T.C.
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SPECTRAL CO-EXISTENCE IN COGNITIVE RADIO NETWORKS USING DIRTY PAPER CODING

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Yüksek Lisans Tezi

T.C.
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Kutubo JAITEH tarafından hazırlanan "**BİLİŞSEL RADYO AĞLARINDA KİRLİ KÂĞIT KODLAMA İLE SPEKTRAL BİRLİKTELİK**" adlı tez çalışması aşağıdaki jüri tarafından oy birliği ile Uludağ Üniversitesi Fen Bilimleri Enstitüsü Elektronik Mühendisliği Anabilim Dalı'nda **YÜKSEK LİSANS TEZİ** olarak kabul edilmiştir.

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- ve bu tezin herhangi bir bölümünü bu üniversite veya başka bir üniversitede başka bir tez çalışması olarak sunmadığımı

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İmza

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ÖZET

Yüksek Lisans

BİLİŞSEL RADYO AĞLARINDA KİRLİ KÂĞIT KODLAMA İLE SPEKTRAL BİRLİKTELİK

Kutubo JAITEH
Uludağ Üniversitesi
Fen Bilimleri Enstitüsü
Elektronik Mühendisliği

Danışman: Prof. Dr. Tuncay ERTAŞ

Bu tezde, spektral verimliliği artırmak için yavaş Rayleigh sönümlemeli 2x2 bilişsel radyo kanalında spektrumun birincil ve ikincil vericiler arasında, asimetrik verici işbirliği ve bilişsel kirli kâğıt kodlama ile eşzamanlı olarak nasıl paylaşılabileceği araştırılmıştır. Birincil kanalın tek girişli tek çıkışlı, ikincil kanalın ise çok girişli tek çıkışlı olduğu bir durumda üzerine bindirme yaklaşımı ile spektral birliktelik (spektrum overlay) genelleştirilmiş bilişsel radyo kanalı üzerinde ele alınmıştır. Yani, aktif spektral bölgelerin kullanımına ek olarak, bulunduğunda birincil aktivitenin olmadığı frekans boşlukları da kullanılmaktadır. Bunun için, uzaysal modülasyona dayalı bir kirli kâğıt kodlama yöntemi önerilmiş ve spektral birliktelik şartları içinde kalarak Uzay-Zaman Blok kodlar ile kullanımı yazılım benzetimi ile incelenmiştir.

Anahtar Kelimeler: Bilişsel radyo, spektrum paylaşma, asimetrik işbirliği, uzay-zaman blok kodlama, kirli kâğıt kodlama.
2016, vii+41 sayfa

ABSTRACT

MSc Thesis

SPECTRAL CO-EXISTENCE IN COGNITIVE RADIO NETWORKS USING DIRTY PAPER CODING

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In this thesis, for the sake of increasing spectral efficiency, the use of Dirty Paper Coding for the spectral co-existence of primary and secondary users in slow Rayleigh fading 2x2 cognitive radio channel through asymmetric transmitter cooperation has been investigated. It is assumed that the primary channel is SISO and the secondary is a MISO channel, adopting spectrum overlay approach over a generalised cognitive radio channel. Namely, in a 2x2 SISO-MISO network, the spectrally active regions of the radio spectrum are also used in addition to the use of inactive parts when available. In this context, a dirty paper coding method based on spatial modulation is proposed and its use with space-time block coding is investigated through software simulation, subject to coexistence-conditions.

Keywords: Cognitive radio, spectrum sharing, asymmetric cooperation, space-time block coding, dirty paper coding.
2016, vii+41 pages

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With my best regards:
Kutubo JAITEH
2016, **REPUBLIC OF TURKEY**

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List of Symbols/Acronyms

$\mathbf{X}$	Matrix $\mathbf{X}$ (boldface capital letter)
$\mathbf{x}$	Vector $\mathbf{x}$ (boldface lowercase letter)
$\mathbf{X}^T$	Transpose of $\mathbf{X}$
$\mathbf{X}_{ij}$	The element on row i and column j of matrix $\mathbf{X}$
$\mathbf{x}^*$	Conjugate of $\mathbf{x}$
$\mathbf{x}^H$	Hermitian transpose of $\mathbf{x}$
Σ_x	The diagonal matrix of the singular values of $\mathbf{X}$
$\mathbf{r}$	Rank of a matrix
R	Data rate
T	Symbol period
η	Spectral efficiency
B	Spectral bandwidth
N_0	Noise power spectral density
N_R	The number of receive antennas
N_T	The number of transmit antennas
Rx	Receiver
Tx	Transmitter
$\mathbf{x}_P$	Primary message
$\mathbf{x}_S$	Secondary message
$\mathbf{G}$	Primary channel matrix
$\mathbf{H}$	Secondary channel matrix
QoS	Quality of service
CR	Cognitive Radio
FCC	Federal Communication commission
ITU	International Telecommunication Union
RF	Radio Frequency
CSI	Channel State Information
CCC	Common Control Channel
MAC	Media Access Control
SNR	Signal-to-Noise Ratio
MIMO	Multiple-Input Multiple-Output
MISO	Multiple-Input Single-Output
SISO	Single-Input Single-Output
DPC	Dirty Paper Coding
STBC	Space Time Block Code
CCI	Co-Channel Interference
ISI	Inter-Symbol-Interference
ML	Maximum Likelihood
BC	Broadcast Channel
MUI	Multiuser Interference
IC	Interference Cancellation
MRC	Maximal Ratio Combining

1 INTRODUCTION

The past two decades has witnessed many advances in physical-layer wireless communication theory along with their practical implementations. This has lead to an increase in the use of wireless applications and services such as internet, on-line shopping and social networking, resulting in an exponential increase in the demand for accessing the radio spectrum.

Due to the current spectrum management style, whereby certain frequency bands are allocated and licensed to specific users, which cannot be accessed by others. This method caused the radio spectrum to be overcrowded and scarced. However, spectrum surveys carried out by the FCC and other international bodies demostrated that most of the licensed bands, such as those allocated for television broadcasting, paging, etc; are underutilised while other bands are heavily used. This traditional method of frequency band allocation leads to a wastage of spectrum. Hence, new spectrum management techniques are required in order to explore the advantages of the spectrum opportunities with an acceptable interference threshold in the licensed band, such as spectrum sensing algorithms, sharing protocols and policies that facilitate access to less occupied bands and help improve wireless communication capacity (Zhang *et. al*. 2010).

Capacity improvement in wireless networks relies on three dimensions: technology, topology and spectrum availability. Traditionally, focus has been on how to develop wireless technologies leading to solutions such as using high-order modulation and coding schemes as well as multiple input multiple output (MIMO) systems. Presently, the focus is shifted to the topology and more efficient use of the spectrum. As a result, solutions such as network densification, that is small-cell networks and sharing of the spectrum among various users (cognitive radio) have emerged. Cognitive radio (CR) can be defined intelligent, because they are aware of their environment in which they are operating and they use learning techniques in order to adapt to the changes in a new surrounding with the following objectives (Zhang *et. al*. 2010):

- Reliable communication whenever necessary
- Efficient utilization of the spectrum (spectrum sharing)

Efficient utilisation of the spectrum may be accomplished in various ways (Goldsmith *et. al*. 2009), in one of which secondary users access the inactive parts of the spectrum (white holes) in a dynamic manner when not used by licenced (primary) users, or concurrently use the same spectrum with the primary users.

However, co-existing with primary users may be realised in two ways. One method is to transmit concurrently with the primary users, however, causing interference to the primary receiver below an acceptable level defined by the network requirements (*underlay* approach). Other method is to co-exist on the same channel with the primary users without causing any interference to the primary receiver, making the primary receiver unaware of the presence of secondary users (*overlay* approach). This approach requires asymmetric cooperation with the primary transmitter to protect secondary receiver from the primary interference, and imposes zero interference to primary receiver or even help improve its SNR (Jovicic and Viswanath 2006). The latter approach is adopted in this thesis and generalised to the case, where secondary users use idle channels when available or co-exist with the primary users by guarantying zero-interference to the primary as in (Koyluoglu, O. O., El Gamal, H. 2009**)** when the channels are all occupied by primary users, using asymmetric transmitter cooperation as explained in chapter four. However, from practical point of view, this scenario requires listenning to the transmission of primary transmitter as opposed to the theoretical genie assumption made in the information theoretic works (Devroye *et. al.* 2006, Devroye and Tarokh 2007).

In this thesis, adopting from (Jovicic and Viswanath 2006), the co-existence conditions imposed to the cognitive user is:

1) It generates no interference to the primary receiver
2) Primary receiver uses single-user decoding, as if in the absence of secondary transmission. Therefore, acting as totally unaware of the presence of secondary

In general, the research on spectral co-existence reported in the literature is mainly information theoretic. Examples include (Serrano *et. al.* 2012, Srinivasa and Jafar 2007, Li *et. al.* 2011, Koyluoglu and El Gamal 2009). However, practical applications of cognitive radio in the literature is very limited and spectrum sharing approaches does not satisfy the coexistence conditions adopted in this thesis. An example similar to the *overlay* cognitive radio scenario considered in this thesis appears in (Bohara *et. al.* 2010). But it violates the second coexistence condition mentioned above, as it relies on orthogonal transmission through beamforming at both receivers to cancel interference. One advantage of the system is that the need for listening the primary transmission is eliminated at the expense of reduced spectral efficiency. Another work on spectral coexistence was published by (Jahja B. 2015), in which overlay approach is used under the same scenario adopted in this thesis and the load of cancelling primary to secondary interference is shifted to the cognitive receiver using SISO-MIMO channel configuration. It is woth noting here that the term *secondary* and *cognitive* is interchangeably used throughout the thesis.

In this thesis, all receivers are constrained to have a single antenna, therefore adopting SISO-MISO channel configuration. Another difference from (Jahja B. 2015) is that a novel method of using the spatial modulation as dirty paper coding to cancel the primary interference at the cognitive receiver is proposed. In this way, by meeting co-existence conditions, primary and cognitive users share the same spectrum at the same time with no interference. In the thesis, space-time block coding is also used along with DPC.

In the second chapter, spectral co-existence and the cognitive cooperation is reviewed. Third chapter reviews space-time block coding and the system model and achievable rates are introduced in chapter four. Chapter five briefly reviews some dirty paper coding methods and illustrates the proposed system and the results. Finally, the conclusion is given in chapter six.

