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SPECTRAL COEXISTENCE IN COOPERATIVE WIRELESS NETWORKS

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ÖZET

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İŞBİRLİKLİ KABLOSUZ AĞLARDA SPEKTRAL BİRLİKTELİK

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Bu tezde, düz Rayleigh sönümlemeli radyo kanalında analog ağ kodlamanın, birincil ve ikincil kullanıcıların aynı spektrum bölgesine işbirlikli röle aracılığı ile eşzamanlı erişiminde kullanımı araştırılmıştır. Birincil ve ikincil sistemlerin tek giriş tek çıkışlı (SISO) olduğu farzedilerek, üzerine bindirmeli spektral birliktelik ile 2x2 SISO-SISO işbirlikli radio ağı ele alınmıştır. Birlikteliğin, ikincil sinyalin analog ağ kodlanmış birincil sinyal üzerine iki farklı senaryo altında bindirilmesi şeklinde sağlandığı farzedilmiştir. Bu bağlamda, gerek birincil iletimin sağlanması ve/veya mevcut sinyal kalitesinin iyileşmesi şeklinde her iki kullanıcı da avantaj elde etmektedir. Birincil sinyal kalitesinin en azından mevcut durumunun korunması veya her iki kullanıcı için de iyileştirilmesi için gerekli koşullar servis dışı kalma olasılığı yönünden incelenmiştir. Ayrıca, bilişsel spektrum algılama farzedilerek ikincil kullanıcının servis dışı kalma olasılığı, iletimin sadece birlikte spektrum kullanımı şeklinde değil, belli bir olasılıkla boş spektral boşlukların doldurularak doğrudan yapılabildiği bir senaryoya genelleştirilmesi ile de elde edilmiştir.

Anahtar Kelimeler: Spektral birliktelik, işbirliği, analog ağ kodlama.

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ABSTRACT

MSc Thesis

SPECTRAL COEXISTENCE IN COOPERATIVE WIRELESS NETWORKS

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In this thesis, the use of analog network coding for the spectral coexistence of primary and secondary users in flat Rayleigh fading through cooperative relaying has been investigated. It is assumed that the primary and secondary systems are all SISO, and thus a 2x2 SISO-SISO cooperative radio network has been considered for concurrent spectrum sharing using overlay approach. The investigated coexistence assumes placing the secondary signal on top of the analog network-coded primary signals at the secondary relay under two different scenarios, from which both users benefit as to either enable primary transmission not possible otherwise or increase signal quality or both compared to that in the absence of cooperation. Conditions of at least maintaining or increasing the primary user's signal quality compared to that in the absence of cooperation have been analyzed in terms of outage probabilities for both users. Assuming cognitive spectrum sensing, outage probability has also been obtained for the secondary users by generalizing the transmission to the case in which spectrum holes may also be available with some probability.

Key Words: Spectral coexistence, cooperation, analog network coding.

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LIST OF SYMBOLS/ACRONYMS

AF	Amplify and forward
AWGN	Additive white Gaussian noise
CCR	Cooperative cognitive radios
CR	Cognitive radio
CRNs	Cognitive radio networks
CSS	Cooperative spectrum sharing
DF	Decode and forward
MRC	Maximum ratio combining
PT	Primary transmitter
PR	Primary receiver
PU	Primary user
QoS	Quality of service
SISO	Single input single output
FFC	Federal communications commission
Ri	Data rate
SINR	Signal to interference and noise ratio
Rpt	Primary user's target rate
Rst	Secondary user's target rate
SR	Secondary receiver
ST	Secondary transmitter
SU	Secondary user
SNR	Signal to noise ratio
ANC	Analog network coding
x_i	Primary signal
x_j	Secondary signal
MISO	Multiple input single output
DCP	Dirty paper coding

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1. INTRODUCTION

In this era, as the wireless and multimedia applications are increasing, there is an ever-increasing demand for more radio spectrum. However, recent surveys have discovered that most of the spectrum (3 kHz to 300GHz) is no longer available for wireless systems due to the location of the spectrum under licensed band (NTIA 2003). Further, it is surveyed that most of the licensed spectrum is either not utilized or under-utilized (Roberson et al. 2006, NTIA 2003). As a result of this inherent inefficiency of current spectrum allocation policies, as considerably as the scarcity of radio spectrum, researchers over the years have proposed alternative spectrum access techniques to improve the spectral efficiency and capacity in radio communication, giving birth to the notion of "cognitive radios" (CR) (Mitola 2000).

For improving the utilization efficiency of the radio spectrum, cognitive radio allows secondary users (SU) also referred to as unlicensed users or cognitive users to coexist with primary users (PU) known as licensed users through spectrum sharing, provided that the secondary spectrum access will not adversely affect the PU’s performance. 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 (Haykin 2005):

- ❖ Highly reliable communications whenever and wherever needed;
- ❖ Efficient utilization of the radio spectrum (Spectrum sharing).

In Cognitive Radio Networks (CRNs), SUs may access the radio spectrum in different ways depending on the type of available network information and regulatory constraints. In the CRN literature (Zhao and Sadler 2007, Peha 2005), three spectrum access paradigms, namely, interweave, overlay, and underlay paradigms have been viewed. These paradigms differ based on the level of knowledge about the surrounding environment and the different mode of functioning.

In the inter-weave or interference avoidance paradigm, the SUs intelligently detect spectrum holes by sensing and then exploit the unoccupied primary frequency bands for their transmissions. This paradigm is also referred to as opportunistic spectrum access (OSA) where no simultaneous transmissions of the primary and secondary users are permitted. On the other hand, in the underlay or interference controlling paradigm, the SU coexists with the PU whereby SU transmits concurrently with the PU in the same frequency band as long as the interference imposed to the PU Receiver (PU-RX) remains below a predefined interference level (Peha 2005, Wang 2014). By doing so, an acceptable level of performance for both primary and secondary networks can be insured, and therefore resulting in a more efficient overall spectrum utilization.

Finally, the overlay or interference mitigating approach allows the SUs and PUs to transmit concurrently over the same spectrum provided that the SUs aid the PUs transmission by cooperative communication techniques, such as advanced coding or cooperative relaying techniques (Goldsmith et al. 2009). In this approach, the SU Transmitter (SU-Tx) requires information about the primary network and its operation, e.g., PU's codebooks. The SU-Tx uses the PU messages either to enhance the performance of the primary transmission through relaying the accumulated messages to the PU receiver (PU-Rx) or to eliminate the interference generated by the PU transmitter (PU-Tx) at the SU receiver (SU-Rx) and hence to boost the network throughput. For achieving this, the overlay paradigm employs sophisticated signal processing and coding techniques like dirty paper coding (Peha 2005), analog network coding (Yong Li et al. 2014, Katti et al. 2007).

In contrast to the underlay model, the overlay model does not require strict transmit power constraints at the SUs due to interference caused to the PUs. Furthermore, the notion of cooperative relaying has gained considerable interest in academia and industry because of its numerous benefits such as improved coverage, increases throughput, power savings, etc.

Nevertheless, most of the prior work has been confined to conventional one way relaying (OWR) wherein the relay retransmits (Bohara 2011) the source information by a different path to the destination to achieve the spatial diversity (Gupta and Bohara 2016). In cooperative relaying, the most common used relaying protocols are decode and- forward (DF) and amplify-and-forward (AF). In DF relaying (Zhou et al. 2010, Gupta and Bohara 2017), a relay attempts to decode the source signal received in Phase I. If decoding is successful, relay regenerates the source signal and transmits it to the destination in Phase II, whereas, in AF relaying, relay amplifies the source signal and retransmits it to the destination. Due to the full processing and sophisticated media access control layer requirement at the relay, the complexity of DF relaying is significantly higher than the AF relaying. So, AF relaying has been preferred on most of the recent work on cooperative relaying.

