sensing

3.1 Types of Radio Spectrum

There have been different protocols for assigning static spectrum to a specific service and users and whenever this band is assigned to specific service then it is fully dedicated for the users of that service [1], [2], [15], [27]. There are some limitations for this static spectrum allocation due to rapid increase in wireless services, CR is the technology that helps in distributing spectrum dynamically to wireless services overcoming the problem of radio spectrum limitations [19], [20]. Radio spectrum is categorized in two main parts:

3.1.1 Licensed Spectrum

When a particular frequency band is sold for a specific service and a license is issued as a confirmation of authority then this purchased frequency band is known as licensed spectrum and it can be accessed by the users of that service whenever they want [17], [19], [20]. For example cellular spectrum, television spectrum, satellite spectrum, aeronautical radio navigation spectrum and etc.

3.1.2 Unlicensed Spectrum

Among licensed frequency band there are some open frequency bands which are used by unlimited number of users [6], [19], [20]. The device must have to satisfy some rules and certain standards whenever it wants to use unlicensed spectrum some of the rules are limitation of transmission power and advanced coexistence capabilities [1], [2], [11]. For example: Industrial Scientific and Medical (ISM) band (900MHz and 2.4 GHz), TV bands (54-72 MHz, 76-88 MHz, 174-216 MHz and 470-806 MHz) and etc.

3.2 Spectrum Sensing Methods

In wireless communication there has been rapid increase in demand for radio spectrum in recent time. It has been observed that the almost 80-85% of the time licensed spectrum remain unutilized. So there is always an opportunity to use the licensed spectrum whenever it is free by the unlicensed users, this novel concept of licensed spectrum usage by unlicensed users gave birth to CR [1], [2], [6]. Because unlicensed users need to use licensed spectrum so it is their responsibility to sense for the presence and absence of licensed users within their territory [19], [20]. During spectrum sensing, it is very necessary to protect the rights of PU, to avoid any kind of interference between PU and SU within licensed spectrum. The unused parts of licensed spectrum are known as "black holes" or "white spaces" [1], [19], [20], [24]. The concept of spectrum holes can be seen in Figure 3.1.

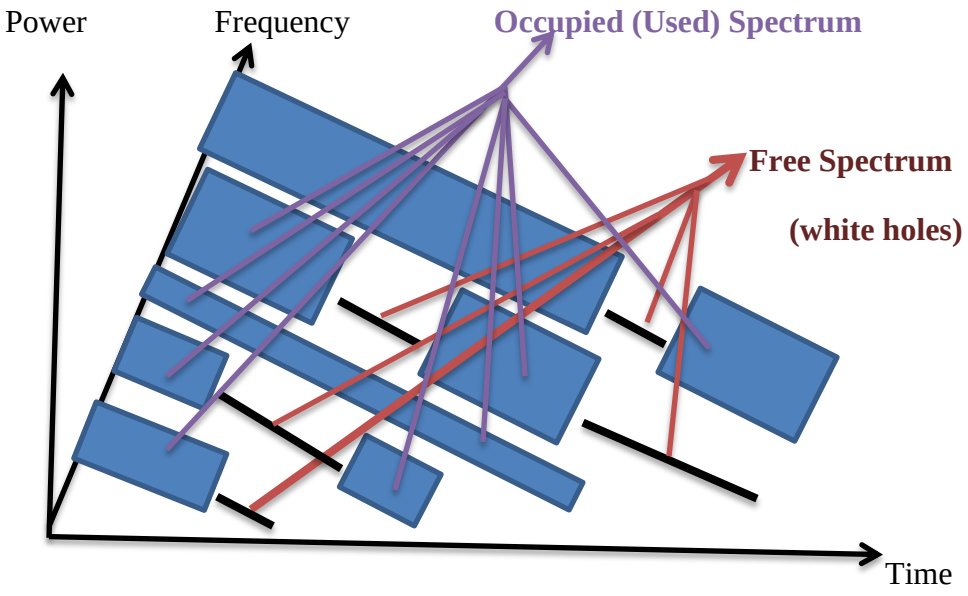

Figure. 3.1. Spectrum Holes Concept [17].

Spectrum sensing can be categorized on the basis of their detection methods: cooperative detection, interference based detection and transmitter detection. One of the basic principles of spectrum sensing is to detect transmitter of PU network. Here the transmitter detection methods are explained instead of all [1], [20].

3.2.1 Transmitter Detection

The first step for the unlicensed user is to detect the signal from licensed user in a particular channel and this is achieved by implementing one technique in Cognitive Controller (CC) of relays among these:

3.2.1.1 Energy Detection

It is a technique in which energy of transmitted signal is detected within a certain time period, further this detected energy is compared with a pre-defined threshold value [2], [6], [8]. If detected energy is below than predefined threshold then it is assumed that licensed spectrum is free and if energy detected is above than the threshold value, it is assumed that the licensed spectrum is occupied by primary users so secondary users can not use the spectrum until primary users vacate the spectrum [18], [19], [20]. Energy detection is nonspecific detection approach because it cannot be used to identify the type of system or user (primary or secondary) that is occupying the channel [17], [20]. The complete energy detection mechanism at relay of cooperative network is shown with the help of Figure 3.2.

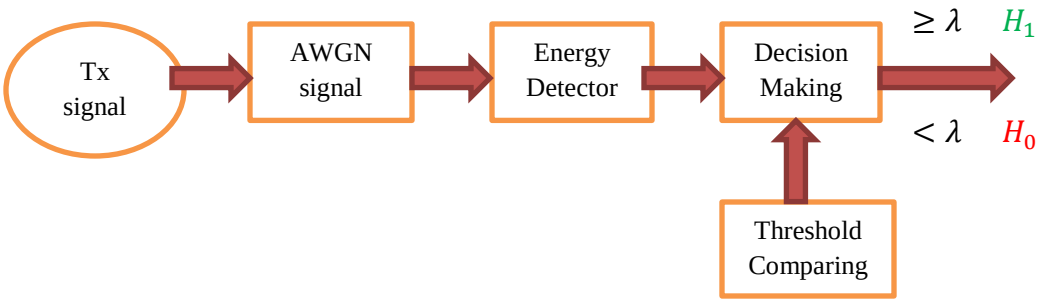

Figure 3.2. Energy Detector [20].

3.2.1.2 Matched Filter (MF) Detection

Matched filter is an optimal signal detecting technique in which unknown signal is correlated or matched with a known signal [19], [20]. If the unknown signal shows similarity with the known

signal template then it is pretended that spectrum is occupied by the users to whom this matched signal [1], [17], [20] belongs and in opposite case if the unknown signal do not show similarity with a known signal then we estimate the licensed spectrum is free to use for other users for a particular time period. For maximizing SNR of the primary user, the transmitted signal is convolved with its own conjugated time reversed template of the signal in the presence of AWGN wireless channel. Matched Filter (MF) is a linear filter that maximizes the output of SNR [5], [7], [19], [28]. Matched filters are used in radars and in digital communication system where in the presence of noise objective of detecting the presence of signal is achieved [19], [20]. The whole MF approach is depicted in Figure 3.3.

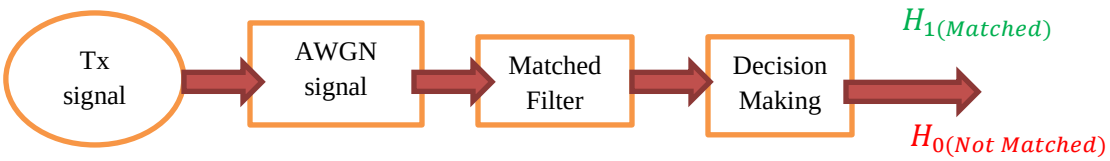

Figure 3.3. Matched Filter Detection [20]

3.2.1.3 Cyclosationary Detection

A cyclostaionary process is a signal having statistical properties that vary cyclically with time [17], [18], [19], [20]. If the licensed users possess cyclic characteristics then with the help of cyclostationary detection method signal can be detected even if it has very low signal to noise ratio [17], [20]. A wide sense cyclostationary process (the analogue of a wide sense stationary process) has an autocorrelation function which is cyclic with a certain periodicity *T*, i.e., *R(t, s) = R(t+T, s)* for all time indices *s* and *t*. Communication signals are typically cyclostationary with multiple periodicities, e.g., the symbol frequency. Other periodicities may be related to coding and guard periods [26], [28], [31]. Due to stationary, the spectrum correlation function of additive white noise Gaussian channel is zero which makes this technique more effective against uncertainty of noise. If the PU's signal is cyclostaionary then by calculating spectrum correlation function of the PU's signal at cyclostationary detector, it is identified either the signal is present or absent. The output of cyclostationary detector is compared with predefined threshold value

for estimating the presence or absence of PU's signal within the spectrum. The cyclostationary detector is shown in Figure 3.4.

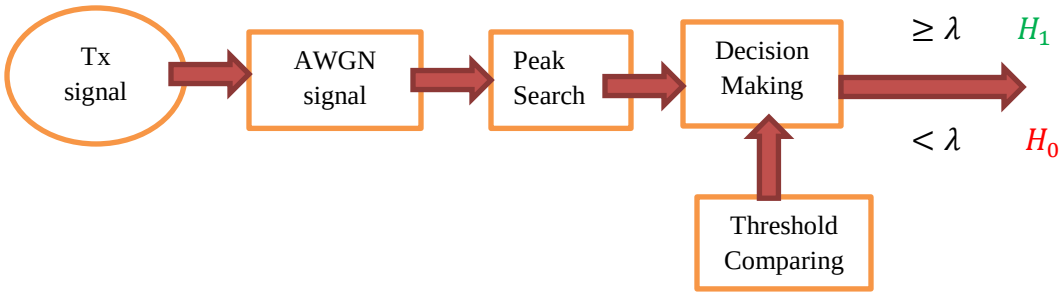

Figure 3.4. Cyclostationary Detection [20]

3.2.1.4 Detection Bases on Radio Identification

PU transmitter can also be detected with the help of priori knowledge available about the particular transmitter. The knowledge of transmitter will be e.g. transmission range, frequency hop, frequency shape [1], [2], [19], [20]. The main issue in this detection is about the initial knowledge of transmitter because it is very difficult to get information about transmitter parameters and dynamic spectrum sensing is preferred always, due to this issue this technique is mainly avoided [16], [18].

3.2.1.5 Waveform Detection

When data is transmitted towards destination, preambles and pilots are also included in data format. Through waveform detection method these preambles and pilots are detected which increase transmitter detection capability with relatively low complexity [8], [12], [19], [20].
In proposed model energy detection method is used for sensing primary user's spectrum because it is not a complex mechanism to be implemented compared with other schemes those are good optimal but complicated to implement and also need prior knowledge about transmitter [19],

[20], [29]. Energy detection method is a sub optimal non-coherent detector scheme, so this technique is used for cooperative spectrum sensing [6], [7], [8].

3.3 Spectrum Sharing Techniques

The spectrum sharing and access of radio spectrum among licensed and unlicensed users is regulated in such a way that the unlicensed users can use licensed spectrum without creating interference with licensed spectrum users . There are many spectrum sharing techniques like underlay spectrum sharing, overlay spectrum sharing, horizontal and vertical spectrum sharing and etc.

3.3.1 Underlay Spectrum Sharing

When an unlicensed signal is spread over a large band of spectrum under an interference line created due to interference temperature model so that it can be seen as an undesired signal below the noise and interference level, by the licensed spectrum users, the process is known as underlay spectrum sharing [13], [14], [19]. It is a technique to access radio spectrum with minimum transmission power that will not increase interference temperature above the predefined threshold line. Orthogonal frequency division multiplexing (OFDM), Ultra Wide Band (UWB) and spread spectrum are the examples which use underlay spectrum sharing technique. Underlay spectrum sharing is shown in Figure 3.5 [20], [23], [28].