2 SPECTRAL CO-EXISTENCE AND COGNITIVE COOPERATION

Considering the radio systems in a broadcast medium, all users operating in the same frequency band can easily interfere with each other. Due to the fast growing number of wireless systems and services in the developed world, almost all frequency bands have already been assigned, leading to the scarcity of prime wireless spectrum and there is little or no new bandwidth available for emerging wireless products and services. As a result of spectrum shortage, the wireless scholars and researchers came up with the idea of cognitive radios. In 1999, Mitola and Maguire defines the term cognitive radio as a radio that understands the context in which it finds itself and as a result can tailor the communication process in line with that understanding (Webb W. 2009). Therefore, the devices employed for implementing such a system must have the ability to utilize advanced radio and signal processing tecnology to support and promot the innovation of new wireless communication mechanisms to operate in the available crowded spectrum without affecting the performance of existing users. Cognitive radio is a new topic in the field of radio communication which attracts a lot of interest at both academic and industrial level, as a technology that will play a strong role in the future of wireless communication systems.

There are many different defitions of cognitive radio, by different scholars and wireless telecommunications organizations such as by F.K. Jondra: A cognitive radio (CR) is a software define radio (SDR) that additionally senses its environment, tracks changes, and reacts upon its findings. A CR is an autonomous unit in a communication environment that frequently exchanges information with the networks it is able to access as well as with other CRs.

In the year 2005, the Federal Communication Commission (FCC), in the United States, and Simon Haykin, describe cognitive radio as the possible means that enables better use of the spectrum. The FCC, defines the cognitive radio (CR) *as a radio that can change its transmitter parameters based on interaction with the environment in which it operates*. S. Haykin, defines it *as an intelligent wireless communication system that is aware of its surrounding environment and use the methology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming Radio Frequency (RF) stimuli by making corresponding* *changes in certain operating parameters (e.g transmit power, carrier-frequency, and modulation strategy) in real-time, with two objectives: highly reliable communications and efficient utilization of the spectrum*.

The ITU defines CR *as a radio system employing technology that allows the system to obtain knowledge of its operational and geographical environment, established policies, and its internal state, to dynamically and autonomously adjust its operational parameters according to the information it obtained in its surrounding environment*.

A cognitive radio is made-up of software and hardware components that enable its wide variety of different configurations it needs for its communication processes. Its technology has four main properties, namely an awareness of its environment in which it operates, an awareness of the communication requirements of the user(s), an awareness of the regulatory policies which apply to it and an awareness of its own capabilities. In summary, a cognitive radio is always aware of its surrounding environment in which it is operating, and processes the information it receives and makes autonomous decisions on how to carry out any communication duty at hand.

In the process of self configuration, the radio attempts to match actions to requirements while at the same time it is aware of any possible constrain (physical, regulatory, etc), that may exist. The development of this new technology will offer us the opportunity to utilize the radio spectrum in the best possible way, since most of the licensed spectrum is not fully occupied at all time, thereby allowing us to implement new wireless systems and improve the quality and capacity of existing ones.

2.1 Role of Cogitive Radio in Spectrum Sharing

The term coordinate means that the various communication systems sharing the same spectrum either cooperate or coexist. The technology of cognition in radio communication systems can play a great role in the present and the future of spectrum management for a better and efficient wireless communications. Hence, it has the ability to collect and process information about the coexisting users within its surrounding environment. This demands advance sensing and signal processing abilities. The technological capacity to backup such systems are either present or on the horizon.

Therefore, there is no significant obstacle to stop the implementation of this beautiful innovation. The principal challenge here requires to make important changes in the manner in which the wireless spectrum is currently allocated and managed, in order to allow different wireless systems with different software technologies to cooperate or coexist (Biglieri *et. al.* 2007).

The main concept of spectral co-existence includes the process of organizing how different users with different software technologies coexist in the same spectrum band. The key purpose of spectral co-existence is to maximise the number of various spectrum users by allowing as many efficient users as possible while ensuring that the level of interference among all the users remains below certain threshold (Biglieri *et. al.* 2007). The current spectrum allocation and management does not promote spectral coexistence and is causing lots of limitations for the development of new applications and services within the wireless communications.

Cognitive radio has an enabling role to play as we move away from the current static spectrum management style. The approach adopted by spectrum allocators around the globe does not encourage spectral coexistence, because the regulators do decides on the use of a particular ranges of frequencies for certain specific applications and services that should be delivered in such frequencies and at the same time indicates what type of technologies are permitted in delivering such services. This model is referred to as the administrative approach to the spectrum management and thus creates scarcity of the spectrum resource. Some new management approaches that are on the scope for the future development of the wireless communications will be achieved through the application of cognitive radio technology.

2.2 Cognitive Radio Network Paradigms

Generally there are three major cognitive radio network paradigms under which spectral coexistence and cognitive cooperation can be possible. These paradigms can be listed as; underlay, overlay and interweave (Biglieri *et. al.* 2007). Each of these paradigms operate under different spectral conditions. For the underlay paradigm, the cognitive users are permitted to operate only and only if the interference caused to noncognitive users is below a certain threshold. While for overlay systems, the use of sophisticated signal processing and coding are the main strategy for the system to maintain and techniques improve the communication of noncognitive users at the same time make some gains for its own bandwidth. The third paradigm, interweave systems, operate based on opportunistically exploiting the spectral holes (white spaces) to carry out its communication process without interfering with other transmissions. Detailed description of each paradigm is given in the following and comparatively summarised in Table 2.1.

***Underlay Paradigm*:** This model of spectral co-existence comprises techniques that allow the co-operation of a cognitive radio with a noncognitive radio in the same frequency band; assuming that the cognitive radio has knowledge of the interference caused by its transmitter to the receivers of noncognitive users. The cognitive radio is commonly referred to as the secondary user, hence it cannot interfere beyond certain level with the communication of noncognitive users, that are commoly referred to as primary users.

The main condition of this spectral co-existing setting is that cognitive and noncognitive transmissions can simultaneously happen only if the interference caused by the cognitive devices at the primary receivers is below a certain threshold. In this cognitive paradigm, the secondary link can employ various transmission strategies in order to fulfill the interference constraint at the primary receivers. If the cognitive user has only one transmitter antenna, then transmit power control is needed to satisfy the primary interference constraint. On the other hand, multiple transmitter antennas can be used to guide the secondary signals away from the primary receivers through transmitter beamforming technique. By applying these techniques we can obtain the objective of maximizing the achievable secondary rate while satisfying the primary interference constraint and the secondary power constraint.

***Overlay Paradigm*:** The overlay system operates differently with respect to the underlay. In this model, the cognitive transmitter has to acquire the knowledge of the the codebooks and messages of the noncognitive user in order to either cancel or mitigate the interference experienced at the secondary and primary receivers in a variety of ways through sophisticated techniques such as dirty paper coding and beamforming.

The secondary transmitter can acquire the knowledge of the primary message or codebook either non-casually (i.e; known in advance before transmission) or casually (i.e; acquired in the first phase of a two phase transmission). By obtaining the knowledge of the primary message or codebook, the secondary transmitter can facilitate the transmission of the primary signal alongside its own signal.

To achieve this kind of spectral co-existence, the secondary transmit power is divided into two shares, one of which is used for relaying the primary signal in order to pay for the primary cooperation or compansate for the interference generated due to the secondary transmission through which a certain primary rate requirement can be maintained, depending on the way by which the first condition of co-existence is satisfied. Then the other share of the secondary transmit power is used for its own transmission.

Interweave Paradigm**:** In an interweave approach, the cognitive system ascertains the spectral holes in time, frequency and geographical location that remain unused by the noncognitive system. Studied results from various parts of the world demostrated that most parts of license spectrum are not fully utilized, which motivates the idea of opportunistic communication through the use of cognitive radio system.

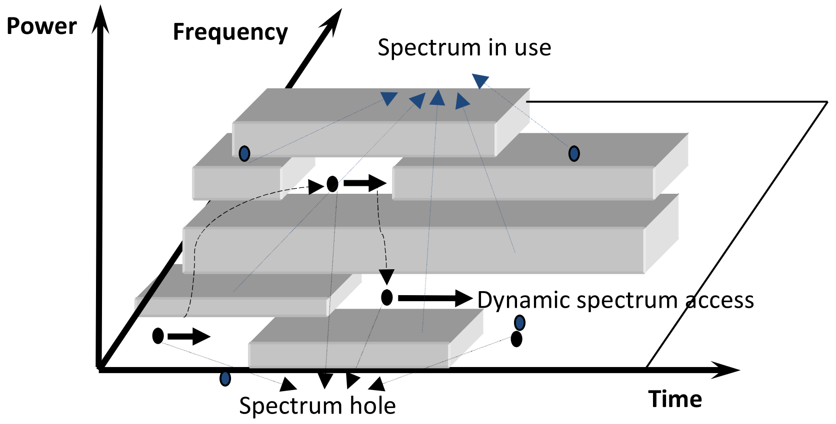

Figure 2.1 Spectrum holes for dynamic access

Thus, the opportunistic frequency reuse over spectrum holes can improve the utilization of the spectrum. In order to implement this approach successfully, it requires knowledge of the activity information of the primary users in a given spectrum band. In other words, the interweave technique is an intelligent wireless communication system capable of monitoring the radio spectrum, detect spectrum holes and carry out its communication process over those holes without disrupting the activities of the primary users. This process is illustrated in Figure 2.1

Cognitive Radio Network Paradigms		
Underlay	**Overlay**	**Interweave**
Information of the channel: The cognitive transmitter must have the knowledge of the interference cause to noncognitive receivers.	Information of the codebook/message: The cognitive devices must have knowledge of the codebooks and messages of the noncognitive users.	Information of the activities: Cognitive users must have the knowledge of the spectral holes in time, frequency and space in case they not in use by the noncognitive users.
Simultaneous transmission of cognitive and noncognitive users is possible provided that the interference generated by the cognitive user is below certain threshold.	Both the cognitive and noncognitive users can transmit simultaneously; the interference to the noncognitive user is compensated by employing part of the cognitive user's power to relay the signal of the noncognitive user.	Simultaneous transmission only occur when there is false detection of spectral holes.
Due to the interference constraint, the cognitive user's transmit power must always be below a given threshold.	In the overlay approach cognitive user can transmit at any power, and the interference to noncognitive user can be compensated by relaying its signal.	The transmit power of the cognitive user is limited depending on the distance of its spectral hole sensing.

Table 2.1 Comparison Table for the Cognitive Radio Network Paradigms

2.3 Principal Functions of Cognitive Radio in Spectrum Management

As an intelligent wireless system that can change its transmission and reception parameters in order to communicate efficiently without interfering with licensed users CR do function as a self-organised and self-configured network where the nodes within the system automatically maintain and establish the connectivity among them.

The system has four main functions that can be expressed as (Webb W. 2009): Spectrum Sensing, Spectrum Analysis, Spectrum Mobility, and Spectrum Sharing. Lets have a litle detailed explanation of each of these functional concepts of CR and their relation in spectrum management.