Recently, to further improve the performance of the primary users effectively as it helps to solve the problems of limited coverage and spectrum scarcity, researchers have proposed the use of cooperative spectrum sharing (CSS) (Goldsmith et al. 2009, Han et al. 2008), which comprises cooperative relaying and cognitive radio (Haykin 2005). In CSS protocol (Bohara et al. 2010), primary and secondary systems coexist in the same frequency band albeit with different priorities. The primary system which has higher priority seeks the assistance of low priority secondary system to improve its quality of service (QoS) in exchange for allowing the secondary system to access its spectrum. The secondary transmitter can choose between retransmitting the primary signal that it overhears and sending its own signal whenever it obtains the spectrum opportunities (Simeone et al. 2007). The primary node can settle to rent a fraction of time to secondary nodes in exchange for cooperation, and secondary transmission can be therefore granted within the rented time (Simeone et al. 2008). In the CSS architecture, the primary and secondary system consists of the PT-PR, and ST-SR pairs respectively.

In the popular cooperative spectrum sharing framework, the SU helps the PU to achieve spatial diversity by forwarding the primary's information via a different path in exchange for accessing the spectrum allocated to primary (Raza et al. 2017).

For instance, in (Han et al. 2008), a CSS protocol with one-way relaying has been proposed. Here, PT transmits the primary signal to PR in Phase I. In Phase II, ST linearly combines the primary and secondary signal with weighing of μ and 1-μ of available power of the secondary system, respectively. The rate of the primary system is then improved with this CSS protocol with the proper choice of μ.

In(Chen and Zhang 2012), the work of (Y. Han et al. 2008) has been extended to cooperative AF relaying. In (Chen and Zhang 2012), the authors derived the bit error rate (BER) for the primary and secondary nodes. It is also shown that one way relaying suffers from the loss of spectral efficiency (pre-log half factor). All of these cognitive relay protocols mentioned above utilize the conventional one-way relaying. On the other hand, due to the broadcast nature of wireless channels, two-way relaying which is enabled by network coding has recently been believed a potentially powerful technique to improve the performance of wireless networks (Ahlswede 2000). The two-way relaying can compensate the spectral efficiency loss occurs due to one-way relaying (Rankov and Wittneben 2007, Xia et al. 2014). In two ways relaying, two users can communicate bi-directionally by using a half-duplex relay node. The simultaneous bidirectional communication between the two users improves the overall spectral efficiency of the system as compared to conventional one-way relaying.

The network coding schemes to support two-way relaying are Digital Network Coding, Physical Network Coding, and Analog Network Coding. The combination of both cognitive radio and network coding has begun to attract research attention as it can be used to improve spectral efficiency. Examples similar to the overlay spectrum sharing models considered in this thesis appears in (Yong Li et al. 2012, 2014) and in (Mittal 2016). Other works on spectral coexistence using overlay approach were published by (Jahja 2015, Jaiteh 2016), in both of which no interference is introduced to the primary receiver by shifting the load of canceling primary to secondary interference to the cognitive transmitter. Spectrum access is granted to the secondary user on the condition that no interference is introduced to the primary receiver, and then the primary receiver performs single-user decoding.

In this thesis, all transmitters and receivers are constrained to have a single antenna, therefore adopting 2x2 SISO-SISO channel configuration and superposition coding with successive interference cancelation enabled by Analog Network Coding are considered using two-phase half-duplex transmission protocols. Conditions of at least maintaining or increasing the primary user's signal quality compared to that in the absence of cooperation have been analyzed in terms of outage probabilities for both users. Outage probability has also been obtained for the secondary users by generalizing the transmission to the case in which spectrum holes may also be available with some probability.

The thesis is organized as follows. In the second chapter, spectral coexistence and cognitive cooperation are reviewed. The third chapter introduces the cooperative network and the system model. Spectral coexistence schemes are analyzed through outage probability using two different protocols in chapter 4 and, finally, the conclusion is given in chapter five.

2. SPECTRAL COEXISTENCE

The widespread adoption of wireless technologies has sparked a vast need for bandwidth that is awaited to grow well into the time to come. Traditionally, Spectrum licensing has been used for ensuring the coexistence of diverse wireless systems. Yet, after many years of spectrum assignment to conform to the ever-increasing demand, the Federal Communications Commission's (FCC's) frequency allocation chart (NTIA 2003) now shows a densely crowded spectrum with most frequency bands already assigned to different licensed users for specific services, and thus resulting to the scarcity of prime wireless spectrum and there is little or no new bandwidth available for emerging wireless products and services.

As solutions to the question of exploring if there is room in the licensed spectrum bands to accommodate secondary wireless devices without disrupting the communications of the primary users of the spectrum, the wireless scholars and researchers came up with the idea of cognitive radios. In a broad sense, the term cognitive radio refers to various solutions to this problem that seek to overlay, underlay, or interweave (Kolodzy 2005) the secondary user's signals with those of the primary users in a manner that the licensed users of the spectrum are as unaffected as possible. In the pioneering work (Mitola and Maguire 1999), Mitola and Maguire stated that " *radio etiquette is the set of RF bands, air interfaces, protocols, and spatial and temporal patterns that moderate the use of radio spectrum. CR extends the software radio with radio-domain model-based reasoning about such etiquettes*". Cognitive radio is a new topic in the field of radio communication which attracts much interest at both academic and industrial stage, as an emerging technology that will play a substantial role in the future of wireless communication systems.

There are various definitions of cognitive radio by different academia and regulatory bodies such as by Joe Mitola: *A cognitive radio* (*CR*) *is a really smart radio that would be self-, RF- and user-aware, and that would include language technology and machine vision along with much high-fidelity knowledge of the radio environment*.

In 2005, S. Haykin defined CR as

"*Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit-power, carrier-frequency, and modulation strategy) in real-time, with two primary objectives in mind: (i) highly reliable communications whenever and wherever needed; (ii) efficient utilization of the radio spectrum"*(Haykin 2005).

ITU-R definition: "*Cognitive radio system (CRS): 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 and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained.*" (Jovicic and Viswanath 2006)

SDR Forum definition: "*Cognitive Radio (design paradigm-1): An approach to wireless engineering wherein the radio, radio network, or wireless system is endowed with awareness, reason, and agency to intelligently adapt operational aspects of the radio, radio network, or wireless system*." (Laneman et al. 2004).

The IEEE (DYSPAN) definition: "*A type of radio in which communication systems are aware of their environment and internal state and can make decisions about their radio operating behavior based on that information and predefined objectives*." (Naganawa et al. 2010)

ETSI RRS definition: "*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 and protocols according to its obtained knowledge in order to achieve predefined objectives, and to learn from the results obtained*." (Giorgetti et.al 2009)

The two main features of CR technology are cognitive capability and reconfigurability. The cognitive capability allows CR to sense its radio environment and collect information (for instance, different signals and their modulation sorts, noise, transmission power,) via real-time interaction and, select the best available spectrum and exploit spectrum holes without or minimum interference with the licensed user. The configurability features of CR allow it to optimally adapt the best spectrum band and the operational parameters as a function of the sensed information. Briefly, cognitive radio is always aware of its surrounding environment in which it is operating and processes the information it receives and makes independent decisions on how to carry out any communication duty at hand.

The development of this new technology will allow us to utilize the radio spectrum efficiently, thereby allowing us to implement new wireless systems and improve the quality, throughput, and capacity of the existing ones.

2.1. Cognitive Radio Network Paradigms

The principal concern of cognitive radio is to guarantee that a cognitive user will not interfere with the licensed user while communicating in a licensed spectrum. Based on available network information and other regulations there are different approaches by which secondary user may use interweave, underlay, and overlay approaches to access spectrum without interfering with the primary user (Zurutuza 2012, Goldsmith et al. 2009).

2.1.1. Interweave

Interweave paradigm uses the opportunistic spectrum access method that was the primary idea of cognitive radio (Mitola 2000). It is based on the fact of spectrum underutilization which indicated that there are temporary space-time-frequency holes that could be utilized by secondary users. The existence of these holes depends on time and geographical location. For efficient and interference-free communication cognitive user demands activity based information of licensed and unlicensed users (Zurutuza 2012). Interweave cognitive radios are intelligent systems that opportunistically detect the unused spectrum, utilizing it for communication and leaving the spectrum when the primary user is detected thus avoiding considerable interference (Zurutuza 2012).