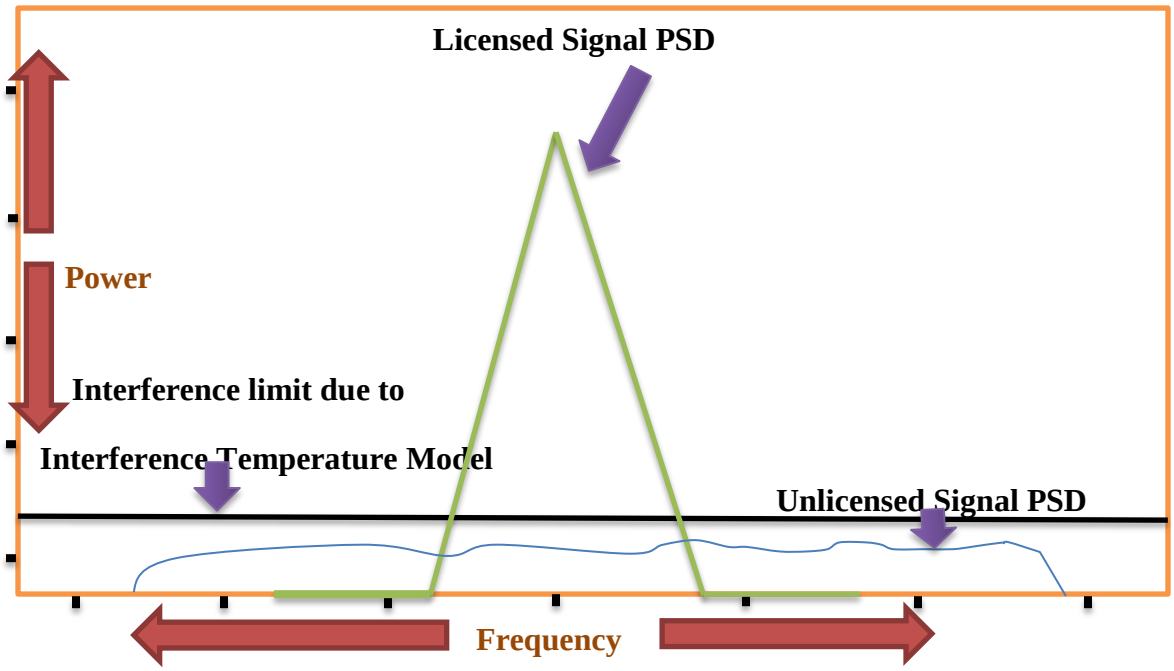

Figure. 3.5. Underlay Spectrum Sharing [23]

3.3.2 Overlay Spectrum Sharing

In this spectrum sharing technique unlicensed use the spectrum of licensed users when it is unutilized by licensed users without creating interference with licensed spectrum users [1], [2], [6], [8]. Before accessing licensed spectrum the unlicensed spectrum users try to find empty slots within the licensed spectrum then use those empty slots for their own users for a particular time period until the licensed users need those empty slots back for their own use. Overlay spectrum sharing is shown through Figure 3.6 [19], [20], [22], [23].

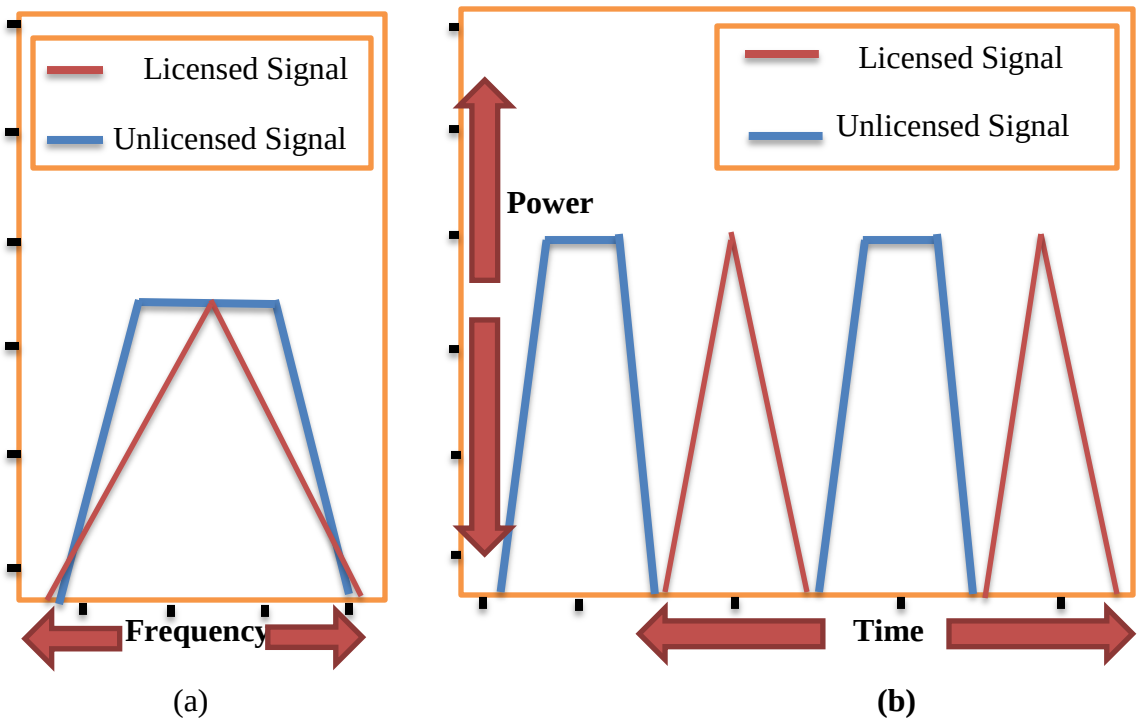

Figure. 3.6. (a) Licensed and Unlicensed Signal PSD.(b) Overlay Spectrum Sharing [23]

3.3.3 Horizontal and Vertical Spectrum Sharing

CR share spectrum in two different ways, either horizontal spectrum sharing or vertical spectrum sharing [1], [2]. The mechanism in which cognitive radio and unlicensed system have ability to share spectrum with licensed spectrum without interference is known as horizontal spectrum sharing [2], [6], [8]. The unlicensed system itself could be another cognitive radio. The mechanism in which cognitive radios share licensed spectrum with primary radio system exclusively is known as vertical spectrum sharing [12], [13], [19]. In both horizontal and vertical spectrum sharing identifying spectrum opportunities is needed. In order to avoid harmful interference licensed radio systems may assist cognitive radios to identify spectrum empty slots in vertical sharing scenario which is called “operator assistance” [1], [20], [23]. The horizontal and vertical spectrum sharing is shown through Figure 3.7.

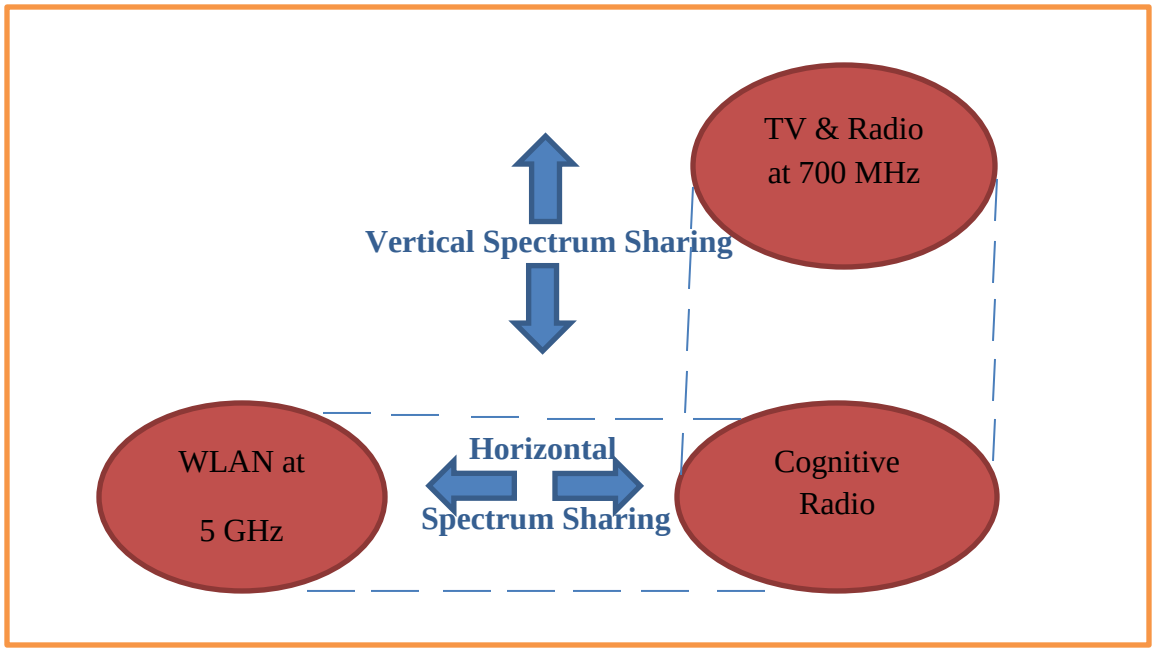

Figure 3.7. Horizontal and Vertical Spectrum Sharing having Cognitive Radios Horizontally and Vertically [23].

3.4 **2-hop Digital Relaying System**

Cooperative spectrum sensing plays an important role in cognitive radio network in order to improve the detection probability of PU or licensed spectrum [1], [2], [6], [7]. The data traveling through wireless medium face the number of problems due to some issues e.g. noise, fading, hidden terminal problem, multipath reflection or refraction [2], [12], [16]. If cooperative diversity is achieved in any system, it helps to overcome all above wireless problems encounter in a communication process [19], [21]. Hence modern research shows that the cooperative diversity can be achieved by using CRs between sender and receiver. The data streams transmitted from source reach at destination through digital relays in 2-hop using TDD mechanism [19], [20], [28].

3.4.1 Soft Cooperation

For PUs spectrum sharing it is necessary for SUs to find empty slot within the PU spectrum [19], [20], [7], [8]. The CRs play an important role for PU network in decision making for presence or absence of PU. In soft cooperation each relay terminal sends its received data bits to fusion centre and fusion centre which holds the authority to make final decision on the basis of received data bits from individual relays. In soft cooperation relays do not have the ability to make decision locally on the basis of received data bits from source [15], [16], [18]. A fusion centre actually acts like a Central Processing Unit (CPU) that is responsible for final decision making and also have the duty to informs relay terminal about final decision [19], [20]. The process of soft cooperation is shown in Figure 3.8.

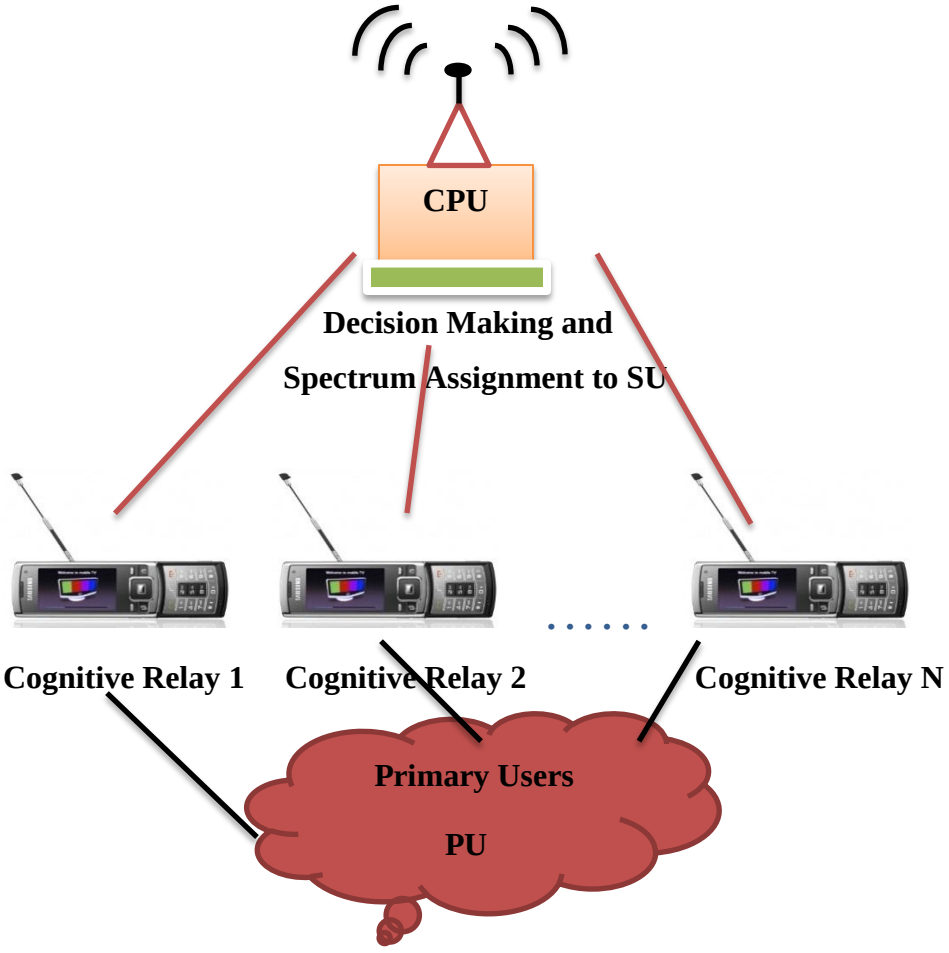

Figure 3.8. Soft Cooperation [20].