Spectrum Sensing

In order to avoid interference, the CR node needs to sense the spectrum within its surrounding environment. The purpose is to detect unused spectrum without causing interference to other users that might be found in the spectrum band. Therefore, the cognitive node try to sense the spectrum to check whether the signal from a primary tansmitter is locally present in a certain spectrum or not. Cooperative detection is also used to incorporate information from multiple users for primary user detection.

Spectrum Analysis

In spectrum analysis, there is a need to capture the best available spectrum to meet user communication requirements. Cognitive radios should decide on the best spectrum band to meet the quality of service (QoS) necessary over all available spectrum bands.

Spectrum Mobility

This is a process where a cognitive radio user exchange its frequency of operation due to a movement or a change of location, to maintain high quality transmission with seamless communication requirements. It targets to use the spectrum in a dynamic manner by allowing the radio terminals to operate in the best available frequency band.

Spectrum Sharing

Spectrum sharing provides the scheduling method of the fair spectrum since there are multiple CR users that are colliding in overlapping portions while trying to access the spectrum. Sharing is a major challenge in open spectrum usage that corresponds to media access control (MAC) in exisiting systems. Spectrum sharing is to distribute the spectrum among the secondary users according to the usage cost.

2.4 Overview of the Cognitive Cycle

Cognitive networks are wireless networks which consist of two types of users which are the primary and secondary users. Therefore, the secondary user (CR) is always entitled to ceratin signal processing activities in its surrounding environment in order to avoid interference to the primary user. The procedure starts with sensing of its surrounding spectrum while analysing the estimation of the sources of interference in the radio environment known as interference temperature and detecting the spectrum holes. It works like a radio scene analysis that determine which portions of the spectrum is available and detect the presence of licensed users operating in a licensed band. The next step is the activation of spectrum decision that quantifies and manages intertefeerence temperature. In this process it select the best available channel and estimate the channel-state information (CSI), thereby predict the capacity of the channel used by the transmitter. The radio needs to consider spectrum mobility in case of high presence of noise and interference due to fading. The activitation of the cognitive users is coordinated by a common control channel (CCC) hence it can vacate the spectrum if a primary user signal is detected and then select the next available frequency band. As part of cognitive cycle, the radio can reconfigure itself through spectrum sensing, scheduling and routing. This may result in a a new type of handoff in CR networks, known as spectrum handoff. As the CR user changes its frequency of operation, the network protocols may require modifications in order to adapt to the new operating parameters. The cognitive cycle is illustrated in Figure 2.2.

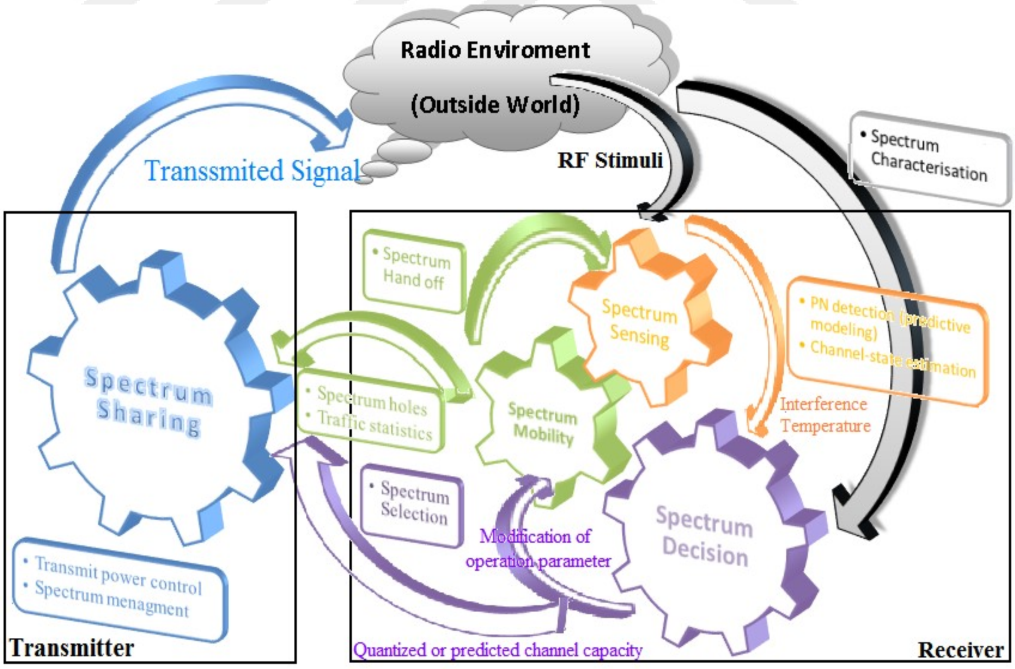

Figure 2.2 Cognitive Cycle

As part of the cognitive cycle, spectrum sharing allow both the primary and secondary users to exchange their channel information, coding details, types of activities and messages in order to improve the capacity of both users. Cognitive radio technology accomodates a scale of differing degrees of cognition (Haykin *et. al*. 2005), simply it picks a spectrum hole at one end and builds its cognitive cycle around that hole. At the other end of the scale, the user may employ multiple technologies to build its cognitive cycle around a wideband spectrum hole or a set of narrowband spectrum holes to provide a better performance in terms of spectrum management.

In other words, spectral sharing in wireless communications is more of a multiple access system (Rappaport T. S. 1996), which is achieved through division of signal dimensions along the frequency, time and space. Sharing of the spectrum can be achieved through coordination of different users by including the functionality of MAC protocol, that are controlled by a central entity known as centralized spectrum sharing. The other spectrum sharing technique is the distribution method where the spectrum is used between different networks, this technique can be attained by exchange of messages among the nodes of the different networks. It uses power control for finding the cut-off level in SNR, supporting the channel allocation and imposing interference power constraints for the protection of primary users, respectively.

2.5 Spectral Coexistenece Approaches

The term spectral coexistence refers to efficient use of the radio frequency band by different entities simultaneouly. These entities are either different in technologies and systems, or different user types. However, the entities can coexist and share the same spectrum in time, frequency and space.

2.5.1 Equal-Opportunity Spectrum Sharing

For this model of spectral coexistence, the frequency band is accessible to different users or entities that do not have any interation among them. A right example of such a spectrum sharing approach is the WiFi system. In this system, the frequency band is shared among many users all having the same right of accessing the band. The users share the spectrum in an opportunistic way.

2.5.2 Primary-Secndary Spectrum Sharing

In this model of spectrum sharing, the frequency band is licensed to the primary user. Both the primary and the secondary users can coexist through cooperation with the secondary user, in order to protect the primary system from interference generated by its transmitter. Thus, the transmit power of the secondary user must be maintained below certain threshold, or opportunistically use the spectrum when the primary system is silence. The later does not always guarantee the quality of service of the secondary system. These two methods are refered to as underlay and interweave paradigms discussed in the previous sections (Biglieri *et. al*. 2007).

2.6 Cognitive Cooperation

Recent studies demonstrated that most part of the license spectrum is not fully utilised. Therefore, cognitive radio was proposed to promote the spectrum utilisation through the employment of cooperative relay technology. This type of communication system is achieved through the combination of the relay message with the original message in frequency, time and spatial domain. The process of combining the two messages allow the system to decode the information rather than considering the relay message as interference (Zhang *et. al*. 2009).

3 SPACE-TIME BLOCK CODING

One of the main feature of wireless systems is the randomness of the communication channel which leads to random fluctuations in the received signal. This randomness of the channel always post a great hinder on the performance of any wireless sytem. The framework for studying performance limits in wireless transmission is the maximum rate for which arbitrarily small error probability can be achieved commonly known as channel capacity. The capacity limit of reliable communication system is predicted by Shannon’s capacity approach. For an effective and practical exploitation of any radio link or maximaizing the capacity of any wireless channel, efficient coding and signal processing is required. The principal challenge in designing a radio link today is the restriction on available bandwidth, imposing that the available channel capacity is always limited, and it is a great deal in moden communication systems. In order to deploy new applications in telecommunications services, high data rates are normally required. Since the bandwidth is a scarce resource, one of the major challenges faced in wireless communication systems is the need to increase capacity without increasing the required bandwith. Space-time coding is an efficient method through which we can achieve an increment in capacity without increasing the bandwidth of multiple-input multiple-out (MIMO) wireless channels. It is a coding scheme designed for multiple transmit antennas. This coding scheme is performed in both spatial and temporal domains in order to introduce correlation between signals transmitted from different antennas at different time instants. The idea of spatial-temporal correlation is to exploit the fading wireless channel and minimize transmission errors at the receiver end. By using space-time coding, we can accomplish transmit diversity and power gain over spatially uncoded systems without requiring excess bandwidth. There are many different approaches used in space-time coding technique, the most popular ones include space-time block codes (STBC), space-time trellis codes (STT), space-time turbo trellis codes and layered space-time (LST) codes (Vucetic and Yuan, 2003). The essential of all these coding schemes is to exploit the multipath effects in order to achieve high spectral efficiencies and performance gains. In this thesis, our center of focus will based on space-time block codes (STBC) in details. But, before going into the details of STBC, we will first discuss design criteria and the advantages of space-time coding. A generic block diagram for space-time coding is shown in Figure 3.1.

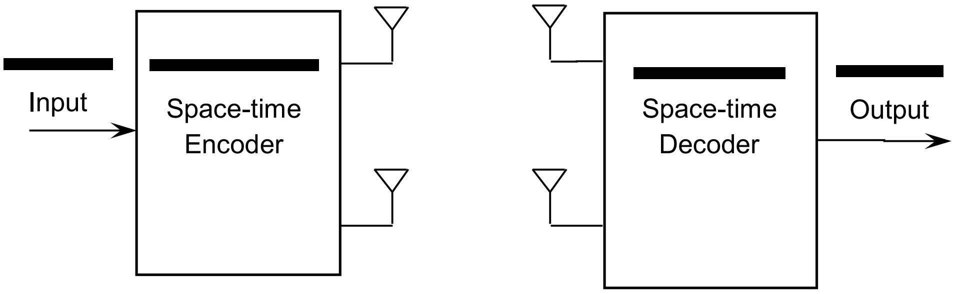

Figure 3.1 General Space-Time Coding system model

3.1 Advantages of Space-Time Coding

The interest for space-time coding has considerably increased at both academic and industrial fields, due to many advantages attached to it. A typical example is the cellular mobile communications systems where multiple receive antennas are used at the base stations with the aim to reduce co-channel interference (CCI) and minimize the bit error rate of the system. However, multiple antennas at the base can be used to create uplink (from mobile to base stations) receive diversity, compensating for the relatively low transmission power from the mobile, thereby improving the quality and the coverage range of the system (Vucetic and Yuan 2003).