2.1.2. Underlay

In this approach, unlicensed users simultaneously transmit with licensed users by maintaining supportable interference. For achieving this, the interference at the primary receiver by secondary users is maintained below a certain threshold (Zurutuza 2012, Goldsmith et al. 2009, Wang and Ray Liu 2011). Underlay approach uses the interference temperature model for measuring interference level at the primary receiver caused by secondary users and uses measured data to minimize the interference caused by the secondary user (Zurutuza 2012). For also solving the interference problem caused by secondary users, the use of multiple antennas can be used, by which secondary user transmission can be guided away from the primary receiver. Another approach for reducing interference is the use of wide bandwidth on which secondary transmission could spread while dispreading signals at the secondary receiver; this technique is also the basis for spread spectrum and Ultra-wide-band (UWB) communication (Goldsmith et al. 2009). The underlay paradigm could also be used in unlicensed bands for providing the various class of service for different users.

2.1.3. Overlay

The overlay paradigm, similarly to underlay, allows coexistence between secondary and primary users in the same band. In this model, there is no power limit for secondary transmission. Secondary users can transmit with maximum power (selfish approach).

For avoiding conflict with licensed users, unlicensed users are assumed to know the primary's codebook and/or message (Goldsmith et al. 2009). Channel information can be obtained in uniform standard or by broadcasting. This information can be used to enhance the primary receiver's power by relaying primary transmission. Since each secondary user has primary codebook and message information, it can split the power (selfless approach) to both send its own message and to relay the primary message (Goldsmith et al. 2009). Thus, this scheme increases the SNR at the primary receiver.

Moreover, as the secondary user knows both message and codebook, to decode the message it can apply various famous coding schemes like Superposition **c**oding, Gel'fand Pinsker (GP), Dirty-paper **c**oding (DPC), Rate-splitting etc. so that data rate of both secondary and primary users could be improved using this information (Jindal and Goldsmith 2005, Khina and Erez 2010, Zurutuza 2012). Among these, Rate-splitting is best known coding scheme till now (Zurutuza 2012). Although there is extra transmission overhead, out of the three paradigms, the overlay is the only one where primary users have a motivation to cooperate with secondary users since their transmission can be improved by allowing coexistence (Goldsmith et al. 2009).

To summarize, both underlay and overlay techniques allow simultaneous transmission of primary and secondary users while interweave paradigm avoids simultaneous transmission and uses opportunistic spectrum access method. Moreover, different paradigms require different information; like underlay, paradigm requires interference information at the primary receiver, overlay paradigm requires codebook and message information and interweave paradigm requires licensed and unlicensed user's activity information for efficient detection and utilization of spectrum holes.

Underlay	**Overlay**	**Interweave**
Network Side Information: Secondary transmitters know interference caused to primary receivers. Simultaneous Transmission: Secondary users can transmit simultaneously with the primary users as long as interference caused is below an acceptable limit. Transmit Power Limits: Secondary user's transmit power is limited by a constraint on the interference caused to the primary users. Hardware: Secondary users must measure the interference they cause to the primary users'receivers by either sounding and exploiting channel reciprocity or via cooperative sensing.	Network Side Information: Secondary nodes know channel gains, encoding techniques and possibly the transmitted data sequences of the primary users. Simultaneous Transmission: Secondary users can transmit simultaneously with primary users; the interference to the primary users can be offset by using part of the secondary users'power to relay the primary users'data sequences. Transmit Power Limits: Secondary users can transmit at any power; the interference to primary users can be offset by relaying the primary users'data sequences. Hardware: Secondary users must also listen to primary user transmissions. Encoding and decoding complexity is also significantly higher than other paradigms.	Network Side Information: Secondary users identify spectrum holes in space, time, and frequency from which the primary users are absent. Simultaneous Transmission: Secondary users transmit simultaneously with a primary user only when there is a missed detection of the primary user activity. Transmit Power Limits: Secondary user's transmit power is limited by the range of primary user activity it can detect (alone or via cooperative sensing). Hardware: Receivers must be frequency agile or have a wideband front end for spectrum hole detection.

Table 2.1. Comparison of interweave, underlay, and overlay of cognitive radio network paradigms (Mohsen 2019).

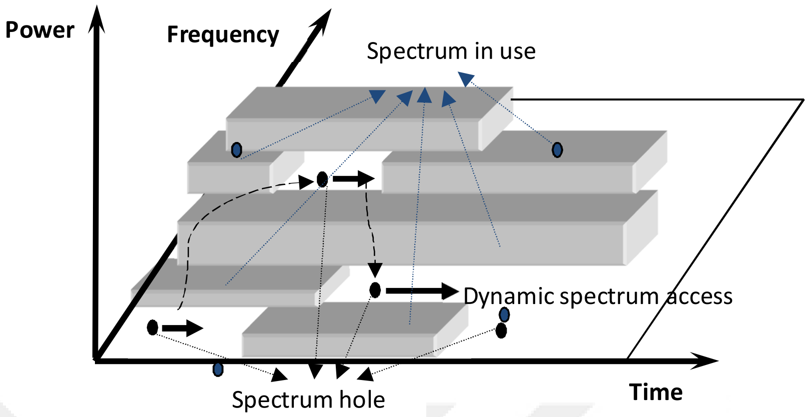

Figure 2.1. Spectrum holes for dynamic access

2.2. Spectral Coexistence in Wireless Networks

The term spectral coexistence refers to the efficient utilization of the radio frequency band by different entities in wireless networks. The coexistence of wireless networks can be broadly separated into two categories: vertical coexistence and horizontal coexistence.

2.2.1. Vertical coexistence

Vertical coexistence concerns the coexistence of two or more networks that have different priorities to access spectrum. For instance, in CR networks, incumbent users have priority over secondary users when accessing the licensed spectrum bands, which is also called incumbent coexistence.

2.2.2. Horizontal coexistence

Horizontal coexistence relates to the coexistence of two or more unlicensed networks that have equal priority to access spectrum. In the OSS paradigm, the coexistence between incumbent users and secondary users is related to as incumbent coexistence. There are numerous works on the incumbent coexistence (Cabric et al. 2004, Chen et al. 2008, Ganesan and Li 2005, Shankar et al. 2005, Wild and Ramchandran 2005), and it has been attracting significant interest from academia and industry. In contrast, horizontal coexistence has garnered less attention thus far. Horizontal coexistence can be further placed into (Kaigui et al. 2014) :

- **Heterogeneous coexistence** that denotes the coexistence of networks that use different wireless technologies (e.g., the coexistence between WiFi and Bluetooth (Huang et al. 2010, Zhou et al. 2010), the coexistence of heterogeneous wireless networks over TV white space.
- **Homogeneous coexistence** (a.k.a. self-coexistence) that refers to the coexistence of networks that employ the same wireless technology (e.g., neighboring CR networks of the same type, or neighboring 802.11 hotspots).

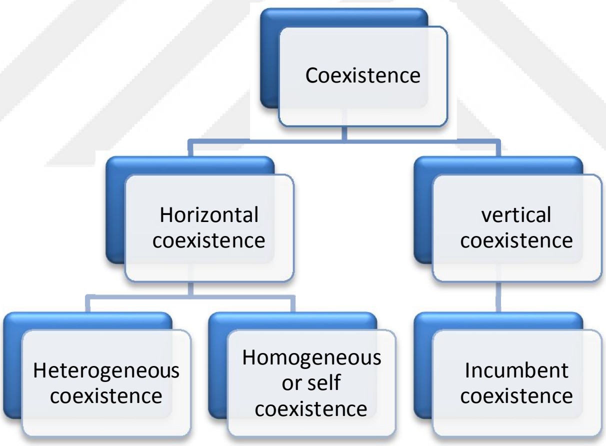

Figure 2.2. Coexistence in Wireless Networks

2.3. Coexistence Schemes for Cognitive Radios

Handling interference is crucial for coexistence between the primary and the secondary system for helping efficient opportunistic utilization of the spectrum. Some of the interference management techniques are explained below.

2.3.1. Interference Cancellation

In the underlay paradigm, the secondary users can opportunistically use the primary spectrum by canceling the interference at the primary receiver. For instance, STs use beamforming and beam nulling schemes for interference cancellation at the PR in a multi-antenna CR system (Ko et al. 2000). On the other hand, interference cancellation of primary interference at the secondary receivers is proposed in (Zhang 1996), which is also called opportunistic interference cancellation (OIC).