3.4.2 Hard Cooperation

In hard cooperation the relay terminal makes individual decision on the basis of received data bits and forwards its decisions to fusion centre [1], [2], [19]. After receiving all local relay decisions the fusion centre makes final decision on the basis of local decisions and informs relay terminal about final decision. It is observed that the soft cooperation provide better overall performance than hard cooperation [15], [16], [17], [20]. Statistically almost 30-40% overall performance in terms of probability of detection and false alarming, is improved through soft cooperation. Hard cooperation mechanism is shown in Figure 3.9:

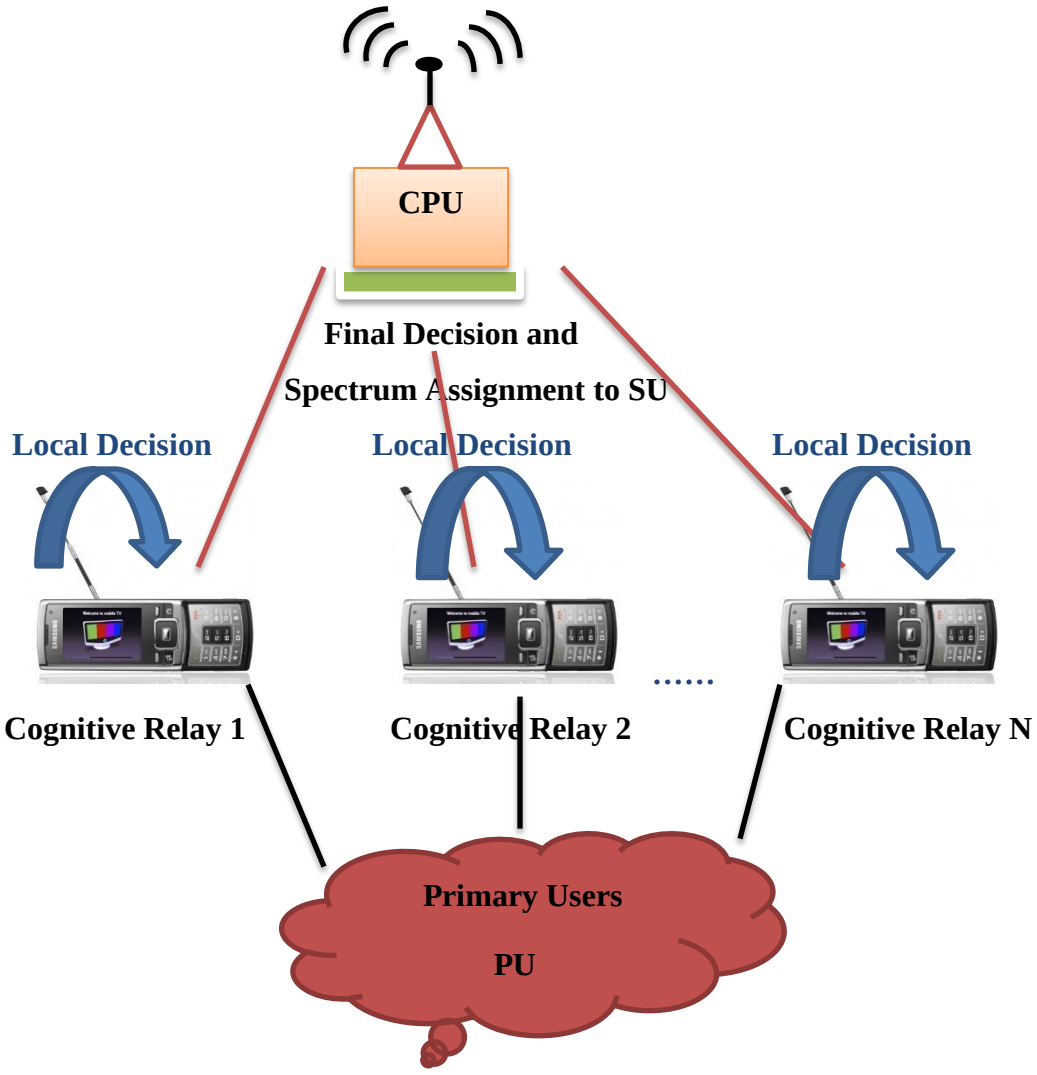

Figure 3.9. Hard Cooperation [20].

3.5 **Conclusion**

Recently, for wireless communication radio spectrum is highly demandable. According to statistics it has been seen that almost 80-85% of the time radio spectrum remain unutilized, so the CR concept was introduced. According to this novel concept licensed users and unlicensed users can share their radio spectrum for communication when it will be free. It is the responsibility of unlicensed spectrum network to find spectrum free holes within the licensed spectrum and use those free holes for their own users without creating interference and problem for owner spectrum users. The process of spectrum sharing is the last step starting from learning the radio environment towards sensing of free holes and then finally sharing spectrum free holes with each other. Most of all among these steps, spectrum sensing is difficult on which decision about presence or absence of PU is based. There are some techniques for spectrum sensing; most prominent is the transmitter detection of PU. SUs use one particular approach among different approaches for PU transmitter detection through PU signal, the PU signal is detected by CRs or SUs on which the particular approach is implemented and decision is made on the result. The transmitter detection approaches are energy detection, matched filter detection, cyclostationary detection, detection based on RFID, covariance waveform method and etc. Energy detection method is used for proposed system to detect the PU signal and for making final decision about presence or absence of PU within the spectrum. There are two ways to share spectrum when decision is made by relay terminal; underlay spectrum, sharing and overlay spectrum sharing both have particular advantages. CRs cooperate in decision making for PU network and SU network about availability or unavailability of spectrum. The cooperation can be soft or hard but it is observed that soft cooperation provide better overall system performance than hard cooperation.

Chapter 4: Decode and Forward (DF) Protocol using OSTBC in MIMO Systems

4.1 Orthogonal Space Time Block Coding (OSTBC)

There are two common ways in wireless communication to transfer multiple copies of reliable data from source towards destination; antenna arrays and MIMO. Most of the wireless networks have antenna array designed at one end either at transmitter or receiver, usually having on receiver side. An alternative technique is to use multiple antennas at both end of the wireless network for reliable data transmission. In 1998 Vahid Tarokh and his group proposed that Space Time Codes (STCs) provide improvement in error rate over single antenna system [5], [6], [7]. STCs can be divided into two sub categories; Space Time Trellis Codes (STTC) and Space Time Block Codes (STBC) [2], [3], [10]. Through STCs multiple copies of original signal is transmitted through multiple antennas used at transmitter and receiver which helps to overcome fading and other errors effected during wireless medium transmission. STTCs were the old and complex technique which distributes the trellis code over multiple antennas to provide good coding and diversity gain [8], [15], [16]. It has complex encoding and decoding which need Viterbi decoder [19], [20], [24] to decode original information from diverse received copies at receiver. In 1998 Sviash Alamouti proposed that if the data streams need to transmit is encoded in the form of blocks and then distributed through MIMO technology then it provide maximum diversity and coding gain as compared to other coding schemes [24], [25]. The STBCs are expressed through matrices in Figure 4.1, in which rows depict number of time slots (time) and columns show about transmitting antennas (space).

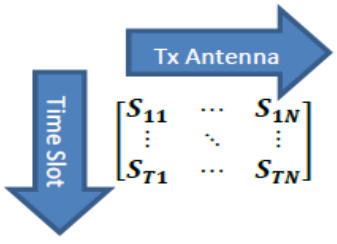

Figure 4.1. STBC transmission scheme

Where S_{ij} is the modulated symbol transmitted through multiple antennas using multiple time slots, in S_{ij} , i represents the time slot and j represents the tranmitting antenna. In above matrix there are T time slots and N transmitting antennas [15], [16], [17]. Any two vectors taken from coding matrix will fulfill the orthogonality principle (e.g. if $a.b=0$ then vectors a and b will be orthogonal) which results linear decoding and code rate optimization at reciever [19], [20]. Hence the coding matrix of STBC is generated in such a manner that its all vectors are orthogonal to each other, due to this reason STBC is known as OSTBC [1], [2], [7], [19], [20]. OSTBC provides good diversity gain and free of Inter Symbol Interference (ISI) communication between transmitter and receiver.

4.2 Alamouti STBC Encoding Scheme

For transmitting information symbols through combination of multiple trasmit and receiving antennas, alamouti schemes are mostly used. Alamouti 2×2 STBC scheme [19], [20], [24] is used in proposed system, which is well known of achieving code rate 1. In this 2×2 coding scheme, there are 2 transmitting antennas and 2 receiving antennas which achieve spatial diversity with the help of two antenas mounted on both end [22], [23], [25]. Conisder a stream of data $\{a_1, a_2, a_3, \ldots \ldots, a_n\}$ which need to transmit using 2×2 Alamouti STBC scheme [24], [25]. A simple 2×2 system can be shown in Figure 4.2.

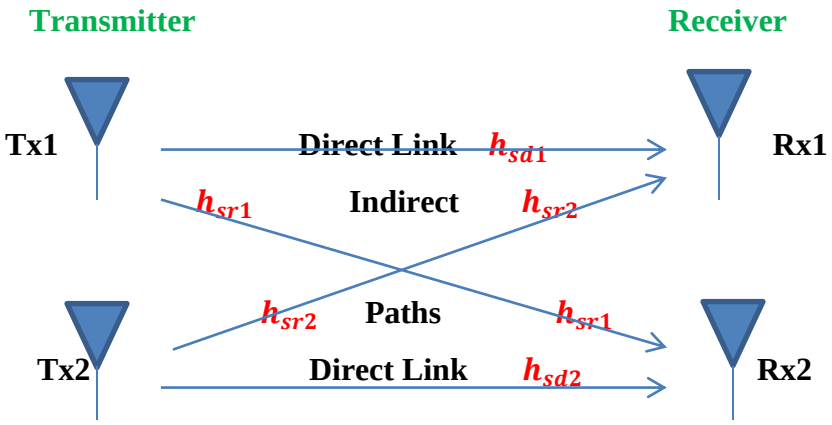

Figure 4.2. Alamouti **2 × 2** STBC Transmission Scheme

Figure 4.2, have 2-transmitting antennas and 2-receiving antennas used in Alamouti transmission scheme to achieve transmit diversity [22], [23], [24]. The transmission of data stream from transmitter to destination completes in 2-hops and takes two time slots using TDD [1], [2], [7]. From supposed data stream $\{a_1, a_2, a_3, \ldots\ldots, a_n\}$ in the first time slot T1,a_1 through antenna Tx1 and a_2 through antenna Tx2 are transmitted towards receiver and in second time slot T2, $-a_2^*$ through antenna Tx1 along a_1^* through antenna Tx2 are transmitted [6], [9], [15]. In time slot T3, a_3 through Tx1 and a_4 through Tx2 are transmitted and in next time slot T4, $-a_4^*$ through Tx1 and a_3^* through Tx2 are transmitted towards receiver and so on, where * shows conjugate [19], [20], [25], [32].

The transmitted data symbols a_1 and a_2 from our above supposed data sequence with the help of vectors in a 2×2 matrix using Alamouti STBC scheme. The code matrix C shown in Figure 4.3 is broadcasted in wireless medium through 2-transmitting antennas of the transmitter towards receiver.

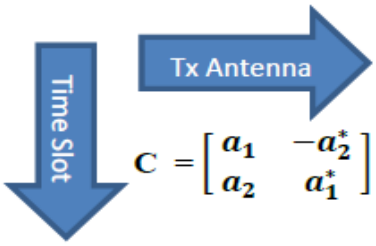

Figure. 4.3. Alamouti 2×2 STBC Encoded Transmission Matrix

Alamouti proposed a novel MIMO technique which is implemented now a days in many networks, before this there was technique of transmitting one symbol in one time slot but Alamouti proposed to transmit two symbols in one time slot [19], [20], [22]. The data rate is not increased through this process because still two time slots needed to transmit two symbols, so data rate remains the same [24], [25], [28], [29].

4.3 DF Relaying Protocol

The Alamouti STBC data is broadcasted through multiple antennas mounted at transmitter towards receiver [19], [20], [27], [31]. SU or relays are present between transmitter and receiver to detect PU signal and then making decision about PU spectrum availibility or unavailibility by

applying multiple protocols on detected PU signal. There are many protocols implemented at relay discussed in chapter 2 among those implemention of DF protocol on relays to detect transmittd PU signal and to achieve diversity gain is the main concern [6], [7], [20]. Implementation of DF protocol at relays complete in two steps, in first step broadcasted data from PU is detected by relays and detected data is estimated (decoded) then in second step estimated data in first step is re-encoded to transmit again towards receiver via wireless medium. ML technique is used for estimation (decoding) in first step of data estimation in our case [26], [34]. In second step Alamouti scheme is used to re-encode decoded data for futher transmission [22], [23], [24]. The wireless channel used in this case is: Multiplath Rayleigh channel which has real and imaginary parts having Gausian distributed nature with mean=0 and variance=$\frac{N_0}{2}$. Each transmitted symbol from data sequence is mutiplied with a randomly varying complex number during transmission through channel [10], [21], [27]. It is assumed that the relay and destination has perfect channel inforamtion for decoding the received signal. It is also assumed that the communication between source and destination is unavailable [19], [20], [25].

Consider a_1, a_2 are the complex symbols transmitted from PU transmitter using Alamouti STBC scheme and the signal received at relays are given below:

$$y_{pr1} = h_{pr1} * a_1 + n_{pr1} \tag{4.1}$$

$$y_{pr2} = -h_{pr2} * a_2 + n_{pr2} \tag{4.2}$$

$$y_{pr3} = h_{pr1} * a_2 + n_{pr3} \tag{4.3}$$

$$y_{pr4} = h_{pr2} * a_1^* + n_{pr4} \tag{4.4}$$

Equations 4.1,4.2 represent the signal received at relays in time slot 1 where Equation 4.3,4.4 represent the signal received at time slot 2 respectively [11], [18], [26]. At relays signal is decoded using ML decoding technique then re-encoded to forward it towards destination [21], [22]. The final received signal at receiver from both links, one through direct link and the other through indirect link are expressed in Equations 4.5,4.6.

$$y_{d1} = h_{sd1}a_1 + h_{pr1}a_2 + n_{11} \quad (4.5)$$

$$y_{d2} = -h_{sd2}a_2^* + h_{pr2}a_1^* + n_{12} \quad (4.6)$$

Equation 4.5, shows the received signal at receiver in time slot 1 and Equation 4.6 shows the received signal at receiver in time slot 2.