Space-time coding does not require channel state information (CSI) at the transmitter, that allows the system to operate in an open-loop, in which there is no need for a feedback channel from the receiver (Biglieri *et. al.* 2007), thus eliminating the risk of channel estimation errors at the receiver and errors in the feedback link, due to noise and interference. By using space-time coding techniques, feedback delay which causes a mismatch in the downlink channel is also eliminated, makeing it more attractive as a robust means for improving the performance of downlink in mobile communications.

The other main benefit of space-time coding is the spectral efficiency achieved by the technique, as it allows us to increase the data rate without increasing the required bandwidth. In the performance analysis of space-time codes, it can be assumed that the transmitted data frame length is L symbols for each antenna. The average data rate R is therefore the number of symbols sent per time period T, namely, $R=\frac{L}{T}$. A space-time code is full rate if $L=T$. The spectral efficiency of a modulation scheme is given by

$$\eta = \frac{Data\ Rate}{Bandwidth} \tag{3.1}$$

The spectral efficiency of a space-time code using two dimensional constellation with *M* points is to be η = $R\log_2 M$ bits/sec/Hz. Diversity can be used to attain high data rate, and improve spectral performance by increasing the symbol constellation size. *M*-PSK and *M*-QAM modulations schemes may be used, as both schemes are bandwidth efficient. Therefore, combining them with space-time coding, higher level of spectral efficiency at a fixed bandwidth and error rate can be acomplished.

3.2 Main Code Design Principles for Space-Time Codes

Space-time codes are designed to optimize error performance and to increase system capacity. They help improve the downlink performance without the need for multiple receive antennas. There are two criteria for the design of space-time codes, which are the well-known rank and determinant criteria.

3.2.1 Rank Criteria

Let us consider x_1 and x_2 to be two different codewords of matrix $\mathbf{X}(x_1, x_2)$. If N_T is greater than the minimum rank **r** of **X** among all the codeword pairs, a diversity order of $\mathbf{r}N_R$ is obtained. The design criteria of space-time codes for slow Rayleigh fading channels is subjected to the values of $\mathbf{r}N_R$. The highest possible value of $\mathbf{r}N_R$ is $N_T\ N_R$. Here **r** stand for the rank of matrix **X**, and $N_T\ N_R$ stand for number of transmit and receive antennas, respectively. The probability of error at high SNRs for all possible pairs of codewords is dominated by the minimum rank **r** of matrix $\mathbf{X}(x_1, x_2)$ (Vucetic and Yuan, 2003).

3.2.2 Determinant Criteria

In a situation where we are able to obtain full rank **r**, the determinant criteria turns to be an interesting case to study. In the interest of maximum coding advantage and to be able to minimize the error probability, the product of nonzero eigenvales λ of matrix $\mathbf{X}(x_1, x_2)$ along all pairs of codewords having the smallest rank **r** should be maximised (Vucetic and Yuan, 2003). In order to maximize the minimum rank **r** we need to find a space-time code with the full rank of matrix $\mathbf{X}(x_1, x_2)$, that means $\mathbf{r} = N_T$. In practice, full rank may not be obtained in all cases due to the restriction of the code structure. In order to achieve full diversity, rank criteria is the most suitable code design principle. The rank criteria can be applied in designing space-time block codes.

3.3 Space-Time Block Code

The phenomenon of fading is one of the major challenges in implementing wireless links. This phenomenon can cause random fluctuations in signal level across space, time and frequency. In order to overcome this problem, the transmission technology of multiple-input multiple-output (MIMO) was invented but certain difficulties continue to persist in the wireless transmission systems yet. Consequently, over the past decade various comprensive studies have been carried out by numerous researchers in search of improving the performance of the MIMO transmission strategies and to mitigate the effect of fading on the wireless links. As a result, different types of space-time coding strategies have been proposed as mentioned in the beginning of this chapter. But most of these coding schemes either have an encoding or decoding complexity which make their implementation difficult. For example, the decoding complexity of STTC (measured by the number of trellis states at the decoder) increases expontially as a function of the diversity level and the transmission rate. For the purpose of addressing this complexity, Alamouti proposed space-time block coding as the solution (Vucetic and Yuan, 2003).

Wireless transmission over Rayleigh fading channels using multiple transmit antennas, applying space-time block codes provide a new paradigm in the field of wireless transmission. Implementing space-time block codes using the theory of orthogonality can allow us to achieve full diversity gain with low decoding complexity. Data encoding is carried out using space-time block codes and the encoded data is transformed into n number of streams such that these streams are simultaneously transmitted through $n = N_T$ transmit antennas. At the receiving end, each antenna receives the signal linear superposition of the N_T transmitted signals together with the noise. The orthogonal structure of space-time block codes makes the decoding of the receive signals from various transmit antennas simple, through the use of maximum likelihood (ML) decoding algorithm whereby the processing of the received signals is completely linear.

3.3.1 Space-Time Block Encoder

In today's wireless world, one of the most popular coding scheme is the Alamouti algorithm because of some useful characteristics pertinent to it, such as its ability to achieve full diversity at the receiver without the transmitter knowledge of CSI and less decoding complexity. Diversity gain N_R, at the receiver can be obtained by using maximum likelihood (ML) decoder, without the transmitter knowledge of the channel state information. The orthogonality theory applied at the transmitters between the time sequence of the signals give a guarantee of achieving full diversity gain of the system.

Lets define N_T and T as the number of transmit antennas and number of time periods for transmission of one block of coded symbols, respectively, then the transmission matrix **X** of size $N_T \times T$, and assume that the signal constellation consists of 2^m points. For every encoding process, a block of *k*m information bits are mapped into the signal constellation to select *k* modulation signals x_1, x_2, x_3, ..., x_k. Here, a constellation signal is selected per group of *m* bits. The space-time encoder encodes *k* modulated signals in order to generate N_T parallel signal sequences of length *L* in accordance with transmission matrix **X**. The encoded signal sequences are transmitted simultaneously through N_T transmit antennas in *T* time periods (Vucetic and Yuan, 2003).

The encoder takes in *k* number of symbols as its input per every encoding operation. Per block of *k* input symbols, each transmit antenna transmit *T* space-time symbols. Therefore, the rate of transmission of space-time block code can be define as the ratio of the number of symbols the encoder takes as its input to the number of intervals space-time coded symbols transmitted. This is mathematically expressed as:

$$R = \frac{K}{T} \tag{3.2}$$

We can also express the spectral efficiency of space-time bolck code as:

$$\eta = \frac{R_b}{B} = \frac{R_s m R}{R_s} = \frac{km}{T} \text{ bit/s/Hz} \tag{3.3}$$

where R_b and R_s are bit and symbol rate, respectively, and B is the bandwidth. The elements of the transmission matrix **X** are linear combinations of k number of modulated symbols, x_1, x_2, x_3, ..., x_k and their conjugates x_1^*, x_2^*, x_3^*, ..., x_k^*. To be able to accomplish full diversity of N_T, based on orthogonal design, the transmission matrix **X** is constructed (Vucetic and Yuan, 2003) such that

$$XX^H = \text{c}\,(|x_1|^2 + |x_2|^2 + \ldots\ldots + |x_k|^2)\,\mathbf{I}_{N_T} \qquad (3.4)$$

where c is a constant, $\mathbf{X}^H$ is the Hermitian transpose of **X** and $\mathbf{I}_{N_T}$ is an N_T x N_T identity matrix. The symbols transmitted consecutively in T transmission periods from the i^{th} transmit antenna is represented as the $\mathbf{i}^{th}$ row of **X**, while the j^{th}column of **X** represents the symbols transmitted simultaneously across N_T transmit antennas at time j. The j^{th} column of **X** is considered as a space-time symbol transmitted at time j. The entries of **X** in the i^{th} row and j^{th} column, $\mathbf{x}_{i,j}$, i= 1, 2, ..., N_T, j = 1, 2, ..., T, represents the signal transmitted from the antenna i at time j as in (Vucetic and Yuan 2003).

With full transmit diversity, a space-time block code can achieve a transmission rate of $R \leq 1$. If the transmission rate is unity, $R = 1$, then no bandwidth expansion is caused, But in situations where the code transmission rate is smaller than 1, $R < 1$, then required bandwidth expansion is on the order of 1/R. Given the transmission matrix is denoted by X_{N_T}, the rows of X_{N_T} are orthogonal to each other. That means that in each block, the signal sequences from any two transmit antennas are orthogonal. Let us consider that i^{th} antenna transmits the signal sequence $x_i = (x_{i,1,}\ x_{i,2,}\ x_{i,3,}.........x_{i,T})$ where i = 1, 2, ..., N_T, then

$$\mathbf{x}_i . \mathbf{x}_j = \sum_{t=1}^{T} x_{i,t} . x_{j,t}^* = 0, \quad i \neq j, \quad i, j \text{ € } \{ 1, 2, ..., N_T\} \qquad (3.5)$$

where $\mathbf{x}_i . \mathbf{x}_j$ is the inner product of the sequences x_i and x_j. For a certain number of transmit antennas, the orthogonality permits us to obtain full transmit diversity. It also allows the receiver to decouple the transmitted signals from various antennas. This makes it possible to use a simple maximum likelihood decoding.

Spatial diversity can easily be obtained by employing multiple receive antennas, as it is the case of the uplink transmission of cellular telephone system. The uplink transmission takes place from mobile terminal to the base station. At the base station multiple antennas can be installed with necessary antenna separation, and the signals transmitted from the mobiles can easily be received and processed by each receive antennas at the base station. But in the oposite case, that is the downlink transmission, it is difficult to attain any diversity gain due to the small size of the mobile terminals, thereby multiple antennas with required separation cannot be implemented on the terminals for the reception of the transmitted signals from the base station. In order to overcome this challenge, scholars and researchers felt the need to implement a scheme that take the advantages of spatial diversity the transmitter. In 1998, Alamouti invented a scheme that can achieve transmit diversity for multiple transmit antennas.

In the history of space-time coding the Alamouti coding scheme is the first type of space-time block code to attain full diversity for two transmit antennas, without the need of channel state information and with less complex detectors at the receiver. Though other transmission schemes such as the delay diversity can also obtain a full diversity, but comes along with lots of negative consequences such as high interference level between symbols and also requires complex detectors at the receiver.

The Alamouti scheme of space-time block code has been extended beyond two transmit antennas employing the theory of orthogonal designs. Alamouti's orthogonal design demostrates the existence of full transmit diversity for all real constellations of two, four and eight transmit antennas only, on the other hand for all complex constellations diversity exist only for two transmit antennas. However, orthogonal designs exist for an arbitrary number of transmit antennas, if and only if a rate loss is acceptable.