2.3.2. Interference Minimization

Opportunistic use of the primary spectrum by the secondary system can be considered as a problem of resource allocation. The aim of the secondary system can be devised to meet a specific design target while minimizing the interference at the primary, for example, the energy efficiency of the secondary system (Hasan et al. 2009). A waterfilling approach is used when the secondary users access the primary band through orthogonal channels for the optimal power allocation (Goldsmith et al. 2009).

2.3.3. Superposition Coding and Successive Interference Cancellation

In the overlay CR model, the opportunistic access of the spectrum by the secondary users can be alleviated by cooperation between the primary and the secondary systems. In cooperative primary-secondary transmission, the available time interval for transmission is split up into two-time slots (TS). In the first TS, the primary transmitter transmits its signal, which is concurrently received and successfully decoded by the PR, the ST and possibly the SR. In the second TS, the ST compiles its message by superposition coding the secondary signal on top of the primary signal and transmits the superimposed signal using the decode-and-forward or amplify-and-forward relaying strategies. The entire usable transmission power at the ST should be carefully split among the primary and the secondary message in a way that the SU's opportunistic access does not penalize the end-to-end rate at the PR after the two-transmission slots transmission.

The most significant condition such that the secondary system can still achieve non-zero rates through collaborative techniques at the secondary system is that the secondary transmitter can successfully decode the primary message received in the first time slot for being able to relay it in the later time slot (Han et al. 2009, Kim 2012). MRC of the signals received in the two TSs can be utilized to recover the primary signal at the PR when equal length time slots are apportioned to the primary source and the secondary relay (Han et al. 2009). If the SR is close enough to the PT, it can receive and decode the primary signal in the first TS with a high probability. After that, the SR can subtract the primary signal from the relayed superimposed signal received in the second TS from the ST, and finally obtain an interference-free version of the secondary signal (Shin and Kim 2011). On the other hand, when the PT is outside the reception range of the SR, and therefore the SR cannot overhear the primary message, the power allocation at the ST should be such that the SR can decode the secondary signal from the message received in the second transmission slot by employing successive interference cancellation (SIC) technique (Kim 2012). However, (partial) knowledge of the different channel gains at the ST and both the receivers is required for determining the optimum time and power allocation ratios in some of the above-discussed solutions. This (partial) knowledge of the different channel gains may limit the applicability of such schemes in practical opportunistic spectrum access scenarios.

2.3.4. Dirty Paper Coding

Dirty-paper pre-coding is also known as Costa precoding refers to communicating over an additive white Gaussian noise (AWGN) channel in the presence of interference that is noncausally known at the transmitter but not at the receiver (Costa 1983).

In the overlay network, the primary interference at the SR can be entirely removed by precoding the secondary signal using an appropriate DPC technique, while guaranteeing there is no degradation in the PU communication. In the low-interference regime, where the secondary signal of concern at the SR is stronger than the primary interference, it has been demonstrated in (Wu et al. 2007) that a system involving DPC can achieve the capacity for the AWGN channels. A multi-level DPC strategy for the single user CR channel that is able of performing very close to the capacity in both low and high rate of interference is proposed in (Uppal et al. 2011).

2.3.5. Interference Alignment

Interference Alignment (IA) is discovered to achieve full spatial multiplexing gain in a Gaussian interference channel (Cadambe and Jafar 2008). Maddah-Ali first proposed it in (Maddah et al. 2006, 2008) for the two users Multiple-Input Multiple-Output (MIMO)-X channel. Later on, this was generalized for the K-user MIMO-IFC by Cadambe and Jafar in (Cadambe and Jafar 2008). The main idea of IA is to adjust the transmission of signals from different transmitters such that all the unwanted interference at each receiver overlaps with each other. This will allow a transmitter-receiver pair to communicate interference free over the remaining interference free dimensions.

On account of the separation of interference and information signal subspaces, interference alignment naturally adds itself to systems where the interference is to be avoided and minimized, such as the CRN. IA in a CR scenario is studied in (Perlaza et al. 2010, Amir et al. 2011). In the seminal works on IA in a CR environment (Perlaza et al. 2010), a MIMO SU safely coexisting with a MIMO PU is studied. The authors provide a power allocation and an IA scheme for the Secondary Transmitter (ST) such that the interference at the PR does not fall into the PU's desired direction of communication, and the secondary rate is maximized. This scheme is introduced as the Opportunistic Interference Alignment (OIA) scheme (Mahmood 2012).

2.4. Cooperation in Cognitive Radio

Smart PUs are willing to establish collaborative relationships with SUs if PUs can obtain benefit by doing so, and SUs have the demand for using the spectrum for transmission, which forms the overlay-type CRN. In response to the challenging issues in spectrum sensing based CRN, a promising alternative approach for SUs to gain transmission opportunities using licensed spectrum is to provide tangible services to PUs such that the PU can transmit its traffic to its intended destination with higher reliability, e.g., faster and with satisfactory QoS. If the SU can provide such service, the PU would be happy to yield a fraction of its licensed spectrum for the SU to use, with the condition that the SU's transmission does not interfere with the PU's transmission. In this way, the PU and the SU mutually benefit from user cooperation, i.e., the PU and the SU cooperate to achieve mutual benefit.

Cooperative transmission in its necessary forms relates to the information of the relay channel, where one node (the relay) forwards the transmission of another node (the source) towards the intended destination. Performance advantages achievable from collaboration arise from power gains; that can be harnessed if the relay is placed in a convenient location, typically halfway between source and destination; and diversity gains; that provide power to act effectively the double path followed by the signal (direct source-destination and relay transmissions) (Nosratinia et al. 2004, Simeone et al. 2009).

In the context of cognitive radio, cooperative transmission can bring about two different basic scenarios, as explained in the following:

- Cooperative transmission between secondary users:

In this scenario (Nosratinia et al. 2004), a SU acts as a relay from the transmission of another (source) secondary terminal (see Figure 2.3). General considerations valid for cooperative transmission can be applied in this case with the critical caution that secondary nodes need to monitor the channel for possible transmissions by the primary continuously. Interestingly, cooperative transmission can be used as a means to enhance the sensing process as well (Ghasemi and Sousa 2005).

The main idea is to permit the secondary relay node to amplify and forward the received signal since the received signal contains not only the transmission from the secondary source but also, if present, the signal from the primary. This forwarding then permits the secondary destination to improve the local detection of the primary user in a scenario where the relay is placed approximately halfway between the primary and secondary destination (Simeone et al. 2008).

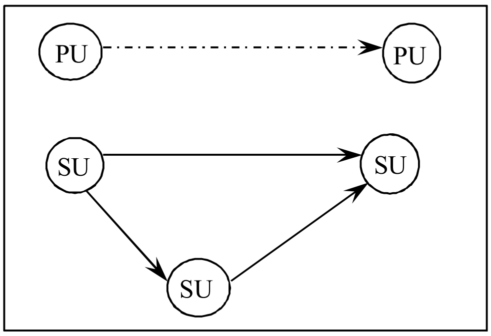

Figure 2.3. Cooperative transmissions between secondary users.

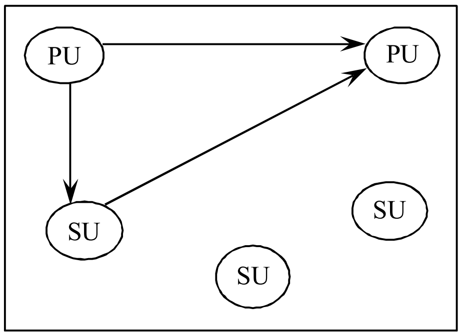

Figure 2.4. Cognitive relay

- Cognitive relay:

Apart from the cooperation between secondary users, a different form of cooperative transmission can be envisioned where a secondary user can relay the traffic of a primary transmitter towards the intended destination (see Figure 2.4). The principle of this choice is that helping the primary to increase its throughput imposes (for a fixed need of rate by the primary) diminished transmission time of the primary, which in turns leads to more transmission opportunities for the secondary (Simeone et al. 2008). Therefore, while cooperation between secondary users aims at increasing the secondary throughput for a given spectral hole, cognitive relaying pursues an enhanced throughput by increasing the probability of transmission opportunities. User cooperation to improve spectrum efficiency and utilization in an overlay CRN is also termed cooperative cognitive radio networking (CCRN) (Simeone et al. 2008, Hua et al. 2011, Cao et al. 2012, Lataief and Zhang 2009).