By simplifying the received data into matrix or vector form as,

$$\begin{bmatrix} y_{d1} \\ {y_{d2}}^* \end{bmatrix} = \begin{bmatrix} h_{sd1} & h_{pr1} \\ h_{pr2}^* & -h_{sd2}^* \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} + \begin{bmatrix} n_{11} \\ n_{12}^* \end{bmatrix} \quad (4.7)$$

In above two equations h_{sd1} , $h_{sd2}, h_{pr1}, h_{pr2}$ are the channel coefficients of PU to destination and PU to relay links where a_1, a_2 are the OSTBC encoded data but * denotes complex conjugate [12], [13], [19], [20].

For decoding original signal at relay, transmitted by PU, we need to estimate channel through which signal reach at relay terminal. For simple $m \times n$ matrix the channel inverse can be calculated using pseudo inverse method which is [20], [23], [24].

$${h_{pr(i)}}^+ = \left({h_{pr(i)}}^H * h_{pr(i)}\right)^{-1} * {h_{pr(i)}}^H \qquad \text{where } i=1,2\ldots..,n \quad (4.8)$$

In Equation 4.8 ${h_{pr(i)}}^+$ is general expression for the channel inverse or pseudo inverse and $h_{pr(i)}$ is the channel coefficient matrix, along these ${h_{pr(i)}}^H$ is the Hermitian matrix, where subscripts *i* is used for specific channel under observation [19], [20], [23]. The estimation of original signal used in Equations 4.1,4.2,4.3,4.4, at relay terminal by simply multiplying Equations 4.7 and 4.8.

$$\begin{bmatrix} \widehat{a_1} \\ a_2 \end{bmatrix} = {h_{pr(i)}}^+ \begin{bmatrix} y_{pr(m)} \\ {y_{pr(m)}}^* \end{bmatrix} \qquad \text{where } m=1,2\ldots,n \quad (4.9)$$

Where the subscript *m* denote the particular received signal at different relays in different time slots [8], [23], [27]. The estimated data in Equation 4.9 will approximately be equal to orignal signal but it will not be exactly the same as original due to addition of noise through channel. Implenting DF protocol at relay terminal by using ML approach relays decode almost 90-95% of the received signal from channel which give better spatial diversity than AF relaying protocol [25], [34].

4.4 Conclusion

There are two common ways of transferring multiple copies of data towards receiver those are antenna arrays and MIMO systems. In multiple antenna system STCs provide improvement in performance in terms of less error as compared to single antenna system. There are two basic types of STBs which are STTC and STBC. The prior coding scheme is complex and decoding is difficult as compared to later one. The coding matrix in STBC is generated in such a manner that all the codes are orthogonal to each other and no two codes will be repeated in it, this orthogonal property makes STBC scheme as OSTBC scheme and decoding at receiver becomes easy. Siavash Alamouti proposed STBC encoding scheme to transfer multiple copies of data transmitting through antennas which provides spatial diversity. The basic idea behind this technique is to send data bits in a group of two instead of transmitting single bit in one time slot using TDD scheme although it does not effect on increase in data rate but provides transmit diversity and reliable data transfer towards receiver. The Alamouti STBC encoded data is broadcasted through multiple antennas in wireless channel towards receiver. Alamouti 2×2 STBC scheme is used to model the system which will help in detecting the PU signal in wireless channel through relays. The detected PU signal is decoded at relay terminal using ML technique and after decoding it is re-encoded then it is forwarded towards its destination through wireless channel. The decoding at relay helps in reliable data transmission from transmitter towards destination and provides transmit and receiving diversity.

Chapter 5: System Model for Implementation of OSTBC in DF Cooperative Cognitive Radio Network with Simulation Results

5.1 Architecture of Cognitive Radio Network

The functions of OSI layers is shown in Figure 5.1, which clearly shows that spectrum sensing, channel estimation, spectrum sharing work on physical layer [1], [2], [6]. The main function of CR is spectrums sensing, spectrum management, spectrum mobility and spectrum pooling. Our thesis is mainly based on layer 1 in OSI layers.

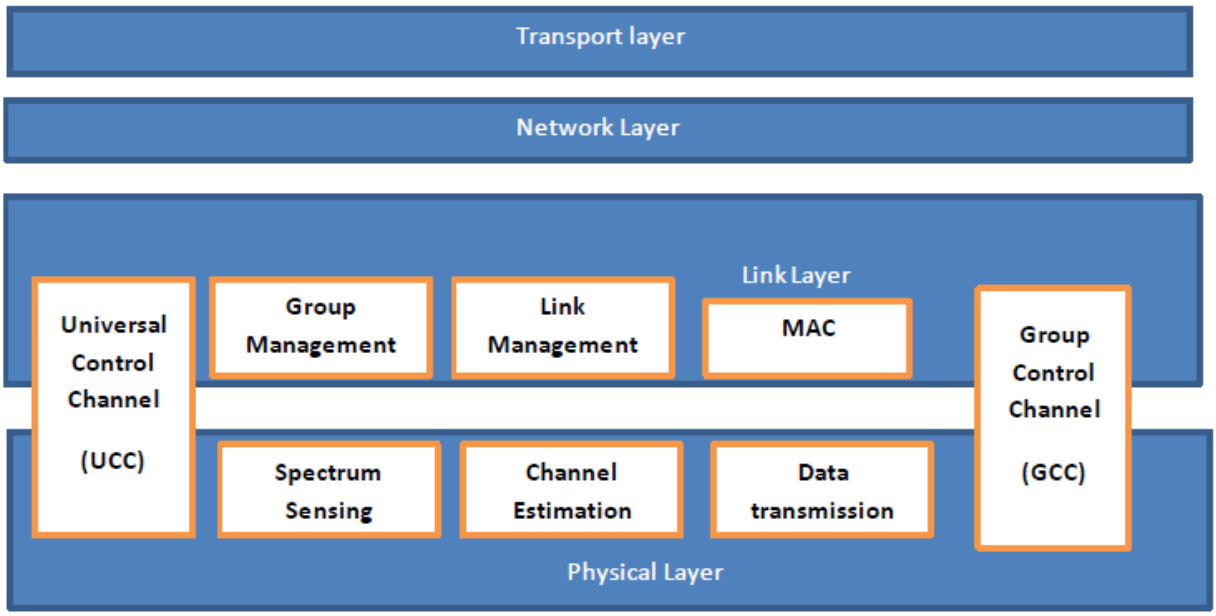

Figure 5.1. Architecture of CR in OSI Layers

The main function of physical layer is to sense free holes in spectrum over all degree of freedom in terms of time, frequency and space which results in finding the free channels for transmission, rest of the layers help in reliable transmission after all security and management clearance [9], [12], [15], [16].

The basic CRN, in which CRs sense the environment for finding spectrum holes then spectrum sharing is started between PU and SU, the process is shown in Figure 5.2.

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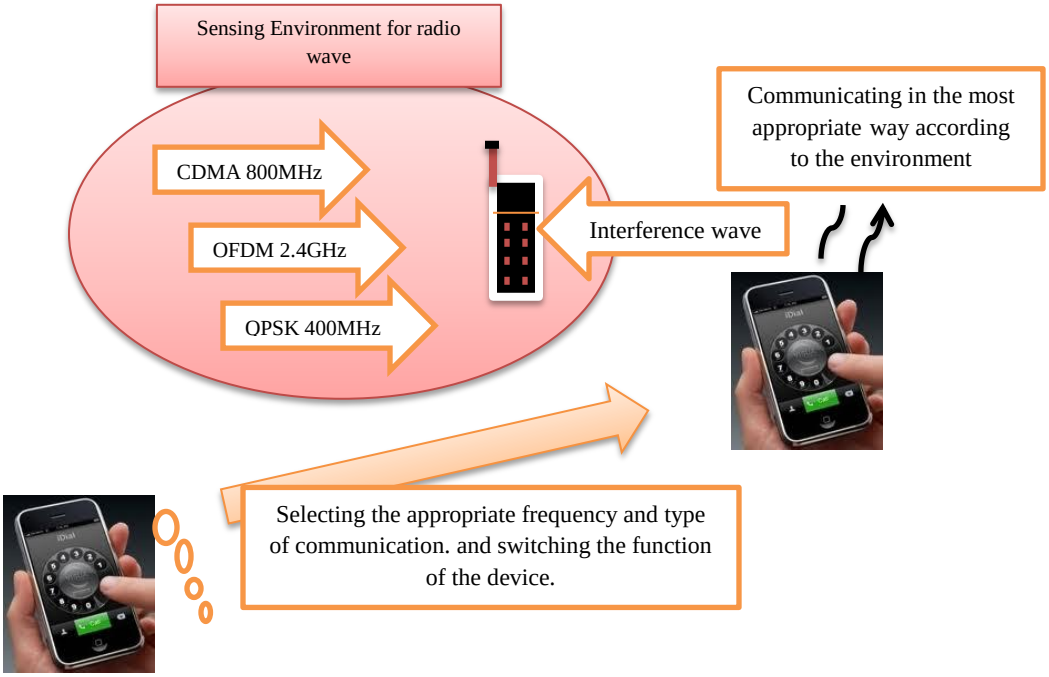

Figure 5.2. Spectrum Sharing between PU and SU in Cognitive Radio Network (CRN) [28]

The reliable data transmission between source and destination in CRN with the help of relays is only possible if relays cooperate with source to transmit towards destination [8], [10], [11]. There are many different schemes implemented at relays as discussed earlier for reliable data transfer, those are, AF, DF, CF and etc.

5.2 Cognitive Radio System Model

CR system model contains of a PU, CRs and CC. The CC acts as a decision maker in the cognitive relays which implement different signal detection technique for making accurate decision [8], [19], [20]. The channel between PU and SU is assumed as Rayleigh fading channel

and the noise added during transmission through wireless links is assumed as AWGN having mean zero and variance $\frac{N_0}{2}$ [19], [20]. CR system model is shown in Figure 5.3.

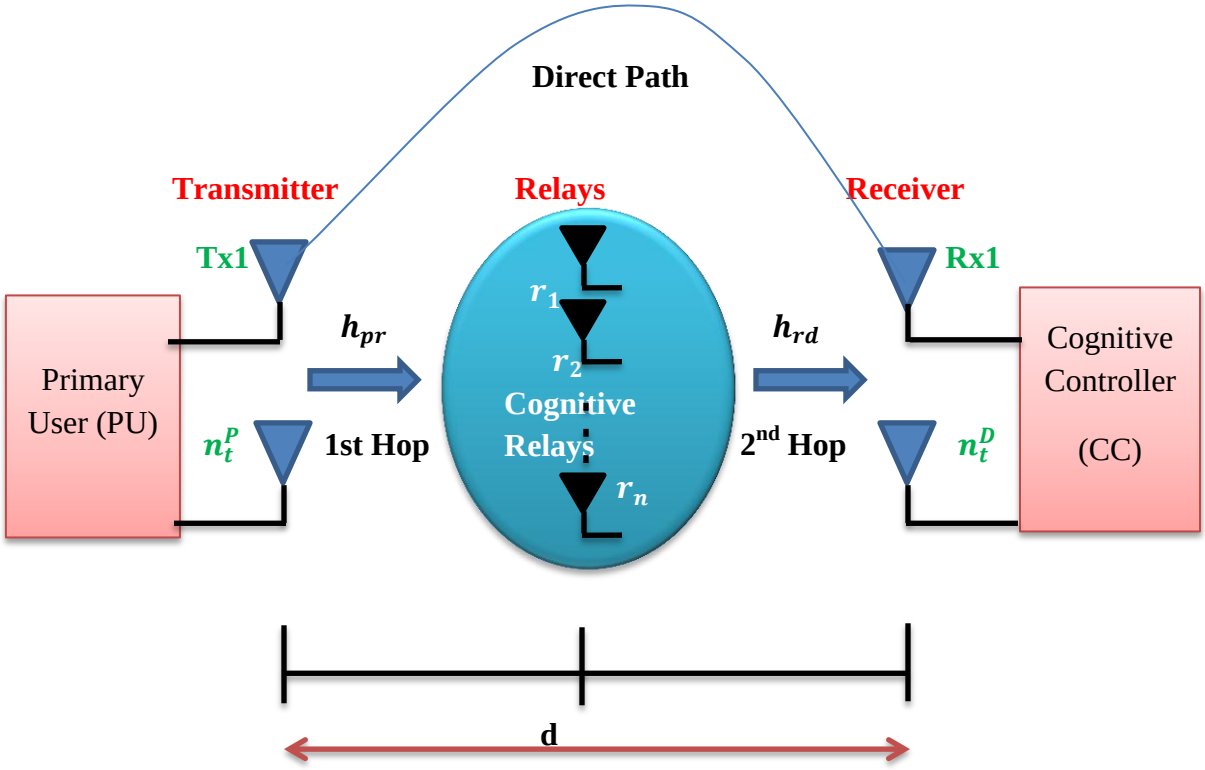

Figure 5.3. Proposed Cooperative Cognitive Radio Network model for Implementation of Alamouti STBC using DF Relaying Protocol