Suppose that an *M*-ary modulation scheme is employed. During the encoding process, each gruop of *m* information bits is first modulated, where $m = \log_2 M$. A block of two modulated symbols x_1 and x_2 is taken by the encoder, for each encoding operation which is mapped to the transmit antennas in accordance with a code matrix given below

$$\mathbf{X}=\begin{bmatrix} x_1 & -x_2^* \\ x_2 & x_1^* \end{bmatrix} \tag{3.6}$$

From the transmit antennas, the outputs of the encoder are transmitted in two successive transmission periods. The signals x_1 and x_2 are simultaneously transmitted from antennas one and two, respectively. During the second phase of the transmission, signlas $-x_2^*$ and x_1^* are simultaneously transmitted from antenna one and antenna two, respectively, where x_2^* and x_1^* are the complex conjugates of x_2 and x_1 (Vucetic and Yuan 2003).

The process of encoding is done in both the space and time domains. We can represent the transmit sequences from antennas one and two x^1 and x^2, respectively.

$$x^1 = [x_1, -x_2^*] \tag{3.7}$$

$$x^2 = [x_2, x_1^*]$$

The inner product of the sequences x^1 and x^2 is zero, that means

$$x^1 . x^2 = x_1 x_2^* - x_2^* x_1 = 0 \tag{3.8}$$

The main property of the code matrix is

$$\mathbf{X} . \boldsymbol{X}^H = \begin{bmatrix} |x_1|^2 + |x_2|^2 & 0 \\ 0 & |x_1|^2 + |x_2|^2 \end{bmatrix} \tag{3.9}$$

$$= (|x_1|^2 + |x_2|^2)\ \mathbf{I}_2$$

where $\mathbf{I}_2$ is a 2 x 2 identity matrix.

3.3.2 Receiver Models for the Alamouti Scheme

The Alamouti space-time block coding scheme can be empolyed for both single and multiple receive antenna configuration systems. In this section, it is considered in detail. Considering that one receive antenna is employed at the receiver site, with two transmit antennas for the transmission of signals x_1, x_2 and their conjugates x_1^*, x_2^*, whereby the transmission is done in two successive phases, as it is being explained in Section 3.3.1. Supposing that the fading coefficients from the first and second transmit antennas to the receiver at time t are $h_1(t)$ and $h_2(t)$, respectively. If the fading coefficients are constant throughout two successive transmission periods, then they can be expressed as

$$h_1(t) = h_1(t+T) \tag{3.10}$$

$$h_2(t) = h_2(t+T)$$

where T is the symbol duration. The receive signals during the two consecutive symbol periods can be represented as r_1 and r_2 for the periods of time t and $t+T$, respectively, as

$$r_1 = h_1 x_1 + h_2 x_2 + n_1 \tag{3.11}$$

$$r_2 = -h_1 x_2^* + h_2 x_1^* + n_2$$

Where n_1 and n_2 are complex AWGN with a zero mean and power spectral density $N_0/2$ per dimesion.

Multiple antennas at the receiver site can be employed to achieve receive diversity for the Alamouti scheme where the number of receive antennas is denoted as N_R. The processes of encoding and transmission are similar to the single receive antenna system. Assume r_1^j and r_2^j as the received signals at the j^{th} receive antenna at time t and t + T, respectively.

$$r_1^j = h_{j,1} x_1 + h_{j,2} x_2 + n_1^j \tag{3.12}$$

$$r_2^j = -h_{j,1} x_2^* + h_{j,2} x_1^* n_2^j$$

As $h_{j,i}$, i = 1, 2, j = 1, 2, denotes the fading coefficient of the transmission path while the noise signals for the receive antenna j at time t and t + T are n_1^j and n_2^j, respectively. The receiver decision statistics can be constructed depending on the linear combination of the received signals. We can assume the decision statistics to be s_1 and s_2 which can be mathematically expressed as

$$s_1 = \sum_{j=1}^{N_R} h_{j,1}^{*}\, r_1^{j} + h_{j,2}(r_2^{j})^{*}$$

$$= \sum_{i=1}^{2} \sum_{j=1}^{N_R} |h_{j,i}|^2\, x_1 + \sum_{j=1}^{N_R} h_{j,1}^{*}\, n_1^{j} + h_{j,2}(n_2^{j})^{*} \tag{3.13}$$

$$s_2 = \sum_{j=1}^{N_R} h_{j,2}^{*}\, r_1^{j} - h_{j,1}(r_2^{j})^{*}$$

$$= \sum_{i=1}^{2} \sum_{j=1}^{N_R} |h_{j,i}|^2\, x_2 + \sum_{j=1}^{N_R} h_{j,2}^{*}\, n_1^{j} + h_{j,1}(n_2^{j})^{*}$$

The two independent signals s_1 and s_2 can be decoded using the maximum likelihood decoder, which can be express as

$$s_1^{\wedge} = [\, (\sum_{j=1}^{N_R} (|h_{j,1}|^2 + |h_{j,2}|^2) - 1)\, |s_1^{\wedge}|^2 + d^2(s_1, s_1^{\wedge})\,] \tag{3.14}$$

$$s_2^{\wedge} = [\, (\sum_{j=1}^{N_R} (|h_{j,1}|^2 + |h_{j,2}|^2) - 1)\, |s_2^{\wedge}|^2 + d^2(s_2, s_2^{\wedge})\,]$$

A block diagram of this decoding process is illustrated in Figure 3.2. Decoupling of the decisions, for the two transmitted symbols is carried out separately over the probable constellation symbols. If we employ the equal energy constellation as in the case of phase shift keying (PSK) modulation, all the signals in the constellation will have equal energy.

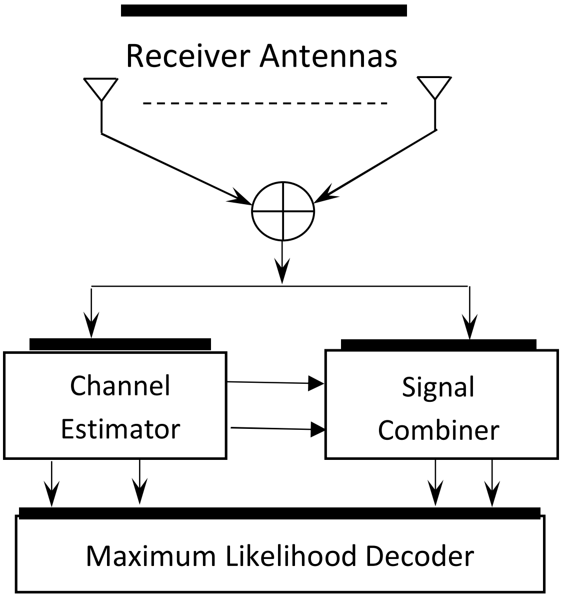

Figure 3.2 Alamouti Receiver Model

3.4 Maximum Likelihood (ML) Decoder

The maximum likelihood (ML) decoder is said to be optimal in the sense of minimum error probability, when all the signals in the modulation constellation are equiprobable. If the code sequences are not equally likely, then, the ML decoder is not certainly optimum. However, we can still consider it as one of the best decoding method. The ML detection technique is based on a test result of all possible codewords and the one that best suits the received signal depending on the selection criterion of the ML decoder is then estimated as the codeword that was transmitted (Vucetic and Yuan, 2003).

Using the given values N_T and M below, a nonsquare matrix for the transmit antennas N_T = 3, 5, 6 and 7 for real signal constellations can be constructed to achieve maximum diversity and rate. For $N_T \leq 8$, the values of M (number of signal constellations) can be expressed as

N_T	2	3	4	5	6	7	8
M	2	4	4	8	8	8	8

However, for all complex constellations full diversity can only be achieved if two transmit antennas are used.

The bit error performance of Alamouti code on slowly flat-fading Rayleigh channel using QPSK modulation is shown in Figure 3.3. It is seen from the figure that increasing the number of either transmitter or receiver antennas improves the error performance. However, its performance is also compared with that of receiver diversity with maximal ratio combining for the same number of antennas in total. It is seen that the performance of Alamouti code has 3 dB disadvantage compared to that of MRC, where Tx=2, Rx=2 antennas were used for the Alamouti code whereas Rx=4 antennas were used for receiver diversity with MRC. It is due to the fact that the bit energy is halved for each antenna in the Alamouti code to keep the total bit enery the same for each transmission scheme.

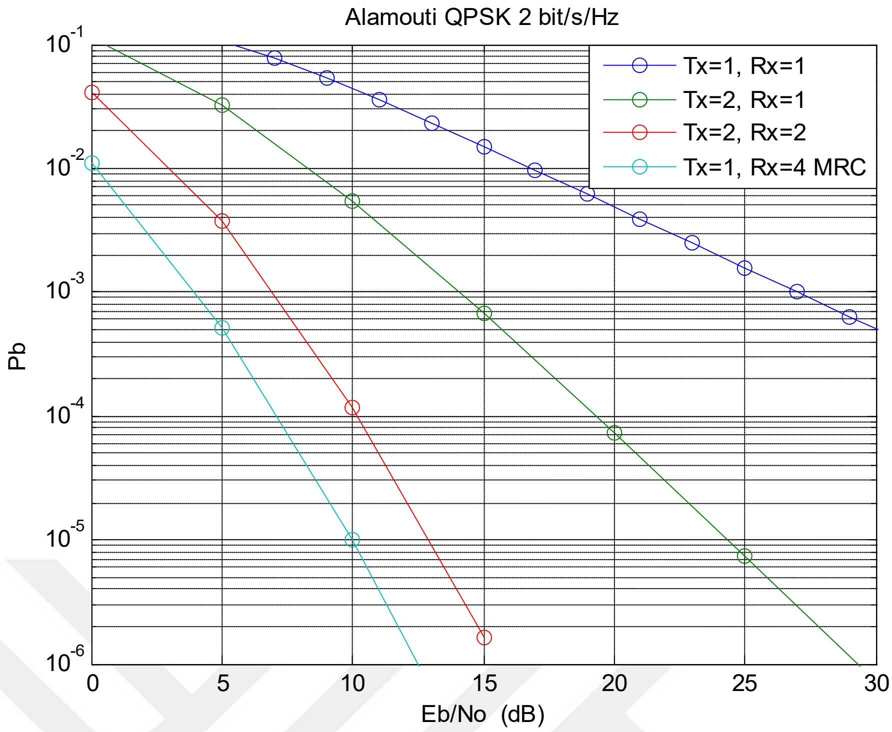

Figure 3.3 Bit error rate of QPSK Alamouti code in slowly fading Rayleigh channel.

3.5 Capacity of STBC

As seen in the prevailing sections, space-time block codes have extremely low encoder/decoder complexity with the provision of full diversity. This simplicity of implementation, however, comes at a cost in capacity (Sandhu and Paulraj 2000), where it is shown that space-time block codes are optimal with respect to capacity when the code is rate one and the channel is rank one. However, it is shown there that they incur a loss in capacity because they convert the matrix channel into a scalar AWGNchannel whose capacity is smaller than the true MIMO channel capacity. Ergodic capacity (Shannon capacity) of STBC signals is shown in Figure 3.4, where the results are illustrated assuming two transmit antennas and various number of receive antennas up to six only. Outage capacity (as a function of SNR) has also received attention for practical reasons for which the Shannon capacity may not be meaningful. For his reason, the outage capacity of Alamouti STBC for various number of receive antennas is computed using (Perez *et*. *al*. 2005), and illustrated in Figure 3. 5.