3. SYSTEM MODEL AND PROTOCOL DESCRIPTION

As mentioned in the introduction, the cooperative network setup considered in this thesis is the scenario in which cognitive users concurrently transmit with active primary users of a radio channel through cooperative spectrum sharing acquiring overlay spectral coexistence by satisfying its requirements imposed on the secondary system. Coexistence conditions are that the operation of the secondary system consisting of a secondary transmitter and secondary receiver does not adversely affect the primary system performance comprising of a primary transmitter and primary receiver , and that the secondary system has to ensure that the achievable rate of primary system (or target rate) under spectrum sharing is not worse than that without spectrum sharing (Yong Li et al. 2014).

In a conventional CSS protocol (Zou et al. 2011) if the primary system is not able to achieve its target rate, it seeks cooperation. The secondary system, which disguises itself as a relay, helps the primary system to achieve its target rate in exchange for opportunistic spectrum access (Cao et al. 2012), by adopting the following two-phase transmission protocol as shown in Figure 3.1. In transmission Phase-I, the primary PT broadcasts its data to the primary PR, which is also overheard by the secondary ST and secondary SR. In transmission Phase-two, the secondary system transmits the primary and secondary signal with μ and $1-\mu$ amount of its available power, respectively. The secondary system works with a constraint that the spectrum access by secondary should not affect the performance of the primary system. At PR, MRC is applied to get the desired data out of the data received in Phase-one and II, considering the secondary data as noise. At SR, the interference cancellation is applied in Phase-two, after successful decoding of primary signal in Phase-one to obtain the secondary data.

Although conventional CSS scheme helps the PU to improve its quality of service with the help of the secondary user in exchange of OSA, it has many drawbacks such as an unavoidable loss in the spectral efficiency due to the pre-log factor one-half (one-way relaying), the performance of SU depends on the successful decoding of PT's data by SR in the first transmission phase (if the decode-and-forward scheme is used for the relaying of data in the second phase), and limitation by interference at the PR due to ST's data which deteriorates the performance of the primary system. However, in this thesis two-way relaying is used to rule out these issues.

3.1. System Model and Notation

In general 2x2 four-terminals network is considered in this thesis with the linear system model as shown in Figure 3.1, where PU1 and PU2 constitute primary transmitter-receiver pair, and on the other hand, ST and SR represent secondary (cognitive) transmitter-receiver pair, respectively. Throughout this thesis, all nodes are constrained to operate in a half-duplex mode and having a single antenna.

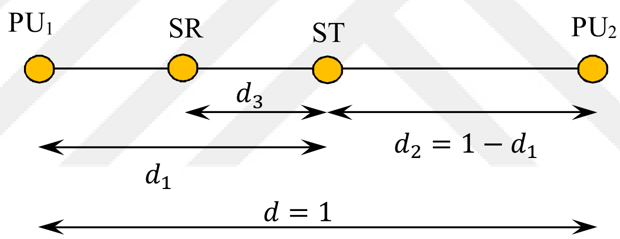

Figure 3.1. Collinear system model

Two different network protocols are studied. In the first network, shown in Figure 3.2, a primary system and a close secondary system is presumed. Two primary users *PU1* and *PU2* are trying to communicate bi-directionally but the direct link between *PU1* and *PU2* deteriorates because of the long distance, shadowing, multipath fading, and deteriorating channel conditions between them, and therefore, direct transmission between them is not efficient. Consequently, PUs look for the help of the nearby secondary user through cooperation by deciding to share a small part of its spectrum. By acting as a relay, ST helps primary transmissions and is permitted to get at the PU's spectrum in exchange.

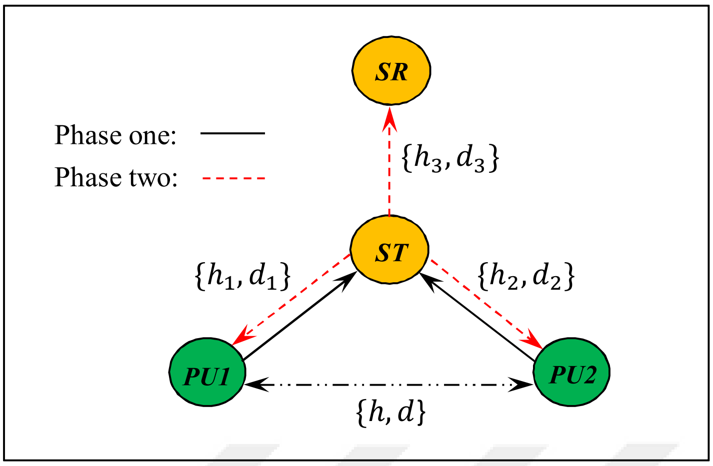

Figure 3.2. Two-phase two-way relaying network with Protocol-1.

In the meantime, ST has its message designated for another secondary user SR. In this protocol, successive interference cancelation for primary users because of their power to remove both the self-interference as a result of the known primary signal and the mutual interference as a result of the secondary signal is suggested. The distance between PU1 and PU2 is considered to be unity. The normalized distance between PU1, PU2, SR to ST is denoted by d_1, d_2, and d_3 respectively. All channels undergo flat Rayleigh fading and are presumed to be mutual in the incoming and return directions. The channel coefficients between PU1, PU2, SR, and ST are denoted as h_1, h_2 and h_3 respectively and they remain constant during at least one protocol cycle, where $h_i \sim CN(0, d_i^{-n})$ with $n > 0$ being the path-loss exponent and $i \in \{1,2,3\}$. It is presumed that perfect channel knowledge is always available at the receiver side for each link. Finally, the AWGN noise terms at PU1, PU2, SR, and ST are all modeled as independent and identically distributed $CN(0, \sigma^2)$ and is denoted by z_1, z_2, z_3 and z_{ST}, respectively(Yong Li, et.al. 2014). Setting $\omega i = |h_i|^2$, P_p and P_s denote transmit power of PT and ST, x_1, x_2 , x_3 denote transmit signals of PT and ST with unit power $E\{X_p X_p^*\} = E\{X_s X_s^*\} = 1$, R_{pt} and R_{st} denote target rate of the primary and secondary system, respectively.

The second network settings differ from the first one in that the SR also overhears the primary users transmission in the first time slot as shown in Figure 3.3. The second-phase takes place in the same way as that of the first network. However, additional d_4, d_5 distances and h_4, h_5 channel coefficients are as shown in the figure.

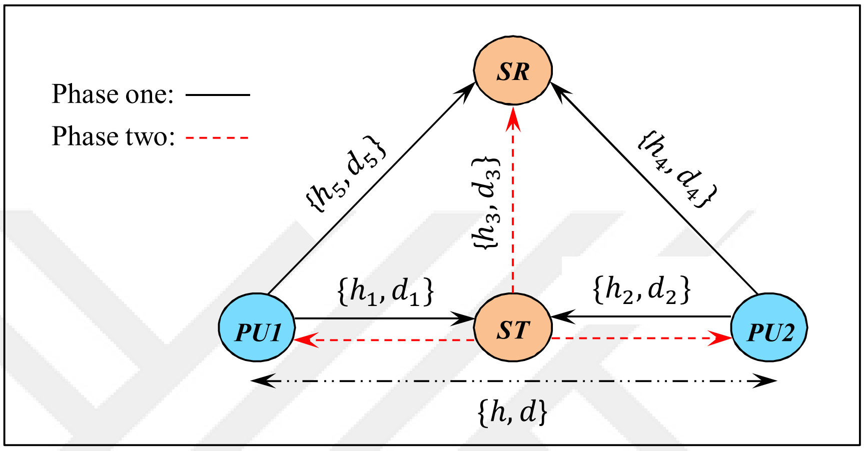

Figure 3.3. Two-phase two-way relaying network with Protocol-2.