where in Figure 5.3 Alamouti 2×2 STBC scheme is implemented. The distance between PU and CC is denoted by *d* and the relations for channel mean power of all wireless links due to path loss effect are expressed mathematically as:

$$h_{pr} = \epsilon^{-\alpha} * d \tag{5.1}$$

$$h_{rd} = (1 - \epsilon)^{-\alpha} * d \tag{5.2}$$

Where h_{pr} is the channel mean power between PU and relays. Similarly h_{rd} is the channel mean power from relays to destination link [18], [19], [21]. In Equation 5.1 and 5.2, ϵ is the distance control factor between PU and CC where α is the path loss exponent used in wireless multipath transmission [22], [23], [24]. The ϵ will vary in different cases to detect PU signal by varying distance between PU and CRs. The path loss exponent α within the model also has varying

capability, which has exponentially decaying property. Each link between transmitter and receiver have fading coefficients denoted by h_{pr}, h_{rd} where h_{pr} is the fading coefficient from PU to CRs and h_{rd} is the fading coefficient between CC and destination link [6], [19], [25]. Fading and noise are the main issues in wireless medium transmission, that destroys the transmitted data and decoding at receiver become complex, sometimes wrong decision is made due to errors at receivers [20], [23], [24], [25]. Data is transferred in 2-hop from source to destination via multipath using Time Division Multiplexing Access (TDMA) technique. In first time slot or in first hop, Alamouti STBC [20], [25], [27] encoded data is broadcasted into air, this broadcasted data reach at destination either by using direct path or by using indirect path which contains CRs in CRN. In second time slot or second hop cognitive controller makes final decision about presence or absence of PU within their spectrum using different transmitter detection techniques [26], [29]. If CC makes a decision, that shows absence of PU within spectrum then spectrum sharing takes place between PU and SU. The signal that transfers from between PU and cognitive controller link or through direct link has particular SNR value, it shows the strength of signal at the link. Maximum data is transferred though the link having high SNR value in the indirect path at those links fading and other errors are assumed to be less affected [23], [24], [28], [29].

In the proposed model two transmit antennas at transmitter and two receiving antennas at receiver are assumed with full duplex capability but CRs contain one transmit or receive antenna having half duplex characteristics [23], [24], [25]. The signal received through direct link at destination and the signals received at CRs are expressed mathematically as:

$$y_{pd} = h_{pd} * a_n + n_{pd} \tag{5.3}$$

$$y_{pr} = h_{pr} * a_n + n_{pr} \tag{5.4}$$

Where h_{pd} , h_{pr} are the channel coefficients and a_n denotes the Alamouti STBC encoded signal. In Equation 5.3, n_{pd} is AWGN added in signal during transmission through wireless channel from PU to destination similarly in Equation 5.4, n_{pr} is the AWGN added during transmission from PU to relays (r_n) [19], [20]. [21], [30].

5.2.1 Energy Detection Method in Cognitive Controller

Every node in CRN cooperates with each other to solve hidden terminal problem and to achieve diversity gain. The main task is to detect PU spectrum free holes and to share with SU. The detection of PU spectrum is a big task for SU to make final decision about presence or absence of primary user on the basis of received signal [2], [5], [6], [9]. CRs cooperate with the transmitter in transmitting reliable data towards destination and make individual decision about PU presence or absence then forwards their individual decisions to a common fusion center known as Cognitive Controller (CC), that holds the authority to make final decision on the basis of received individual relay decisions [7], [8], [12], [15]. The major technique used in detecting PU spectrum availability or unavailability is known as transmitter detection of PU has further sub-methods e.g. energy detection, MF detection, wavelet detection, covariance detection and etc, as explained in chapter 3 [16], [19], [20], [24]. For implementing Energy detection method in CC of relays it is important to complete some tasks on detected PU signal before making final decision. The energy detection method is shown in Figure 5.4 [23], [25], [27], [34].

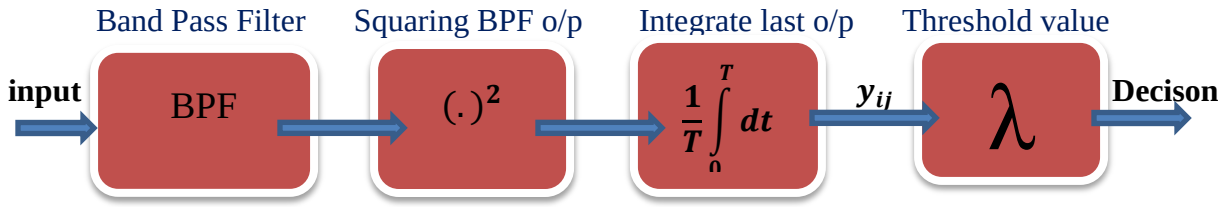

Figure 5.4. Energy Detector Implemented in Cognitive Controller of Relays

For calculating PU signal energy (E), detected PU signal is first passed through Band Pass Filter (BPF) having carrier frequency f_c and bandwidth B Hertz, to bind the bandwidth of received signal, the output of the BPF is forwarded to squaring device then further to integration device for integrating over time interval T [17], [18], [19]. The number of samples for each component of received signal is denoted by $v = TB$ which is an integer value where T is the time over which samples are obtained [19], [20], [22], [23]. The result from integral device is denoted as y_{ij} here which further is forwarded towards threshold device for comparing the resulted signal energy

with predefined threshold energy value of a signal. In threshold device if calculated signal energy of PU signal is less than predefined energy value, it is assumed that the PU is available, otherwise CC makes final decision that the PU spectrum is unavailable and primary users are using their spectrum [19], [20], [24]. The final decision from CC is always in binary form either 1 or 0; 1 when PU spectrum is occupied and 0 for free spectrum. The signal y_{ij} calculated after integral device in energy detection method is given by [23], [25], [28]:

$$y_{ij} = \emptyset\, a_{ij} + n_{ij} \tag{5.5}$$

Where a_{ij} is the input signal and n_{ij} is the AWGN having zero mean and variance $N_0/2$.

Case 1: PU is absent within spectrum

When $\emptyset = 0$ the PU signal is not present within spectrum and SU have opportunity to use spectrum until PU need back spectrum for their own users. The received signal energy *E* follows chi square distribution with 2*v* degree of freedom [19], [20], [22]. The Equation 5.5 will become as:

$$y_{ij} = n_{ij} \tag{5.6}$$

The energy detector form the statistical equation as

$$T(y_{ij}) = \left| y_{ij} \right|^2 \tag{5.7}$$

The Cumulative Distributive Function (CDF) of Equation 5.7 can be expressed as

$$F_0(t) = P[T(y_{ij}) > t \,|\, \emptyset = 0]$$

$$= \int_t^{\infty} f(t)\, dt$$

$$F_0(t) = e^{-t} \tag{5.8}$$

Case 2: PU is present within spectrum

When $\emptyset = 1$, it shows PU spectrum is already occupied and SU will have to wait for spectrum availability. For this reason SU inspects PU spectrum again and again for its availability and when they get spectrum free they use it for their users [18], [19], [21], [22]. The received signal

E follows non-central chi square distribution with 2*v* degree of freedom [19], [20]. The Equation 5.7 will become as.

$$y_{ij} = \ a_{ij} + n_{ij} \tag{5.9}$$

and

$$T(y_{ij}) = \left| a_{ij} \right|^2 + \left| n_{ij} \right|^2 \tag{5.10}$$

Similarly the CDF of Equation 5.10 can be calculated as:

$$F_1(t) = P[T(y_{ij}) > t \,|\, \emptyset = 1]$$

$$= \int_t^{\infty} f(t)\, dt$$

$$F_1(t) = \ e^{-\frac{t}{A1+A2+1}} \tag{5.11}$$

Where $A1 + A2$ are the signal powers of the transmitted symbols [19], [20], [27].

The probability of detection and probability of false alarming are calculated by:

$$P_d = Q\ (\sqrt{\gamma}\ , \sqrt{\lambda}) \tag{5.12}$$

$$P_f = \frac{\Gamma(v, \frac{\lambda}{2})}{\Gamma(v)} \tag{5.13}$$

Where *Q* is the Marcum-Q function [19], [27], [23] and Γ (pronounced as "capital gamma") is the upper incomplete gamma function having degree of freedom (.). The upper incomplete gamma function is defined as:

$$\Gamma(a, t) = \ \int_t^{\infty} x^{a-1} e^{-x} dx \tag{5.14}$$

The Equations 5.12, 5.13 respectively, show the probability of detection and probability of false alarming (detection of bit 1 at receiver even if the transmitter would have transmitted bit 0). From both equations it is clear that probability of false alarming does not depend on end-to-end SNR that is why it remains the same in any kind of fading channel [19], [20], [24], [25].

5.2.2 End-to-End SNR for Direct Path

The Alamouti STBC 2×2 encoded data broadcasted through two transmitting antennas reach at destination in two ways, either through direct path or from multipath relay channels [19], [20], [23], [24]. Direct path transmission plays key role in determining P_d of PU spectrum and for achieving spatial diversity [20], [25]. The calculated end-to-end SNR for direct path in a cooperative CR network is:

$$\gamma_D = d * a_{ij} * \| h_{pd} \|^2_{Frob} \tag{5.15}$$

where h_{pd} is the fading matrix from PU to SU or destination and *Frob* is the Frobenius norm or Eucledian norm which is used for position calculation of eigenvectors and has the relation [18], [26].

$$\| H \|^2_{Frob} = \sqrt{H.H} = \sum_{i=1}^{n_t^P} \sum_{j=1}^{n_r^D} \left| h_{ij} \right|^2 \tag{5.16}$$

Where *i* and *j* represent as a tag for symbols transmitted through multiple antennas towards destination [20], [24].

5.2.3 End-to-End SNR for Indirect Path (Multiple Relays)

In proposed technique four relays are placed between source and destination whereas the distance between source and relays is controlled by distance control factor $\in$. The end-to-end SNR for relay path is calculated in the same as it is done in direct path but the calculated fading matrix will be different due to complex random nature of the Rayleigh channel having fast fading [8], [16], [17], [20].

MRC technique is implemented at receiver to calculate the overall end-to-end SNR of the PU→ SU link, where C denotes a constant in Equation 5.17 [19], [20], [22].

$$\gamma_{PU \rightarrow SU} = \mathrm{C} * \sum_{n=1}^{N} \frac{\gamma_{pr}^n \gamma_{rd}^n}{\gamma_{pr}^n + \gamma_{rd}^n} \tag{5.17}$$

Selection Combining (SC) technique is used at receiver to combine the signal coming from relay link with direct path [23], [24], [25]. In SC receiver selects the highest SNR relay link between

source and destination and adds with direct path transmitted data to get original transmitted information from source [23], [24].

$$\gamma_{PU\rightarrow SU(SC)} = \mathrm{C} * \max_{n=1\ldots N}\left(\frac{\gamma_{pr}^{n}\,\gamma_{rd}^{n}}{\gamma_{pr}^{n}+\gamma_{rd}^{n}}\right) \tag{5.18}$$

5.3 **Maximum Likelihood (ML) Decoding**

The signal received at relays is decoded using ML decoder [23], [32], [35]. The process of decoding a signal has resemblance with the estimation of a signal. The purpose of ML decoding is to find the parameters which maximize the probability of detection of PU spectrum [24], [25], [36]. The method of decoding the received signal at relay is done by taking one code word $k_1$among all possible codes *K* which were encoded by Alamouti STBC scheme and were transmitted through transmitted antennas towards Binary Symmetric Channel (BSC) with the probability of error *p* [35], [36], [37], [38]. The distorted version of transmitted signal is received at relay due to fading and noise present within channel. The transmitted sample code is represented with "k_1" and received signal at relay with *'k_2'* then ML decoding can be mathematically expressed as [38], [39]:

$$\mathbb{P}(k_1\ transmitted \,|\, k_2\ received) \tag{5.19}$$

The receiver computes all possible probabilities by each receiving symbol e.g. $\mathbb{P}(k_{11}, k_2), \mathbb{P}(k_{12}, k_2), \mathbb{P}(k_{13}, k_2), \ldots\ldots\ldots\ldots, \mathbb{P}(k_{1n}, k_2)$ where received signal k_2 is the distorted signal affected during Rayleigh faded channel. The coding diversity is achieved by implementing DF protocol at cognitive relays [38], [40]. It is known that relays do not know about input signal transmitted from transmitter but only know the received faded signal, so ML estimation method is used to find the parameter values which make the received data to most likely format. For estimating mean of a received signal using normal distribution is done by taking sample average [24], [34], [40]. The estimated mean $\tilde{\mu}$ of the signal is calculated in Equation 5.20:

$$\tilde{\mu} = \frac{k_{11}+k_{12}+k_{13}+\cdots+k_{1N}}{n} \tag{5.20}$$

For using ML method it is important to find joint density function for all observed observations which are independently and identically distributed (iid) [19], [20], [36]. The joint density function of observed observations will be:

$$f(X_1, X_2, X_3, \dots., X_n|\theta) = f(X_1|\theta).f(X_2|\theta).f(X_3|\theta) \dots \dots f(X_n|\theta) \quad (5.21)$$

Where $X_1, X_2, X_3, \dots., X_n$ are the fixed observed parameters of the function and θ is the varying free parameter [35], [36], [38], [39]. Due to this aspect the distributed function is known as Likelihood function defined in Equation 5.22:

$$Ł(\theta|X_1, X_2, X_3, \dots., X_n) = f(X_1|\theta).f(X_2|\theta).f(X_3|\theta) \dots \dots f(X_n|\theta) = \prod_{i=1}^{n} f(X_i|\theta) \quad (5.22)$$

The logarithm of Likelihood function is known as log-Likelihood which is more convenient to use as shown in Equation 5.23.

$$\ln Ł(\theta|X_1, X_2, X_3, \dots., X_n) = \sum_{i=1}^{n} \ln f(X_i|\theta) \quad (5.23)$$

and the estimation of a single observation is denoted by $\tilde{l}$ defined as:

$$\tilde{l} = \frac{\ln Ł}{n} \quad (5.24)$$

The process of estimation for θ is known as Maximum Likelihood Estimator (MLE) of θ.

$$\tilde{l}_{mle} = \arg\max_{\theta \epsilon \Theta} \tilde{l}(\theta|X_1, X_2, X_3, \dots., X_n) \quad (5.25)$$

In BSC hamming distance or Euclidian distance is used to compute the probability of detection of PU signal that is why the process of decoding is known as maximum likelihood or minimum distance decoding [28], [34], [39]. The link between PU to relays which has maximum SNR that decodes maximum of the received data and is used for information transmission towards destination helping source to achieve spatial diversity resulting code diversity. Sometimes relay does not decode properly because of erroneous received signal due to heavy noisy and faded channel then ADF relaying protocol is used to overcome this issue, in which source retransmits towards destination when source-relay transmission is unsuccessful [21], [23] , [37], [38], [40].