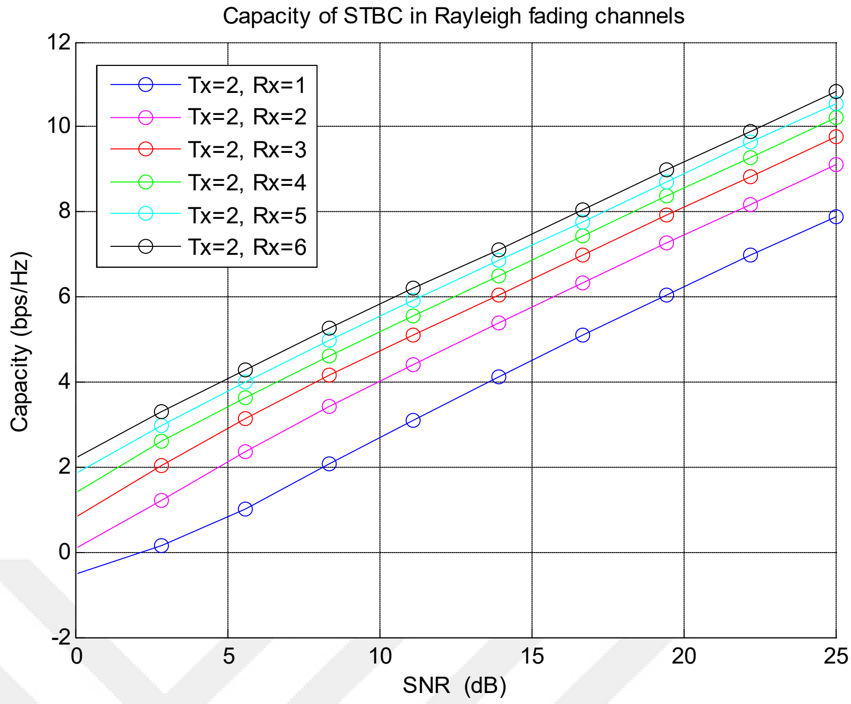

Figure 3.4 Ergodic capacity of two antenna Alamouti STBC system for various number of receive antennas.

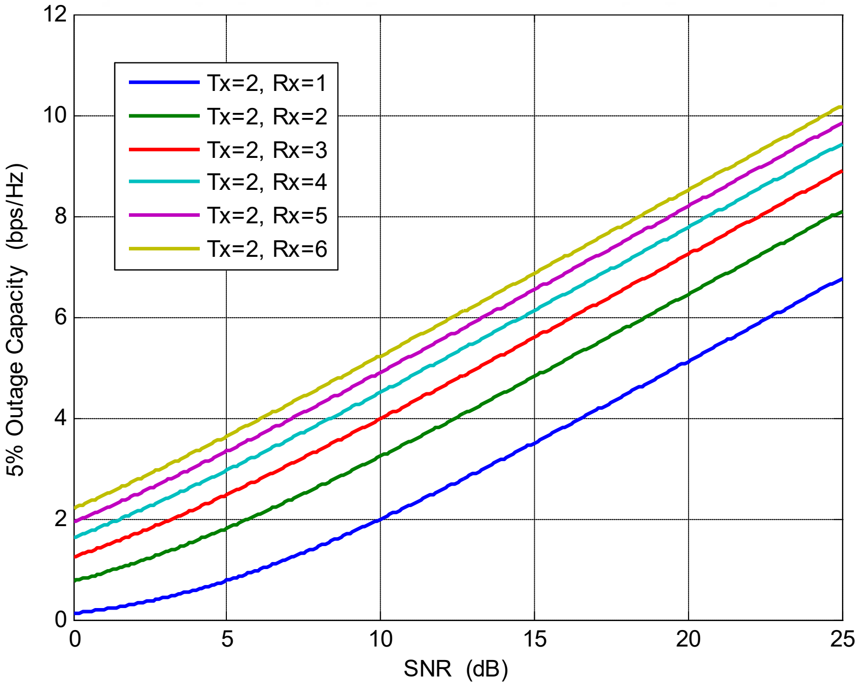

Figure 3.5 5% outage capacity of two antenna Alamouti STBC system for various number of receive antennas.

4 COGNITIVE RADIO NETWORK MODEL

As mentioned in the introduction, the cognitive radio setup considered in this thesis is the scenario in which cognitive users concurrently transmits with active primary users of a radio channel through asymmetric cooperation, adopting overlay spectral co-existence by satisfying its requirements imposed on the cognitive transmitter (Jovicic, and Viswanath 2006). Co-existence condition is that the cognitive transmitter guaranties zero interference to primary receiver while transmitting to its receiver so that the primary receiver uses single-user decoding (being unaware of the secondary transmission, it continues receiving as if there is only primary activity in the channel). Cognitive transmitter also protects its receiver from primary interference by dirty paper coding of its message. However, this spectral co-existence of primary and secondary users is realised through asymmetric cooperation of primary and the cognitive transmitters. The price for the cooperation is paid by the cognitive transmitter by using a fraction of its power to facilitate the transmission of primary message (Goldsmith *et. al.* 2009).

4.1. System Model and Notation

In this thesis, general 2x2 four-terminal network in Fig. 4.1 is considered (Koyluoglu and El Gamal 2009) with the linear system model as shown in Fig. 4.2, where node 1 and 3 represents primary transmitter-receiver pair whereas node 2 and 4 represents cognitive (secondary) transmitter-receiver pair, respectively. $\mathbf{x}_P$ and $\mathbf{x}_S$ denote the primary and the secondary message, respectively.

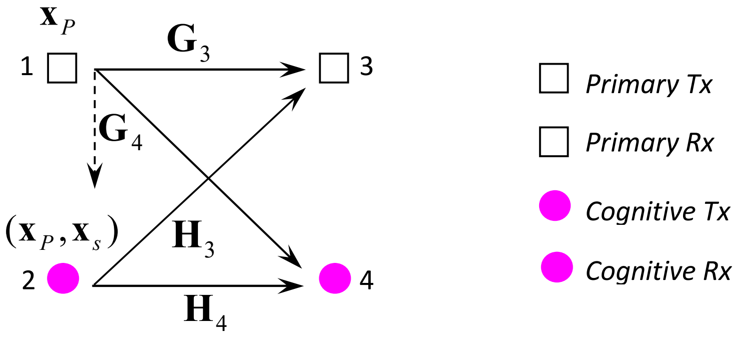

Figure 4.1 Four-terminal cognitive radio network.

Before both transmission take place, primary transmitter informs the cognitive transmitter of primary message through asymmetric cooperation. In the linear system model, the distance between primary users (nodes 1, 3) is normalised to 1 and fixed, whereas the positions of cognitive users (nodes 2, 4) are adjustable between the primary users by keeping d_{24} fixed to some value. Adobted linear model illustrating the positions of the users is shown in Fig. 4.2, where the cognitive users are represented as purple circles. Half-duplex transmission is assumed at each node.

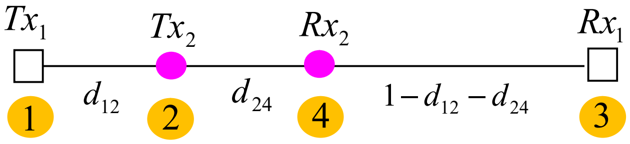

Figure 4.2 Linear sistem model

In general, **G** and **H** represent the channel matrices from primary and cognitive transmitters, respectively. However, in this thesis, **G** is a complex scalar and **H** is a vector $\mathbf{H}_k = \mathbf{h}_k = [h_k^{(1,1)} \quad h_k^{(1,2)} \quad \dots \quad h_k^{(1,\mathrm{N_T})}]$ as only the SISO-MISO configuration is considered. Here, $h_k^{(i,j)}$ in general represents the channel coefficient between the *j*th antenna of cognitive transmitter and the *i*th antenna of *k*th node, where *k*=3, 4. Since the receivers are equiped with a single antenna, *i* is always equal to 1 in the thesis. $h_k^{(i,j)}$ coefficients are zero-mean circularly symmetric statistically independent complex Gaussian random variables of unit variance *CN*(0,1). It is assumed that all channel information is known exactly by cognitive users. Magnitude square of the channel coefficient is set as $\left|h_k^{(i,j)}\right|^2 = d_{2k}^{-n}$ and $\left|g_k\right|^2 = d_{1k}^{-n}$ according to the path loss model, where $k = 3,4$ and d_{ik} is the distance between the *i*th and the *k*th node.

2x2 SISO-MISO cognitive radio network considered in this thesis is illustrated in Figure 4.3. It seen from the figure that the cognitive transmitter is equiped with multiple antennas and the remaining users have a single antenna. Cognitive transmitter first precodes its message to protect the the primary receiver from its own interference (from cognitive transmitter). Cognitive transmitter not only prevents primary receiver from interfernce but also relays the primary transmitter message to the primary receiver, requiring no extra processing at the primary receiver, while transmitting its own message to cognitive receiver through dirty paper coding to protect its receiver from the primary transmitter’s interference.

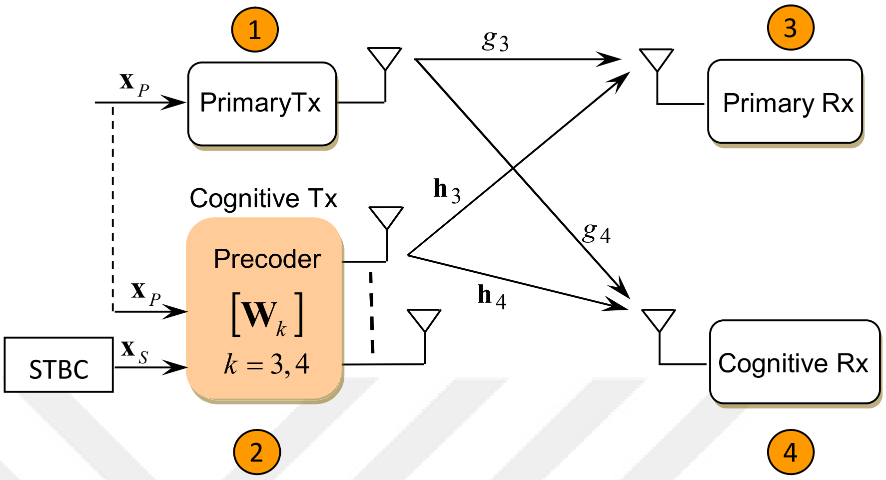

Figure 4.3 2x2 SISO-MISO Network.