3.2. Extension to Generalized Cognitive Channel

It is assumed that the secondary users are cognitive and therefore can listen to the available spectrum. As shown in Figure 3.4, the generalized cognitive channel is considered to have two-states (Koyluoglu And El Gamal 2008). In the first state, the channel is free to be used by secondary users (there is no primary activity), 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 users through cooperation using ANC of course if there is any primary user seeking cooperation. It is assumed that the probability of the absence of primary activity in the channel is p, in which case the secondary users freely use the channel on their own. Therefore, the probability that the channel is used by both primary and the secondary users with spectrum overlay is (1-p) with total power P_S in both phases. With this scenario, the power used by the cognitive transmitter in the second-phase is $P_2 = tP_S$, $0 \le t \le 1$, whereas it is $P_1 = (1-t)P_S$ such that $P_S = P_1 + P_2$.

Denoting the outage probability of secondary receiver in the first-phase as $P_{SU-1}^{ANC}(P_1)$ and $P_{SU-2}^{ANC}(P_2)$ in the second-phase, the power allocation problem for the cognitive user reduces to the solution of Equation (3.1).

PHASE-I: CHANNEL IS FREE WITH PROBABILITY ***p***

ALLOCATED POWER $P_1 = (1-t)P_S$, $P_1 + P_2 = P_S$

PHASE-II: COOPERATIVE TRANSMISSION WITH PROBABILITY **(1-*p*)**

ANC TRANSMISSION WITH TOTAL POWER $P_2 = tP_S$

P_2 IS SPLIT IN TWO FOR THE PRIMARY AND SECONDARY

Figure 3. 4 The two states of the extended cognitive channel.

$$P_{SU}^{(g)} = \min_{pP_1+(1-p)P_2 \leq P_S} \left\{p\, P_{SU-1}^{ANC}(P_1) + (1-p)\, P_{SU-2}^{ANC}(P_2)\right\} \quad (3.1)$$

Since $t \in [0,1]$ and recalling channel-state probabilities, $P_1 = \frac{P_S(1-t)}{p}$ and $P_2 = \frac{P_S t}{(1-p)}$, rewriting Eq. (3.1) we obtain

$$P_{SU}^{(g)} = \min_{t \in [0,1]} \left\{p\, P_{SU-1}^{ANC}\left(\frac{P_S(1-t)}{p}\right) + (1-p)\, P_{SU-2}^{ANC}\left(\frac{P_S t}{(1-p)}\right)\right\} \quad (3.2)$$

It is noted that the secondary transmitter in the second-phase of the generalized channel splits its power into two, and uses $\mu t P_2$ frthe action of its power to relay the ANC signal and $(1-\mu)tP_2$ of its power to transmit its own message to the secondary receiver using two-phase protocol described above. Additionally, there are two power-split factors, one of which is *t* to allocate power between the two states of the channel and the other is μ to allocate secondary power in channel state-two between primary and secondary users. These should not be mixed with each other.

4. SPECTRAL COEXISTENCE

There has always been a trend of increasing capacity of a communication system by using various means including Orthogonal Frequency Multiplexing (OFDM), Multiple Input Multiple Output (MIMO), and Cognitive Radios, etc. In all these techniques, interference reduction is one of the main tasks. Thus interference is considered as main preventive in increasing the capacity of a communication system. Analog network coding (ANC) is a strategy in which interference is used as an advantage rather than a disadvantage (Katti et al. 2007). In analog network coding, the router adds (interferes) the two signals coming from two different points concurrently and broadcasts the combined signal. Receiver subtracts its sent signal from the combined signal received from the router and obtains the transmitted signal.

Analog network coding gets its name from digital network coding in which the router XORs (exclusive or) the bits coming from two different sources and transmits the XORed signal. At receiving end, the receiver XORs the received signal with its own bitstream to get the transmitted signal. Analog network coding has better throughput than digital network coding as explained in the literature. The use of ANC in combination with multiuser cooperative diversity where a relay node helps the corresponding receivers to achieve a better quality of service was studied in (Liu et al. 2016). Also, Analog network coding where relays simply amplify-and forward received mixed signals is presented in (Katti et al. 2007). In (Wang et al. 2011a, 2011b), the outage performance of ANC in a multihop bidirectional network was analyzed. One of many advantages of using the Analog Network Coding is that it is suitable for decoding a superimposed transmission consisting only of two simultaneous transmissions. Perfect synchronization for the collided transmission is not required, and knowing one of the two collided transmissions is enough for decoding a superimposed transmission.

In this thesis, ANC is considered for concurrent spectrum sharing because of its power to take out both the self-interference as a result of the known primary signals and the mutual interference as a result of the secondary signals. In the following subsections, the performance of the spectrally coexisting primary and secondary systems are analyzed through outage probability. Outage probability of both users is obtained and compared to that of without cooperation.

4.1. Coexistence Using ANC with Protocol-1

As shown in Figure 3.2 and Figure 3.3, the considered spectrum sharing protocol comprises of two phases. In phase-one, primary users PU1 and PU2 transmit their respective signals concurrently to relay ST as in the ordinary ANC scheme without any extra overhead. *ST* receives the mixed signals from PU1and PU2 and calculates the appropriate secondary data rate R_3 based on the current channel coefficients of h_1, h_2, and h_3. In the meantime, SR is idle and may even not recognize the presence of PU1 and PU2 as spectrum sharing is managed between the primary system and ST. Hence, the signal y_{ST} received at ST in Phase-one can be depicted as

$$y_{ST} = \sqrt{P_P}\ h_1 x_2 + \sqrt{P_P} h_2 x_1 + z_{ST} \tag{4.1}$$

where x_1 and x_2 are signal messages meant for PU2 and PU1, respectively.

In phase-two, the relay ST uses a small part μPs of its total power Ps to broadcast the mixed primary signals received in Phase-one by using the ANC strategy, as proposed in (S.Katti,et. al.2008) and uses the remaining (1-μ) Ps small part of power to transmit its own message x_3 intended for the secondary user SR with the data rate R_3, where μ (0 < μ < 1) is the power-split factor. Consequently, the signal broadcast by ST in phase-two is given by

$$x_{ST} = \sqrt{\mu Ps}.\frac{y_{ST}}{\beta} + \sqrt{(1-\mu)Ps}.x_3 \tag{4.2}$$

where $\beta = \sqrt{Pp(\omega 1 + \omega 2) + \sigma^2}$, $\omega i = |h_i|^2$, and x_3 is the unit-power information-bearing symbol intended for secondary user SR. β is the normalization factor used to ensure that the transmit power for the superimposed primary signals always equals μP_S. During this second-phase, PU1 first removes self-interference x_2 from the signal transmitted in Phase-one as in normal ANC scheme, then decodes and removes the mutual interference x_3 from the superimposed secondary signal, and finally, decodes its desired signal x_1. The same process occurs for PU2 (Yong Li, et.al. 2014). Starting with the signal y_1 received at PU1 in Phase-two which can be denoted as

$$y_1 = h_1 x_{ST} + z_1 \quad (4.3)$$

$$= \frac{\sqrt{\mu PpPs}\, h_1 h_2}{\sqrt{Pp(\omega 1 + \omega 2) + \sigma^2}} x_1 + \frac{\sqrt{\mu PpPs}\, h_1^2}{\sqrt{Pp(\omega 1 + \omega 2) + \sigma^2}} x_2 + \sqrt{(1-\mu)Ps} h_1 x_3 + \frac{\sqrt{\mu Ps} h_1 z_{ST}}{\sqrt{Pp(\omega 1 + \omega 2) + \sigma^2}} + z_1.$$

Given that x_2 is the symbol sent by PU1 in phase-one and is therefore known perfectly by PU1, this self-interference can be removed from the received signal and the remainder signal Y_1' is written as

$$Y_1' = \frac{\sqrt{\mu P_P P_S} h_1 h_2}{\sqrt{Pp\omega 1 + Pp\omega 2 + \sigma^2}} x_1 + \sqrt{(1-\mu)Ps} h_1 x_3 + \frac{\sqrt{\mu Ps} h_1}{\sqrt{Pp(\omega 1 + \omega 2) + \sigma^2}} z_{ST} + z_1 \quad (4.4)$$

Even though free of the self-interference, the signal Y_1' still contains the mutual interference due to the secondary signal x_3. To obtain the desired information symbol x_1, PU1 may choose between treating the secondary signal x_3 as noise, and decoding x_1 directly; or first decoding x_3, and then, striping this interference off the received signal before decoding x_1. The first strategy is not efficient as it requires allocating the major portion of relay power to forward the primary signals, but merely achieves a rather limited primary data rate of 0.5 bit/s/Hz, and remains only a little power for the secondary transmission (Yong Li et al. 2014).