5.4 Simulation Results

To see system performance for implementation of Alamouti STBC in DF cognitive relay network MATLAB simulated results are observed. The parameters used in simulation are defined as:

1. The distance control factor between PU and cognitive relays is $\in$.
2. The channel mean power for direct link is *d*.
3. The path loss exponent used in wireless communication is $\alpha = 3$
4. The wireless channel assumed, is Rayleigh faded channel and AWGN with mean 0 and variance $N_0/2$.
5. The received waveform time-bandwidth product for pulse duration and width is $v = 2$
6. P_d is the probability in detection of PU signal.
7. P_f is the probability of false alarming (wrong answers).
8. The energy of the PU signal is denoted with λ known as threshold value and is used by cognitive controller within cognitive relays.

In proposed model, detection of PU signals in Alamouti $T_x = R_x = 2$ STBC encoding, using DF protocol at CRs has been observed under different cases. Here four cognitive relays are used, placed at different ranges between PU and SU to observe system performance. It explains different cases, that how the system performance improves, using DF protocol at relay in cooperative cognitive network.

5.4.1 Relays are placed in middle between PU and SU

If CRs are placed in the middle between PU and SU to observe the system performance in terms of probability of detection P_d of PU signal, when the distance control factor is $\in = 0.5$, channel mean power for direct link is assigned $d = 0.3$ system performance in terms of P_d to detect weak PU signal (SNR=-8dB) is shown in Figure 5.5.

Figure 5.5 clearly indicates that when energy level or threshold λ is increased, the P_d decreases and for detecting weak power PU signals, use of relays play an important role [19], [20], [24], [25]. As the number of relays are increased between PU and SU the detection of weak PU signal is improved in comparison with direct link transmission detection. By comparing direct link and with using n=1 relay, 2 times improvement in performance can be observed for PU detection and 6 times improvement with n=4 relay. In Figure 5.6, P_d is improved using number of relays as the P_f increases the PU detection is improved maximum as compared to direct link detection [19], [20], [25]. In Figure 5.7, a threshold λ =40 is defined at system to detect signal having energy within this range by comparing the detection of signal through direct link with the signal detection through relays, decision can easily be made in favor of using relays for higher system performance [20], [24]. More than 80% performance is improved when the detection probabilities are compared with direct link only and n=4 relay link. Using relays between PU and SU, P_d is increased for detecting PU weak signal.

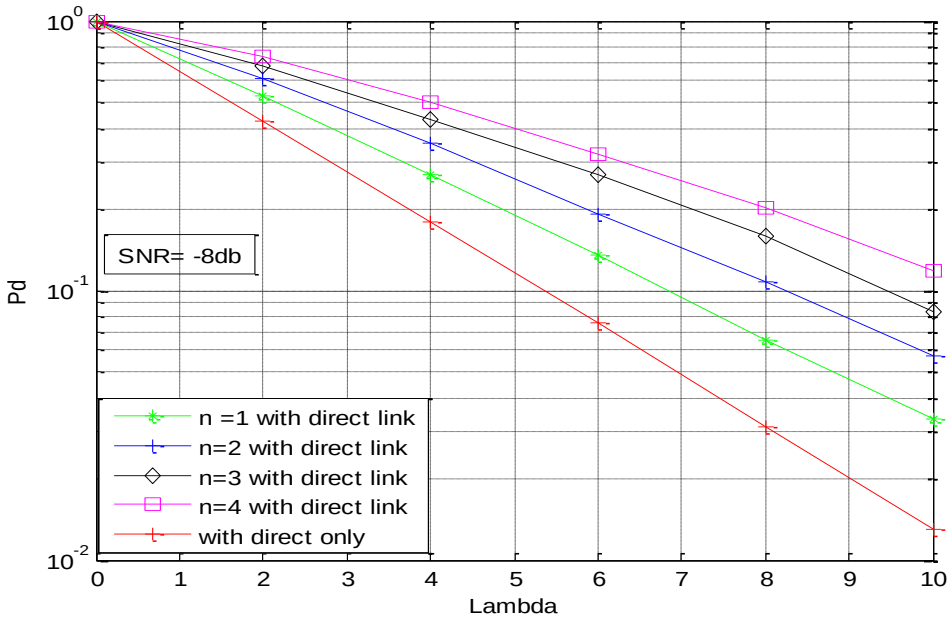

Figure 5.5. Probability of Detection (P_d) vs. Energy Threshold (λ) in Alamouti STBC using $T_x = R_x = 2$ Antennas with different number of Relays.

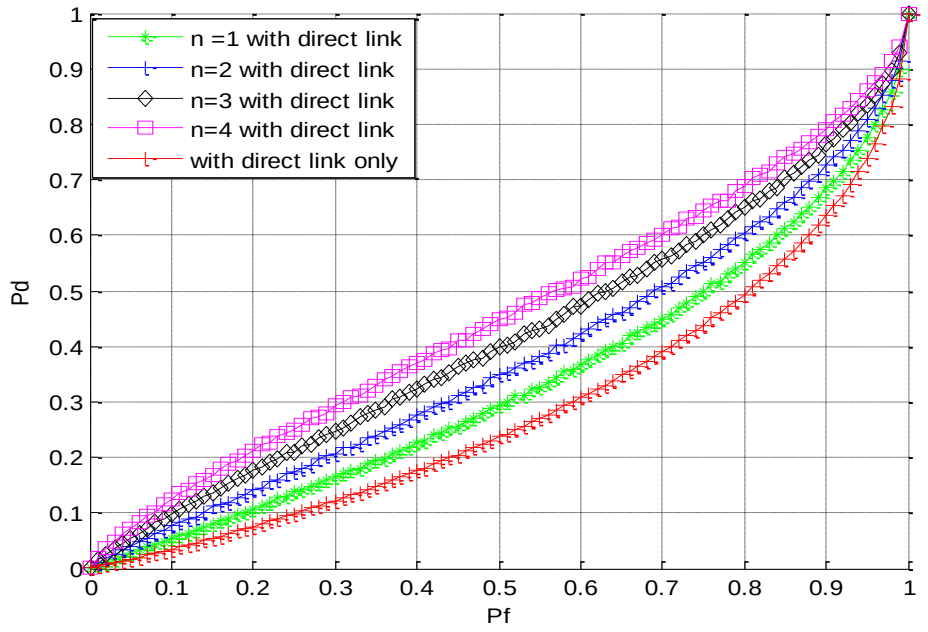

Figure 5.6. Probability of Detection (P_d) vs. Probability of False Alarming (P_f) in Alamouti STBC using $T_x = R_x =$ 2 Antennas with different number of Relays.

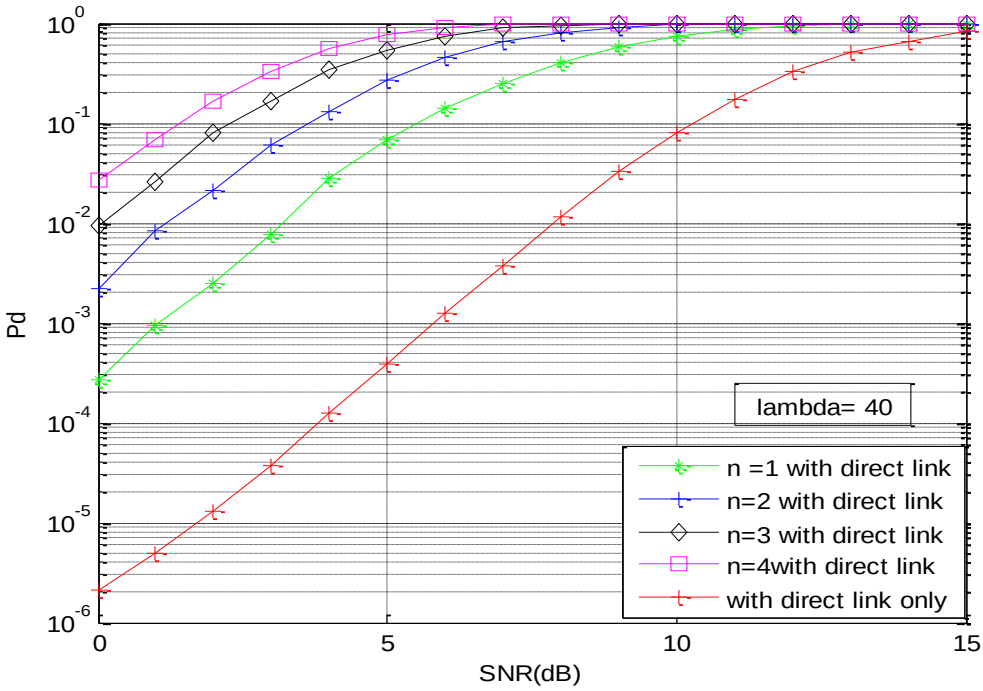

Figure 5.7. Probability of Detection (P_d) vs. End-to-End SNR in Alamouti STBC using $T_x = R_x = 2$ Antennas with different number of Relays.

5.4.2 Relays are placed close to PU

If CRs are placed close to PU to observe the system performance in terms of probability of detection P_d where the distance control factor is assigned $\in = 0.3$ and channel mean power for direct link is assigned $d = 0.2$ then system performance to detect signal having range (SNR= -8=>3dB) is shown in Figure 5.8.

Figure 5.8 shows that when energy level or threshold λ is increased, the P_d decreases and when λ decreases then P_d increases [19], [20], [24]. In the present case signal power is already stronger than in case 1, so the detection is expected to be high. Almost 2 times improvement in performance can be observed between direct link only and using n=1 relay for PU detection and in the same way more than 4 times improvement with n=4 relay. In Figure 5.9 P_d is improved by using number of relays as the P_f increases and it is clear that the PU detection is improved maximum as compared to direct link detection [20], [24]. When $P_f = 0.4$, detection probability to detect strong signal is almost 100% in case of n=4. In Figure 5.10 threshold λ =20 is pre-defined in the system to detect signal having energy within this range. It is evident that signal detection through relays in comparison with the signal detection through direct link, results in higher performance [19], [20]. Almost 7 times performance improvement is observed by comparing the PU signal detection between direct link and using n=1 relay. Similarly more than 80% performance in terms of PU signal detection is improved, when comparison between the detection probabilities of direct link only and n=4 relay link is made, as the SNR of PU signal is increased. In this case PU signals are detected maximum because of strong power signal and lower threshold value at CC. Using relays between PU and SU, P_d increases for detecting PU strong signal even by decreasing pre-defined threshold value at CC.