4.2. Achievable Rates by the Cognitive System

As shown in Figure 4.4, the system has two phases. In the first pase, the channel is free to be used by cognitive users (there is no primary activity in the channel), and in the second there is no idle channel (spectral hole) available to secondary users, in which case the spectrum is concurrently used by both primary and secondary users through overlay approach. It is assumed that the probability that there is no primary activity in the channel is *p*, in which case the cognitive users freely use the channel on their own. Therefore, the probability that the channel is used by both primary and the cognitive users with spectrum overlay is (1-*p*) with total power *P* in both phases. This setup corresponds to generalised cognitive radio channel. With this scenario, the power used by the cognitive transmitter in the second phase is $P_2 = tP$, $0 \le t \le 1$, whereas it is $P_1 = (1-t)P$ such that $P = P_1 + P_2$. Denoting the instantaneous rate of cognitive transmitter in the first phase as $R_1(P_1)$, and $R_2(P_2)$ in the second phase, the power allocation problem for the cognitive user reduces to the solution of Equation (4.1).

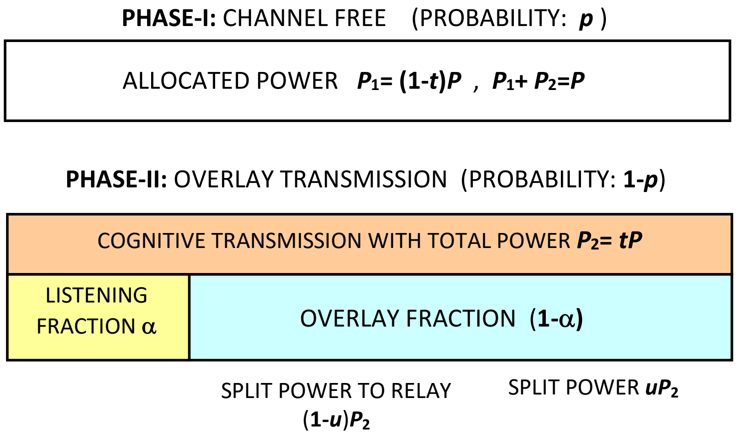

Figure 4.4 The two phases of the cognitive communication.

$$R^{(g)} = \max_{p P_1 + (1-p) P_2 \leq P} \left\{ p R_1(P_1) + (1-p) R_2(P_2) \right\} \tag{4.1}$$

Since, $t \in [0,1]$, $P_1 = \frac{P(1-t)}{p}$ ve $P_2 = \frac{Pt}{(1-p)}$, rewriting Eq. (4.1) we obtain

$$R^{(g)} = \max_{t \in [0,1]} \left\{ p R_1\left(\frac{P(1-t)}{p} \right) + (1-p) R_2\left(\frac{Pt}{(1-p)} \right) \right\} \tag{4.2}$$

It is noted that the cognitive transmission in phase two is possible if the channel between transmitters is better than the channel between primary users, i.e. $|h_{12}| > |h_{13}|$. For the 2x2 SISO-MISO network considered in this thesis, cognitive transmitter receives the primary data in the $0 \leq \alpha \leq 1$ fraction of the transmission block (listenning period), and transmits its own data in the remaining (1-α) fraction of the transmission block by Dirty Paper Coding (DPC) to prevent its receiver from the intereference stemming from the primary transmission. The cognitive transmitter splits its power in two, and uses u, $0 \leq u \leq 1$, fraction of its power, namely uP_2, to transmit its own data and uses $(1-u)P_2$ of its power to relay the primary message (obtained in the listenning period) to the primary receiver to help increase its signal to noise ratio by appropriately arranging its transmitted signal. By this way, it pays for the primary cooperation that enables it to protect its receiver from interference through DPC. Under this scenario, (Koyluoglu ve El Gamal, 2009), the throughput achievable by cognitive user using Eq.(4.2) is illustrated in Figure 4.5.

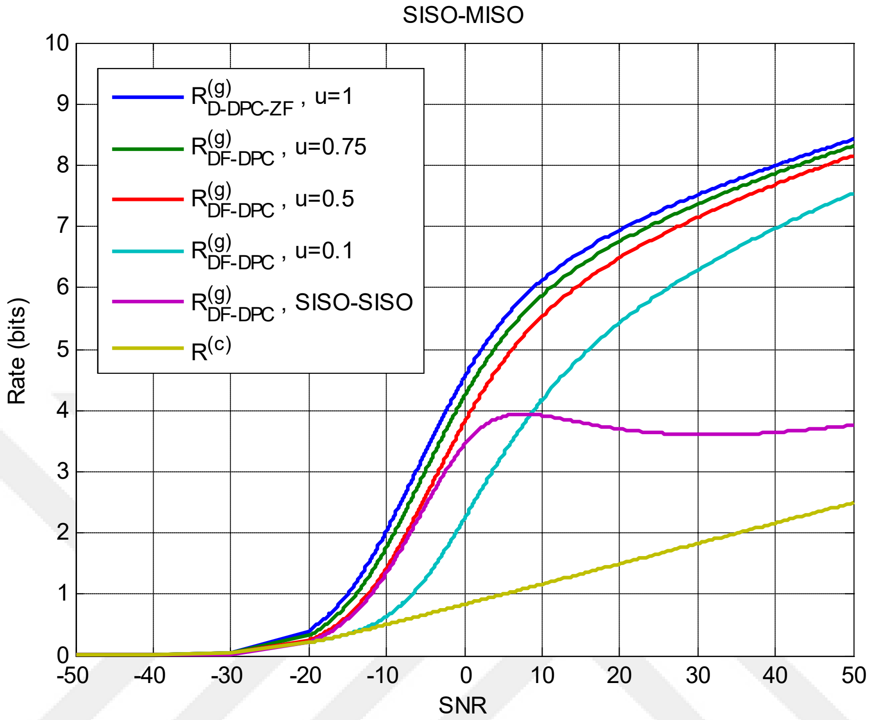

Figure 4.5 Achievable cognitive rates for $d_{12} = 0.125$, $d_{24} = 0.25$, p=0.1, and various power split factors (u).

In the figure, superscripts {g} and {c} stand for generalised and classical (transmission in inactive-primary channels, in other words no co-existing) cognitive transmision, respectively. DF-DPC stands for Decode and Forward-Dirty Paper Code, which means cognitive transmitter decodes primary message and relays it to primary receiver using (1-u)<1 fraction of its power while sending its signal to cognitive receiver by DPC. D-DPC-ZF means Decode-Dirty Paper Code-Zero Force, in which case the cognitive transmitter decodes primary message and sends its message to cognitive receiver using its full power by DPC, and at the same time zero forcing its transmission to primary receiver to meet the co-existence condition. In this way, note that power split factor of the cognitive transmitter is u=1, which corresponds the highest rate achievable by the cognitive users (top blue curve in Fig. 4.5).

5 COEXISTENCE USING DIRTY PAPER CODING

The dirty paper coding (DPC) is due to Costa (Costa M., 1983), which is a technique for efficient transmission of data in the presence of interference known to the transmitter. It can achieve the channel capacity with no power penalty and without requiring receiver to have the knowledge of the interference state. The technique consists of precoding the transmitted data in order to cancel the interference. It is known that for MIMO Gaussian broadcast channel (BC), DPC can achieve the entire capacity region. Suboptimal approximations of DPC include Tomlinson-Harashima precoding (Tomlinson M. 1971, Harashima H. and Miyakawa H. 1972) and the vector perturbation technique of (Hochwald *et. al.* 2005).

Since DPC is too complicated for practical systems due to high computational burden, linear pre-coding techniques for suppressing multi user interference are motivated due to their lower complexity (Weingarten H., *et. al.* 2006). Sub-optimal transmission schemes can also be used such as orthogonal transmission (TDMA) and multi-user beamforming without interference cancellation. Many papers have been subsequently published that focus on approximating DPC using other equalizers such as zero-forcing precoding, Minimum Mean Square Error precoding, Tomlinson-Harashima precoding etc. A more practical and general technique to perform interference pre-subtraction based on nested lattice codes is provided in (Erez U., Shamai S. and Zamir R. 2000). These results have found applications to ISI channel (Erez U., *et. al.* 2005), MIMO BC (Weingarten H., *et. al.* 2006), watermarking (Cohen A. and Lapidoth A. 2002), multiple-cell environment with cooperation between base-stations (Shamai S. and Zaidel B. M. 2001) and models for cognitive radio (Devroye N. *et. al.* 2006). A practical DPC for the MIMO-BC was proposed in (Hwang I. *et. al.* 2007).

Recently, the use of STBC with spatial modulation was investigated in (Başar E. *et. al.* 2011), in which the antenna indices are used to increase the data rate. In this thesis, inspiring from this paper, antenna indices are used in the context of DPC to precode the transmitted data to help cognitive receiver cancel the interference from the primary transmitter. In this chapter, the use of spatial modulation for DPC and the system details are illustrated.

5.1. Cognitive Transmitter

The detailes of the cognitive transmitter in 2x2 SISO-MISO network shown in Figure 4.3 is illustrated in Figure 5.1 in the context of dirty paper coding. Codeword of the cognitive transmitter is $\mathbf{X}_S = [\mathbf{x}_s(1) \ldots \mathbf{x}_s(C_L)]$, where $\mathbf{x}_s(k)$ is the kth transmitted symbol vector and C_L is the codeword length. For the Alamouti codes, $C_L = 2$, symbol vector $\mathbf{x}_s(k)$ is a 2×1 vector, and the codeword $\mathbf{X}_S = [\mathbf{x}_s(1)\ \mathbf{x}_s(2)]$ is therefore a 2×2 matrix. The number of cognitive transmitter antenna is $K\,N_T$, where K is the number of precoders corresponding to the size of the primary signal constellation.