In this thesis, the second strategy is therefore investigated where PU1 first decodes x_3, and then strip this interference off the received signal before decoding x_1. For this strategy, PU1 can employ a multiuser decoder based on an interference cancelation technique for avoiding the interference from the secondary signal on the primary signals. Primary user PU1, treating its desired signal x_1 as interference, first attempts to decode the undesired secondary signal x_3 (Yong Li et al 2014). The SINR obtained by PU1 to decode x_3 can be given by

$$\gamma_{1,3} = \frac{(1-\mu)\psi_s\omega_1}{\frac{\mu\psi_s\omega_1\left(\psi_p\omega_2 + 1\right)}{\psi_p(\omega_1+\omega_2)+1} + 1} \tag{4.5}$$

where $\psi_S = \frac{P_S}{\sigma^2}$, and $\psi_P = \frac{P_P}{\sigma^2}$ .Therefore, the mutual information achieved at PU1 by overhearing x_3 is given by

$$\tau_{1,3} = \frac{1}{2}\log_2(1+\gamma_{1,3}) \tag{4.6}$$

where the factor $1/2$ describes the fact that two phases are used in the overall transmission. If the instantaneous data rate R_3 of the secondary signal x_3 satisfies

$$R_3 < \tau_{1,3} \tag{4.7}$$

PU1 can successfully decode x_3 and then deduct it from (4.4), thus removing the mutual interference due to the secondary signal. It is worth noting that here, the instantaneous data rate R_3 does not correspond to the maximum achievable data rate of x_3 . R_3 is chosen to be less than the maximum achievable data rate of x_3, which is denoted by $\tau_{3,3}$ in (4.17) below, to guarantee successful decoding of x_3 at both primary users. The final remainder signal Y_1'' observed by PU1 can be represented by

$$Y_1'' = \frac{\sqrt{\mu P_P\,P_S}h_1h_2}{\sqrt{Pp(\omega1+\omega2)+\sigma^2}}x_1 + \frac{\sqrt{\mu P_S}h_1}{\sqrt{Pp(\omega1+\omega2)+\sigma^2}}z_{ST} + z_1 \tag{4.8}$$

It shows that, after removing both the self-interference and the mutual interference, the remainder SNR at PU1 to decode its desired signal x_1 can be given by

$$\gamma_{1,1} = \frac{\mu\psi_P\psi_s\omega_1\omega_2}{\mu\psi_s\omega_1 + \psi_p(\omega_1+\omega_2)+1} \tag{4.9}$$

Therefore, the mutual information (maximum achievable data rate) achieved at PU1 to receive x_1 is given by

$$\tau_{1,1} = \frac{1}{2}log_2(1+\gamma_{1,1}) \tag{4.10}$$

Similarly, the SINR obtained at PU2 to decode x_3 when PU2 first treats its desired signal x_2 as interference, is given by

$$\gamma_{2,3} = \frac{(1-\mu)\psi_s\omega_2}{\frac{\mu\psi_s\omega_2(\psi_p\omega_1+1)}{\psi_p(\omega_1+\omega_2)+1}+1} \tag{4.11}$$

moreover, the mutual information achieved at PU2 by overhearing x_3 is given by

$$\tau_{2,3} = \frac{1}{2}log_2(1+\gamma_{2,3}) \tag{4.12}$$

moreover, therefore if

$$R_3 < \tau_{2,3} \tag{4.13}$$

PU2 can also successfully decode x_3 and then remove this mutual interference. The remainder SNR obtained at PU2 to decode its desired signal x_2 is denoted as

$$\gamma_{2,2} = \frac{\mu\psi_P\psi_s\omega_1\omega_2}{\mu\psi_s\omega_2+\psi_p(\omega_1+\omega_2)+1} \tag{4.14}$$

On the other side, SR decodes its desired secondary signal x_3 by treating the interference from the two primary signals x_1 and x_2 as noise; therefore, the ordinary single-user detection is sufficient for SR to decode x_3, which is not considered computationally expensive during phase-two.

Therefore, signal y_3 received at SR in phase-two can be expressed as

$$y_3 = \sqrt{(1-\mu)P_S}h_3\,x_3 + \frac{\sqrt{\mu P_P\,P_S}h_2h_3}{\beta}\,x_1 + \frac{\sqrt{\mu P_P\,P_S}h_1h_3}{\beta}\,x_2 + \frac{\sqrt{\mu P_S}h_3}{\beta}z_{ST} + z_{SR} \tag{4.15}$$

In this protocol, given that the spectrum sharing is negotiated between the primary system and ST, SR does not know about x_1 or x_2 contrary to the two primary users as explained before. Consequently, the SINR obtained at SR to decode its desired signal x_3, in the presence of the mutual interference from the two primary signals, is given by

$$\gamma_{3,3} = \frac{(1-\mu)P_s\omega_3}{\mu P_s\omega_3+\sigma^2} = \frac{(1-\mu)\psi_s\omega_3}{\mu\psi_s\omega_3+1} \tag{4.16}$$

Moreover, the mutual information (maximum achievable data rate R_3) obtained at SR to decode x_3 is given by

$$\tau_{3,3} = \frac{1}{2}\log_2(1+\gamma_{3,3}) \tag{4.17}$$

Where the factor 1/2 accounts for the fact that the secondary transmission occurs only in one phase. As the mutual information $\tau_{3,3}$ in (4.18) can be interpreted as the maximum achievable data rate for SR to decode x_3 , the instantaneous data rate of x_3 should satisfy

$$R_3 < \tau_{3,3} \tag{4.18}$$

Combining (4.7), (4.13), and (4.18), the instantaneous data rate R_3 at which the relay R can send a secondary message x_3 to SR in phase-two should satisfy

$$R_3 \leq min\{\tau_{1,3}, \tau_{2,3}, \tau_{3,3}\} \tag{4.19}$$

to guarantee that PU1, PU2, and SR can all successfully decode x_3 such that PU1 and PU2 can proceed to remove the mutual interference due to x_3 .

4.1.1. Outage probability for the primary system

An outage event will occur when the maximum instantaneous data rate supported by the transmission link is lower than the target data rate, i.e.

$$\text{Ƥ} = Pr\{\tau < Rpt\}$$

For a given primary target rate Rpt in our scheme, an outage event occurs for primary user PU1 in the case that $\tau_{1,1} < Rpt$. Therefore, the outage probability for the primary user PU1 under the considered two-phase spectrum sharing protocol can be given by

$$\text{Ƥ}_{PU1}^{ANC} = \frac{(2^{2R_{pt}} - 1)\left[\psi_p d_1^n + \left(\psi_p + \mu\psi_s\right) d_2^n\right]}{\mu\psi_s\psi_p} \tag{4.20}$$

Similarly, the outage probability for the primary user PU2 can be obtained as

$$\text{Ƥ}_{PU2}^{ANC} = \frac{(2^{2R_{pt}} - 1)\left[\psi_p d_2^n + \left(\psi_p + \mu\psi_s\right) d_1^n\right]}{\mu\psi_s\psi_p} \tag{4.21}$$

Figure 4.1 shows that the outage probability of the primary system decreases as the power split factor μ increases because, with larger μ, more power of the secondary relay is allocated for forwarding network-coded primary signals. In all figures, $\psi_p = \psi_s$ is used.