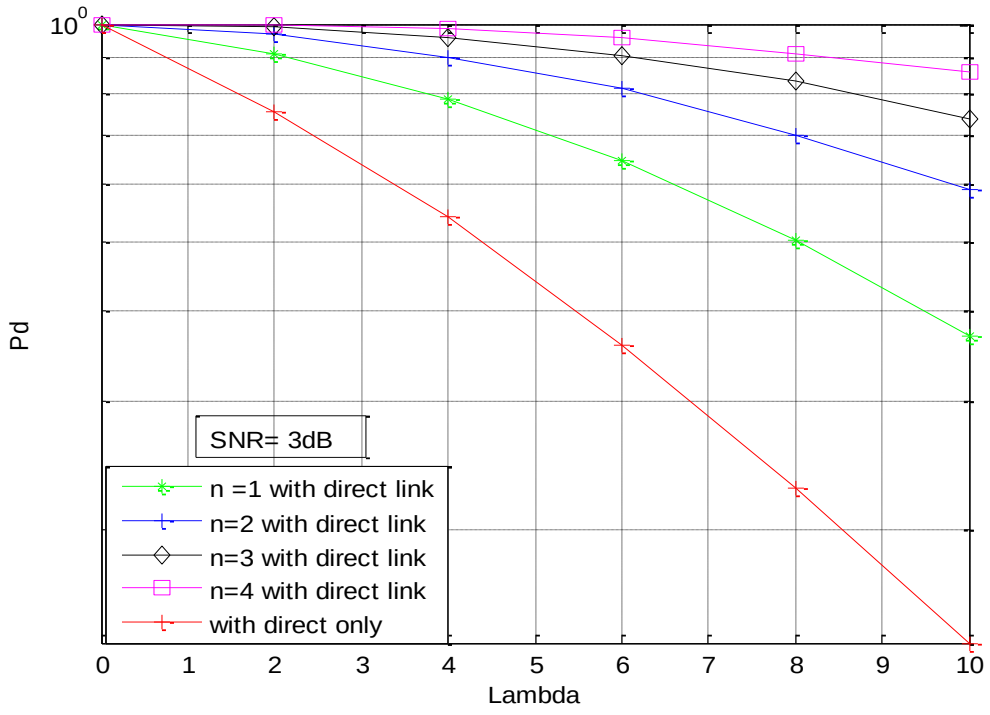

Figure 5.8. Probability of Detection (P_d) vs Energy Threshold (λ) in Alamouti STBC using $T_x = R_x = 2$ Antennas with different number of Relays.

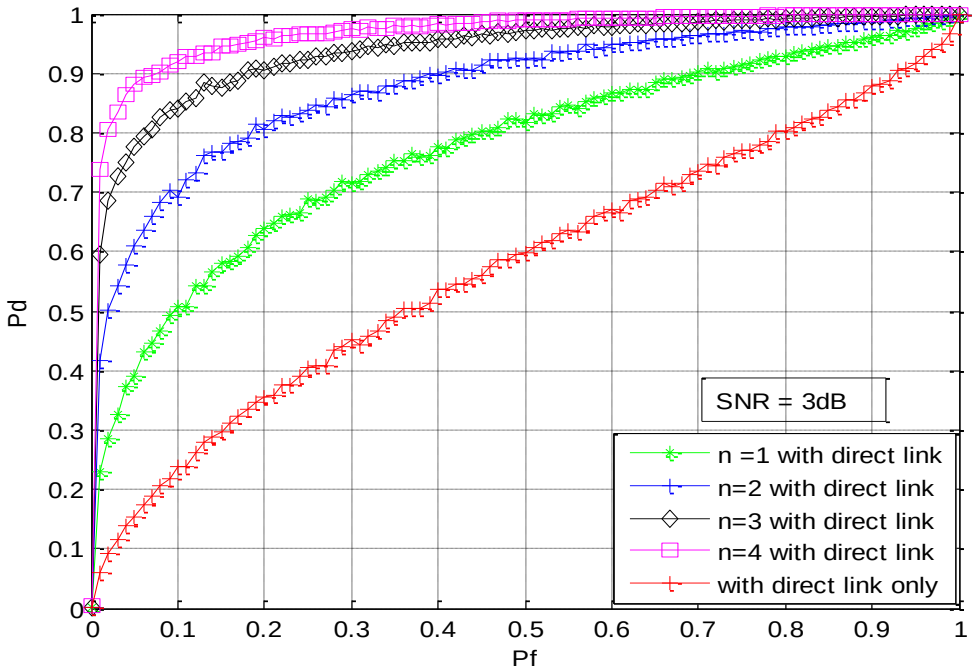

Figure 5.9. Probability of Detection (P_d) vs Probability of False Alarming (P_f) in Alamouti STBC using $T_x = R_x = 2$ Antennas with different number of Relays.

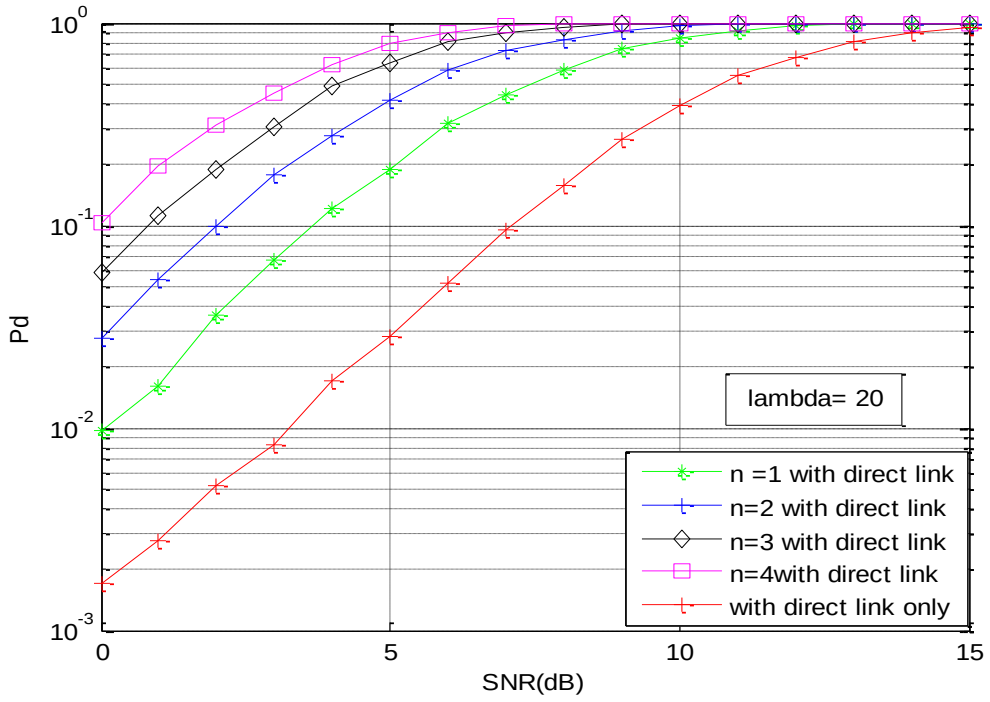

Figure 5.10. Probability of Detection (P_d) vs End-to-End SNR in Alamouti STBC using $T_x = R_x = 2$ Antennas with different number of Relays.

5.4.3 Relays are placed close with PU but increase in Energy Threshold

In case 2 it is observed that the PU signal have strong power with λ =20. In case 3 capability of proposed system to detect strong PU signal is observed by increasing λ =50 and ∈= 0.2, the results are shown in Figures 5.11, 5.12, 5.13 respectively. It is cleared that using relays between PU and SU and implanting DF relay plays vital role in achieving spatial diversity and code diversity that results in improved system performance. By increasing number of relays and threshold value, the probability to detect PU signal also increases as compared to case 1,2 as shown in Figures 5.11, 5.12, 5.13 respectively.

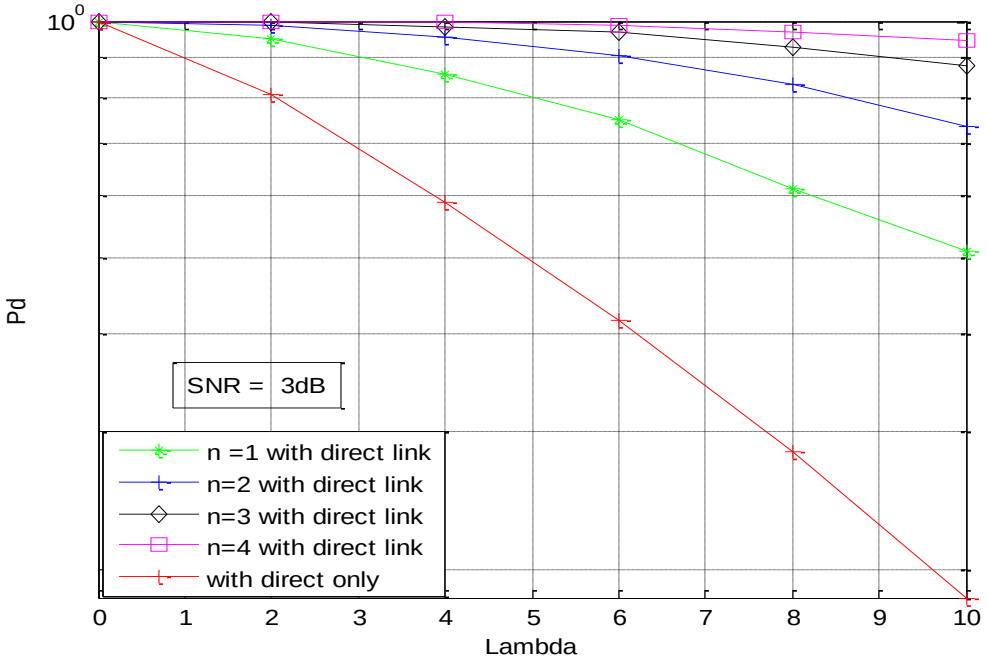

Figure 5.11. Probability of Detection (P_d) vs Energy Threshold (λ) in Alamouti STBC using $T_x = R_x = 2$ Antennas with different number of Relays.

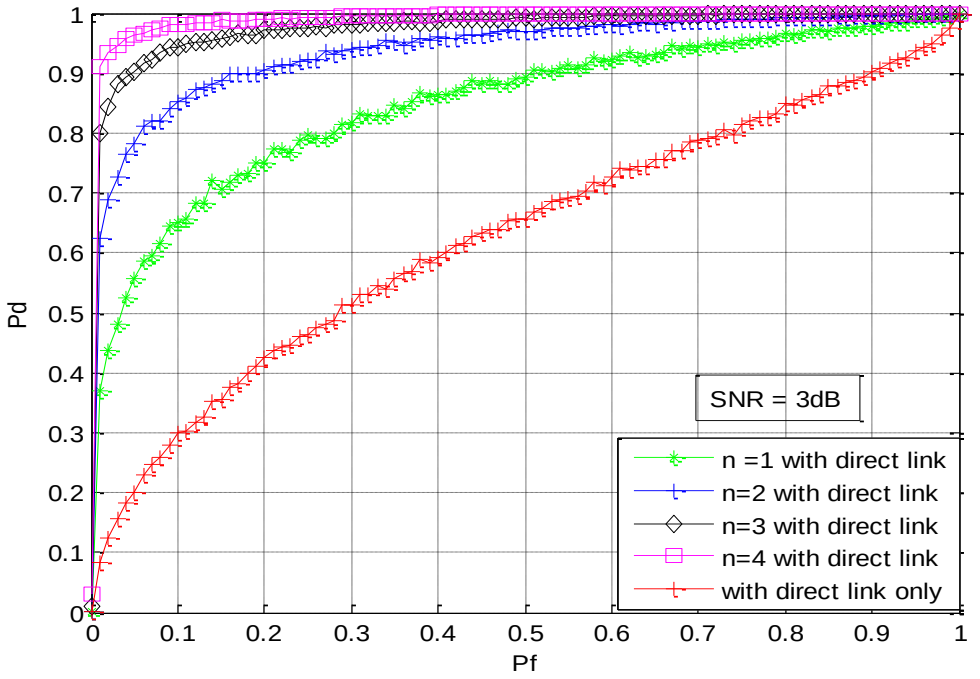

Figure 5.12. Probability of Detection (P_d) vs Probability of False Alarming (P_f) in Alamouti STBC using $T_x = R_x = 2$ Antennas with different number of Relays.

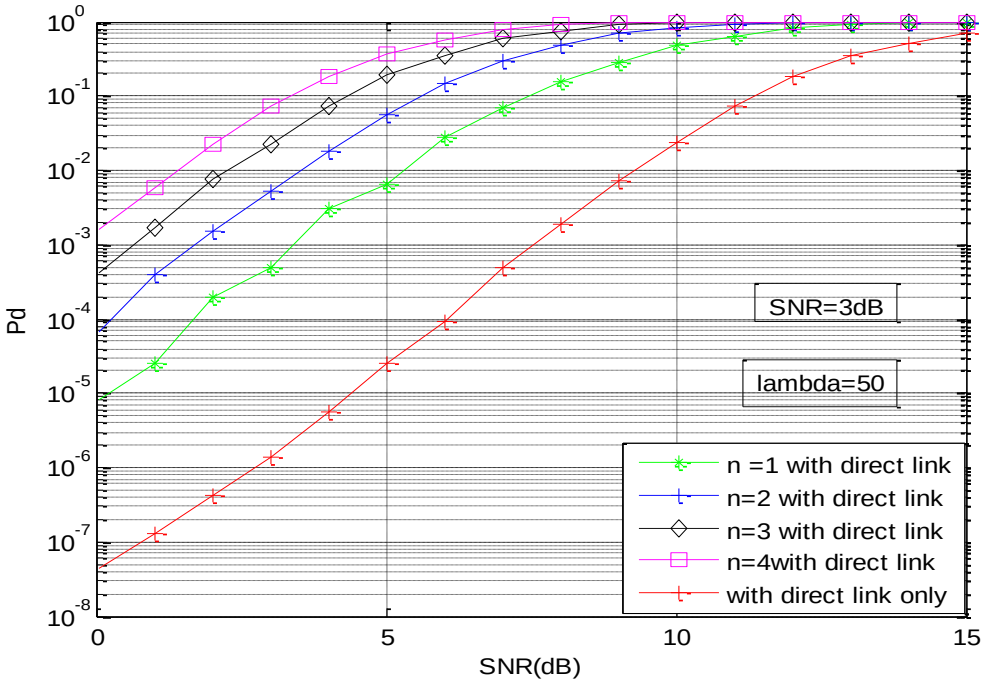

Figure 5.13. Probability of Detection (P_d) vs End-to-End SNR in Alamouti STBC using $T_x = R_x = 2$ Antennas with different number of Relays.