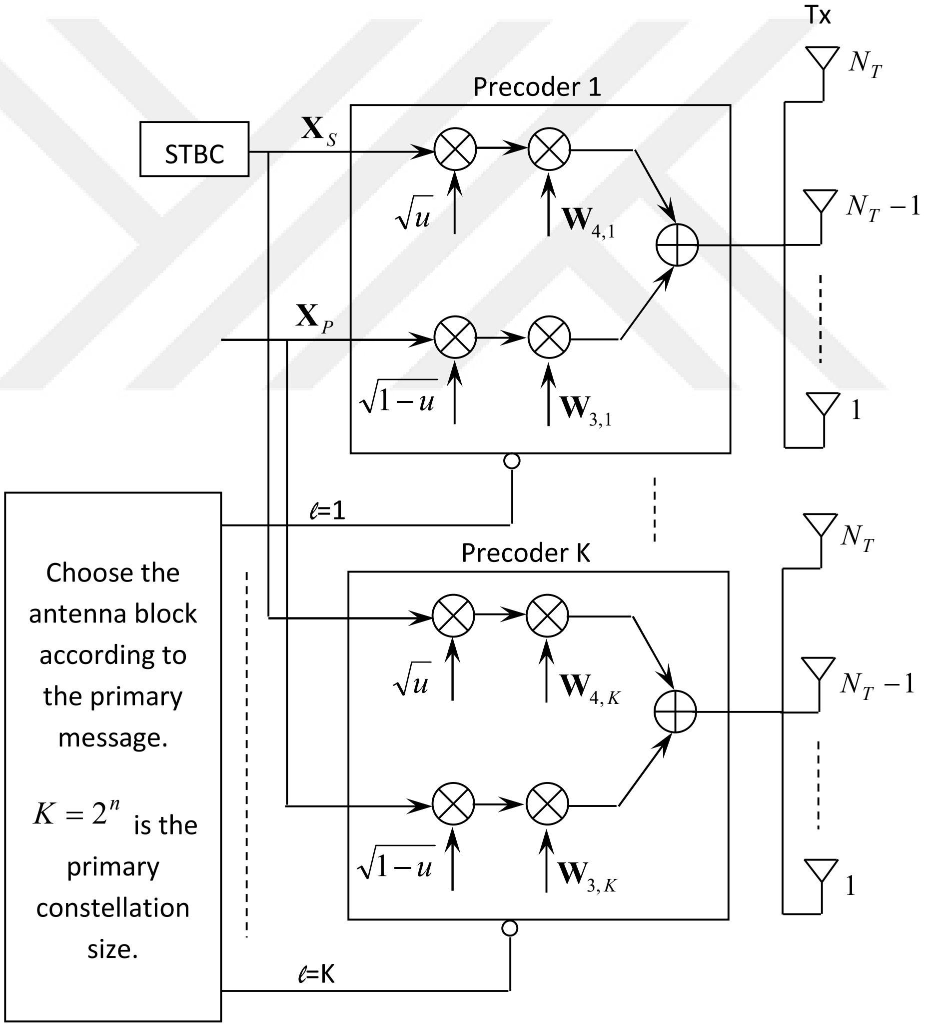

Figure 5.1. Cognitive transmitter using DPC.

It is seen from the figure that the cognitive transmitter splits its power in the overlay mode to send its signal to the cognitive receiver by using the $u < 1$ fraction of its power, and relays the primary message to the primary receiver by using the remaining $(1-u)$ fraction of its power to compensate for the cooperation with primary transmitter. Since the cognitive transmitter needs to meet the first coexistence condition, $\mathbf{H}_3$ and $\mathbf{H}_4$ are considered as broadcast channels to guaranty that the primary receiver is protected from secondary interference. Introducing the spatial dimension, $\mathbf{H}_3$ and $\mathbf{H}_4$ now takes the form $\mathbf{H}_3 = \mathbf{h}_{3,\ell} = (h_{3,\ell}^{(1,1)}, h_{3,\ell}^{(1,2)}, \ldots, h_{3,\ell}^{(1,N_T)})$ and $\mathbf{H}_4 = \mathbf{h}_{4,\ell} = (h_{4,\ell}^{(1,1)}, h_{4,\ell}^{(1,2)}, \ldots, h_{4,\ell}^{(1,N_T)})$, respectively. Here, $h_{k,\ell}^{(1,j)}$ represents the channel coefficient from the *j*th antenna of the *l*th precoder of the cognitive transmitter to the antenna of the *k*th node (receivers have a single antenna). It is assumed that the channel is flat and the coefficients remain the same during the transmission of a codeword, and independently change from one codeword to another. Needles to say that the cognitive users have all the channel state information.

Under these conditions, received signal by the primary and the cognitive receivers are

$$y_3 = \mathbf{h}_{3,\ell}\left(\mathbf{W}_{3,\ell}\sqrt{(1-u)E_S / N_T}\, e^{j\phi}\mathbf{x}_P(n) + \mathbf{W}_{4,\ell}\sqrt{u\,E_S / N_T}\,\mathbf{x}_S(n)\right) + g_3\sqrt{E_P}\,\mathbf{x}_P(n) + n_3 \tag{5.1}$$

$$y_4 = \mathbf{h}_{4,\ell}\left(\mathbf{W}_{3,\ell}\sqrt{(1-u)E_S / N_T}\,\mathbf{x}_P(n) + \mathbf{W}_{4,\ell}\sqrt{u\,E_S / N_T}\,\mathbf{x}_S(n)\right) + g_4\sqrt{E_P}\,\mathbf{x}_P(n) + n_4 \tag{5.2}$$

Here, n_3 and n_4 are zero mean, circularly symmetric, identically distributed independent complex Gauss random variables with power spectral density $N_0/2$, and ϕ represents the phase alignment factor. Since the precoding matrices are designed such that

$$\begin{aligned} &\mathbf{W}_{k,\ell}^H\,\mathbf{W}_{k,\ell} = \mathbf{I}, \quad k = 3,4 \\ &\mathbf{h}_{i,\ell}\mathbf{W}_{j,\ell} = \mathbf{0}, \quad i,j = 3,4, \;\; i \neq j \end{aligned} \tag{5.3}$$

received signals reduces to

$$y_3 = \mathbf{h}_{3,\ell}\mathbf{W}_{3,\ell}\sqrt{(1-u)E_S/N_T}e^{j\phi}\,\mathbf{x}_P(n) + g_3\sqrt{E_P}\mathbf{x}_P(n) + n_3 \tag{5.4}$$

$$y_4 = \mathbf{h}_{4,\ell}\mathbf{W}_{4,\ell}\sqrt{u\,E_S/N_T}\,\mathbf{x}_S(n) + g_4\sqrt{E_P}\mathbf{x}_P(n) + n_4 \tag{5.5}$$

To satisfy Equation (5.3), the precoding matrices are computed as

$$\mathbf{W}_{3,\ell} = \left(\mathbf{I} - \mathbf{h}_{4,\ell}^{\dagger}\,\mathbf{h}_{4,\ell}\right)\mathbf{D}_{3,\ell} \tag{5.6}$$

$$\mathbf{W}_{4,\ell} = \left(\mathbf{I} - \mathbf{h}_{3,\ell}^{\dagger}\,\mathbf{h}_{3,\ell}\right)\mathbf{D}_{4,\ell} \tag{5.7}$$

Here, † pseudo-inverse and $\mathbf{D}_{k,\ell}$ is the eigenmode selection matrix to maximise the spatial diversity (to maximise $\left\|\mathbf{h}_{k,\ell}\mathbf{W}_{k,\ell}\right\|_F^2$ Frobenius norm).

Assuming that dirty paper decoding parameter ℓ, representing the primary symbol index in the primary modulation constellation, is correctly estimated at the cognitive receiver, the received signal by the cognitive receiver at time *n* reduces to

$$y_4 = \mathbf{h}_{4,\ell}\mathbf{W}_{4,\ell}\sqrt{u\,E_S/M}\,\mathbf{x}_S(n) + n_4 \tag{5.8}$$

from which the ML decoding of the cognitive message $\mathbf{x}_S$ can be performed.

5.2. SISO-MISO Cognitive User Bit Error Rate Results

$N_T = 2$ and $N_R = 1$ cognitive user bit error rate has been simulated in Rayleigh fading environment with different power split factor *u*. Note that *u* represents the fraction of power that the cognitive transmitter uses for its own transmission to the cognitive receiver. Then the remaining fraction of its power is used to relay the primary message in coherence with the primary signal. Bit error rate results are shown in Figure 5.2. It is seen that error probability naturally decreases with increasing *u*.

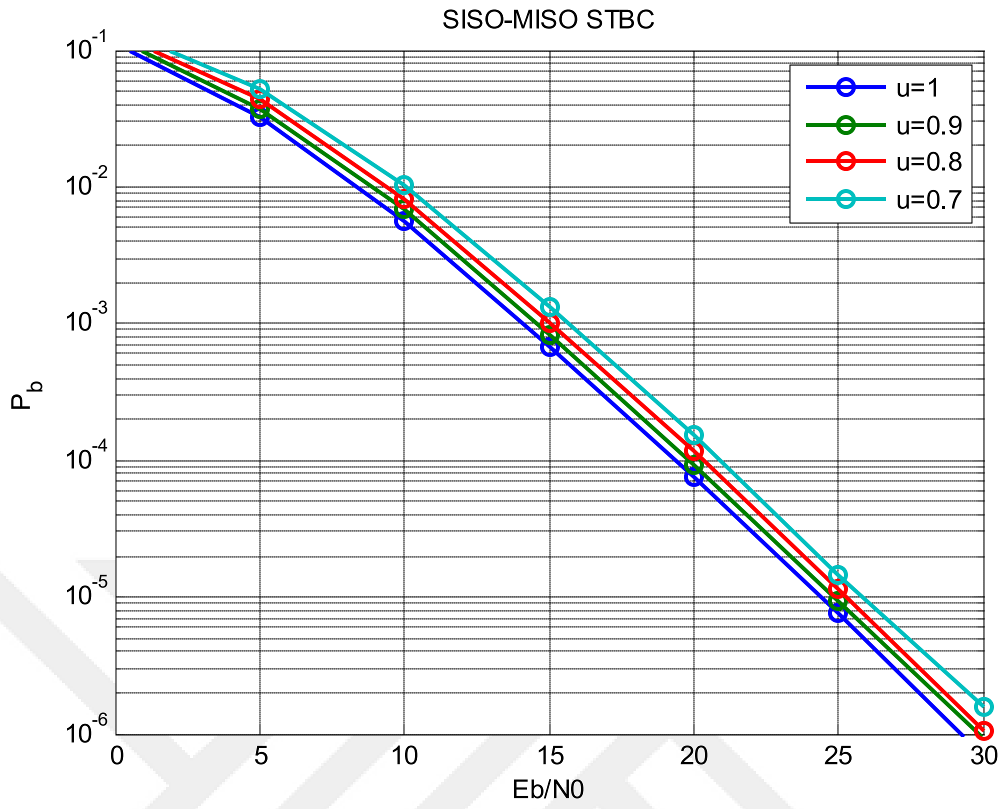

Figure 5.2. Bit error probability of cognitive user for various values of *u*.

6 CONCLUSION

The use of Decode-Forward and Dirty Paper Code strategy for the spectral co-existence of primary and secondary users in slow Rayleigh fading 2x2 SISO-MISO cognitive radio channel through asymmetric transmitter cooperation has been investigated by adopting spectrum overlay approach. In a general cognitive radio context, achievable cognitive rates have been obtained, and a novel dirty paper coding method is proposed to prevent cognitive receiver from the interference of primary transmitter subject to coexistence-conditions, and its use with space-time block coding is investigated through software simulation and bit error rates for the cognitive users are presented.

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