Figure 5.13 shows that when CRs are placed close to the PU then the probability to detect PU signal increases. As discussed in previous cases, when the energy threshold to detect PU signal is increased at CC, the P_d decreases and in opposite case if energy threshold is reduced, P_d increases but if source transmit strong power signal then it provides better detection opportunity in the presence of high λ. As the SNR of PU signal increase, CRs detect strong PU signal from PU transmitter which help CC to make accurate decision using energy threshold which additionally inform about licensed user's spectrum current status [20], [24]. The result clearly shows that CRs play an important role in data transfer through multipath transmission. By comparing performance in terms of P_d, through direct link and through CR link, it shows that using relays and decoding the received signal at relays before transmitting towards final destination, provide better PU detection performance than transmitting data via only direct link [23], [24]. Hence ML decoding technique implemented at CRs provide better performance in cooperative cognitive radio network [36], [40].

5.5 **Conclusion**

This chapter explains the structure of CR network that relates to spectrum sensing, channel estimation and data transmission lie on physical layer of OSI layers. Cognitive radio system model consists of PU, cognitive relays and SU have been explained. The distance between PU and relays are controlled by distance controlling factor $\in$, gives information about both PU and relays are close to each other or away. When CRs are close enough then it will be easier for relays to detect PU signal and relays that can easily decode the detected signal by using ML decoding technique at relays. ML technique finds the parameters that help to find maximum probability to detect PU signal. All the relays within the system send their decision to CC having the authority to finalize decision on the basis of relays provided data and by using different transmitter detection technique, help in making final decision. There are many transmitter detection techniques, helps to detect PU signal among those energy detection is implemented on CC in proposed system, plays a key role in decision making. CC compares the calculated signal energy of the received signal with pre-defined signal energy then makes decision about presence or absence of PU within the spectrum. In the last part of the chapter simulation results for implementation of Alamouti 2×2 STBC encoded data in DF cooperative CRN clearly show that by using and increasing the number of relays between PU and SU, the performance to detect PU signal increases. Simulation results show that it is better to decode the incoming data at relay before re-transmission towards destination that improves the overall system performance in detection of PU spectrum.

Chapter 6: Performance Evaluation between AF and DF Alamouti STBC Cognitive Relay Network

6.1 Amplify and Forward (AF) Alamouti STBC Cognitive Relay Network

To achieve spatial diversity multiple copies of data is transmitted through MIMO technology that provides reliable data transmission from source to destination. The data is transmitted to destination either via direct link or by indirect path [1], [2], [19], [20]. CRs help source in transmitting information towards destination providing good coding diversity and receive diversity. The relays detect the signal transmitted from PU and implement different protocols to forward newly form of the data towards destination which play its role in improving probability to detect PU signal. In AF [5], [20], [25] protocol CRs cooperate with source in forwarding signal by amplifying the received data before transmitting towards destination. Amplifying signal at relays improves power of transmitted signal and then it is added with direct path transmitted signal to provide reliability in receiving original data at destination. The simulation results taken from [20], [25], [26] showing AF protocol implementation and data encoding with Alamouti STBC having $T_x = R_x = 2$.

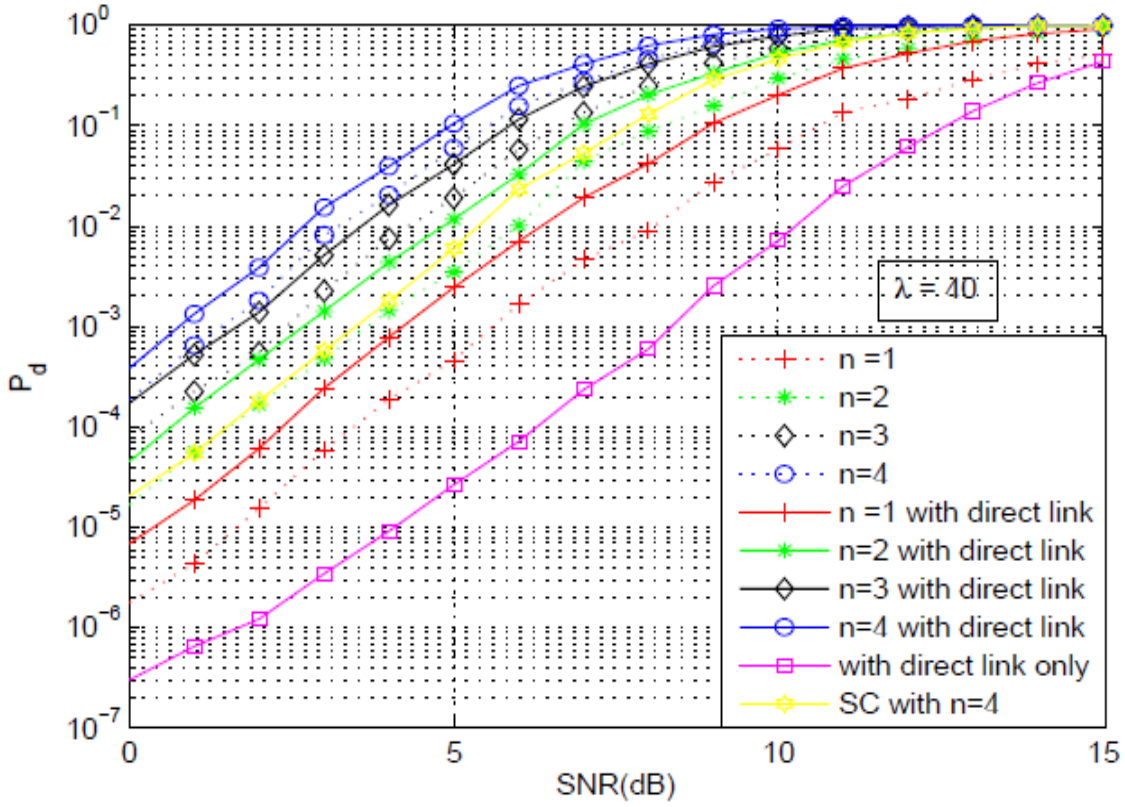

Figure 6.1. Probability of Detection (P_d) vs. End-to-End SNR, with Tx=Rx= 2 Alamouti STBC (Rayleigh Fading Channel), for different number of Relays (n) [20].

6.2 Decode and Forward (DF) Alamouti STBC Cognitive Relay Network

In cognitive relay networks, implementation of DF protocol at CRs using Alamouti $T_x = R_x = 2$ STBC scheme provides higher performance than using AF relaying protocol [24], [32], [36]. Relays decode the received signal using ML decoding technique, after decoding the signal relays re-encode the signal then forward the newly encoded data towards destination without amplification [24], [36], [37], [40]. The probability to detect PU signal is improved by using DF protocol in cognitive cooperative network implementing Alamouti STBC with two transmitting and two receiving antennas. A simulation result from proposed technique using the same threshold value λ=40 used in AF cognitive relay network as shown in Figures 6.1, 6.2 respectively . Their clear observation indicates that DF protocol give 67% higher performance in detecting PU signal than AF protocol.

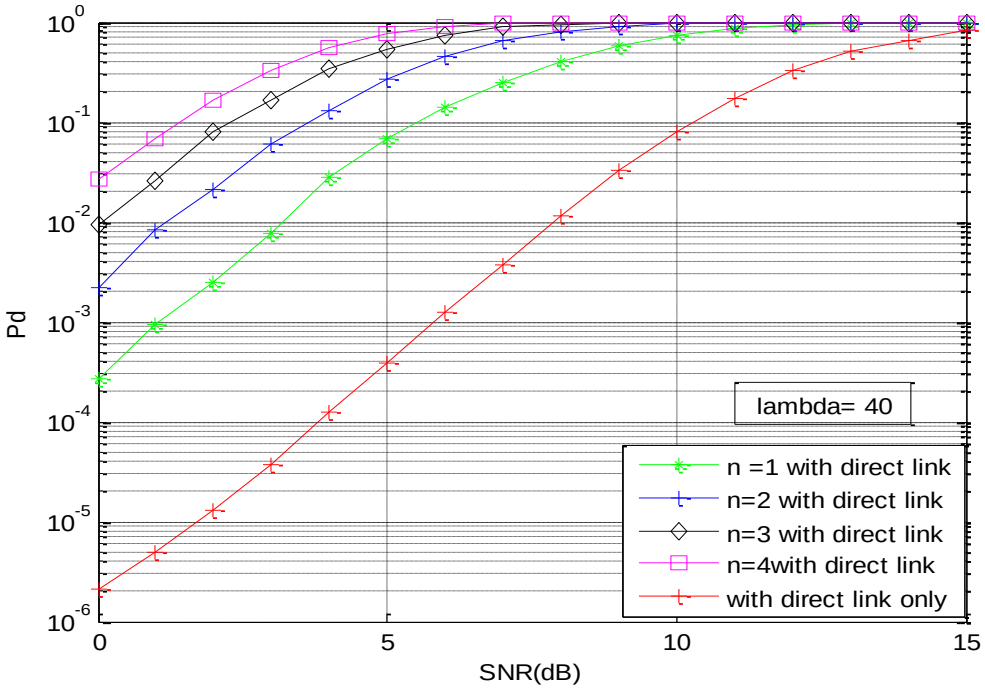

Figure 6.2. P_d vs. SNR in Alamouti STBC using $T_x = R_x = 2$ Antennas with different number of Relays.

6.3 **Conclusion**

By the comparison of Figures 6.1,6.2 it is clear that using same energy threshold λ=40, the detection probability of PU signal is better in Figure 6.2 than in Figure 6.1. Using Alamouti STBC with 2×2 transmit and receive antennas implementing DF protocol at relays provides better detection probability of PU than AF protocol. Hence DF protocol provides better performance than AF protocol in cooperative cognitive networks using 2×2 Alamouti STBC encoding scheme. Instead of forwarding amplified signal through relays towards destination, decoding the detected signal then re-encode it to forward without amplifying re-encoded signal at relays, provides higher performance in terms of probability of detection P_d of PU signal, further play an important role in making final decision about presence or absence of PU within the spectrum. A careful observation and comparison of Figures 6.1,6.2, reveals that simulation result of Figure 6.2 using DF protocol gives 67% higher performance in detecting PU signal than AF protocol used at relays in CRN.

Chapter 7: Conclusion

7.1 Conclusion

The main objective was to implement DF protocol at CRs using Alamouti STBC with 2×2 transmit-receive antennas in cooperative CRN focusing 2-hop communication. The proposed technique is implemented in MATLAB to observe the performance of the system.

Detection of PU signal then to make decision about presence or absence of PU within their spectrum on the basis of received signal in CRN is under research in recent era. This work is helpful in detecting PU signal by cognitive relays and then CC plays vital role in determining the availability or unavailability of PU spectrum.

With the help of simulation results it came to light that decoding at CRs using ML decoding give 67% better performance than just amplifying the received data at CRs, before forwarding towards destination. Using limited number of relays for experiment the proposed work can be generalized for *n* number of CRs providing better performance in terms of detection probability as the number of relays increase.

The proposed solution is helpful in spectrum sensing for making accurate decision about status of spectrum and when spectrum sensing is completed the process of spectrum sharing is started between licensed users and unlicensed users to save congested radio spectrum for new services. Through this technique spatial diversity is achieved and code diversity is improved by transmitting data using spectrum sharing without creating interference for licensed spectrum users.

Chapter 8: Future Work

8.1 Future Work

The suggested future work in cognitive radio network can be:

- Spectrum sensing using different transmitter detection techniques either matched filter detection, cyclostationary detection, wavelet detection and etc. instead of energy detection method.
- Implementing DF protocol in 3-hop communication process in which relays should have different capabilities regenerative and non-regenerative. The system in 3-hop consist of a source, regenerative relays, non-regenerative relays and destination. In first hop source transmit information towards regenerative relays and in second hop regenerative relays forward data towards non-regenerative relays and then in third hop non-regenerative relays forward information towards destination to achieve receive diversity for reliable data transmission.
- Implementation of DF relaying protocol in cooperative cognitive networks using STTC instead of using STBC.
- Error detecting and correcting mechanism at relays to detect wrong decoding bits and to correct them to ensure perfect decoding at relays.
- Cooperation between cognitive relays is also one of the issues in cognitive radio network under research.
- How the control and management planes of the cognitive radio network interfere with the global internet?
- Seamless spectrum handover problem.
- Cross layer designing issues between OSI layers.
- Security for PU when SU is sharing their spectrum to avoid interference.

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