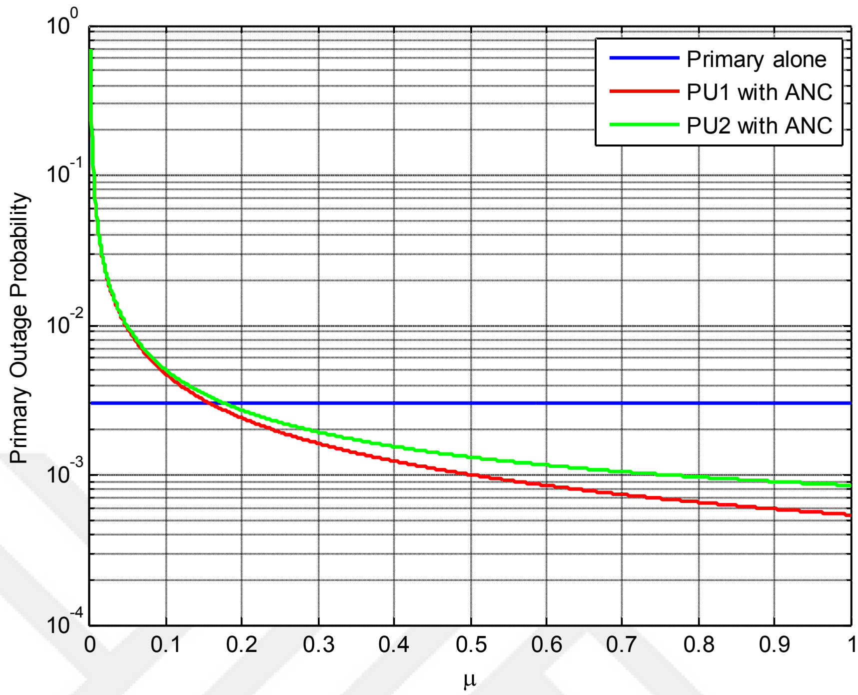

Figure 4.1. Outage probability for primary users with $d_1 = 0.6, d_2 = 0.4, n = 4$ at 30 dB.

It can also be seen that there exist a lower value for μ above which the two-phase ANC can achieve lower outage probability than direct transmission without spectrum sharing which is the coexistence condition in our scenario. The lower value of μ at which the primary user performance is the same as in the case of no cooperation can be found for each primary user as

$$\mu_1 = \frac{\psi_p}{\psi_s} \frac{(2^{2R_{pt}} - 1)[d_1^n + d_2^n]}{\psi_p\left(1 - e^{-\frac{(2^{2R_{pt}} - 1)}{\psi_p}}\right) - (2^{2R_{pt}} - 1)d_2^n} \tag{4.22}$$

$$\mu_2 = \frac{\psi_p}{\psi_s} \frac{(2^{2R_{pt}} - 1)[d_1^n + d_2^n]}{\psi_p\left(1 - e^{-\frac{(2^{2R_{pt}} - 1)}{\psi_p}}\right) - (2^{2R_{pt}} - 1)d_1^n} \tag{4.23}$$

Therefore, in cooperation, to maintain the performance of primary users at least the same as that in the case of primary activity alone, required power split factor must at least be

$$\mu = \max\{\mu_1, \mu_2\} \tag{4.24}$$

from which the lower value of μ is found to be approximately 0.15 for Rpt=1bit/s/Hz. This implies that the two-phase ANC protocol only requires a small portion of power to forward primary signals, and as a result, it can uphold more power for transmitting the secondary messages, therefore improving the performance of the secondary system. Finally, although the interference of the secondary signals on the primary signals can be removed in ANC scheme through successive interference cancelation, the interference from the primary signals on the secondary signal, remains, thus limiting the performance of the secondary signal. In primary system spectrum sharing (i.e., no cooperation with the secondary system) in which direct transmissions between PU1 and PU2 are carried out, the outage probability is given by:

$$\mathrm{P}_{PU1}^{direct} = \mathrm{P}_{PU2}^{direct} = 1 - e^{-\frac{(2^{2R_{pt}}-1)}{\psi_p}} \approx \frac{(2^{2R_{pt}} - 1)}{\psi_p} \tag{4.25}$$

4.1.2. Outage probability for the secondary system

The probability that the maximum allowed data rate R_3 is less than the secondary target data rate Rst at which ST wishes to send secondary messages to SR can be given by

$$\Pr\{\mathrm{R}_3 < \mathrm{R}_{st}\} = \Pr\{\gamma_3 < 2^{2\mathrm{R}_{st}} - 1\}$$

where $\gamma_3 = min\{\gamma_{1,3}, \gamma_{2,3}, \gamma_{3,3}\}$. Since the derivation of the exact pdf of γ_3 is a challenging task, two bounds may be found for the outage probability of secondary user SR as (Yong Li et al. 2014)

$$\begin{cases} P_{SR} = 1, & \frac{1}{2^{2R_{st}}} < \mu < 1 \\ P_{SR} \geq 1 - \exp\left[-\frac{d_3^n(2^{2R_{st}} - 1)}{\psi_s(1 - \mu 2^{2R_{st}})}\right], & 0 < \mu < \left(\frac{1}{2^{2R_{st}}}\right) \\ P_{SR} \leq 1 - \exp\left[-\frac{(d_1^n + d_2^n + d_3^n)(2^{2R_{st}} - 1)}{\psi_s(1 - \mu 2^{2R_{st}})}\right], & 0 < \mu < \left(\frac{1}{2^{2R_{st}}}\right) \end{cases} \quad (4.26)$$

which implies that Rst should not exceed $\frac{1}{2}\log_2\left(\frac{1}{\mu}\right)$ to allow successful secondary transmission (Yong Li et al. 2014). Figure 4.2 illustrates the outage probability for primary and secondary users for various rates of secondary users at 30 dB SNR. A close inspection on the figure reveals that there exist an upper bound on μ for a given secondary target rate above which the secondary transmission is not possible at all (100% outage probability). For instance, the upper bounds of μ are 0.25 and 0.50 for Rst=1bit/s/Hz and Rst=0.5bit/s/Hz, respectively.

The gap between the lower and the upper bound on the outage probability given by (4.26) is clearly observed from the figure for each secondary target rate as a function of power split factor μ. This is because the outage probability, reflecting system performance under the worst case, is dominated by the lower bound of τ_3, which corresponds to the upper bound for the outage probability. It is also noted that, in the cases where d_3 becomes larger, i.e. $d_3 = 1$, and therefore the event that $|h_3|^2$ is the smallest one among $\{h_1, h_2, h_3\}$ has a higher probability, the upper and lower bounds become much closer (Yong Li et al. 2014).

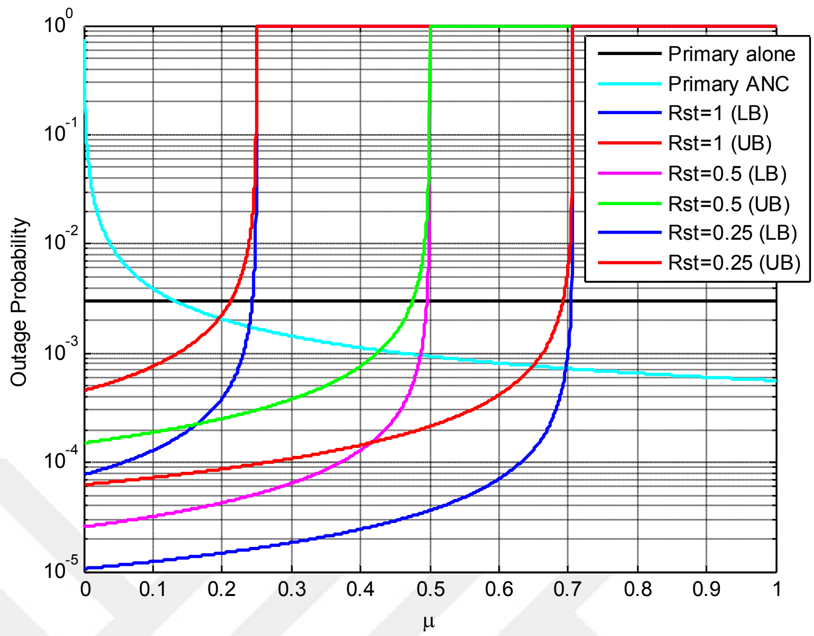

Figure 4.2. Outage probability for the primary and secondary users with $d_1 = d_2 = 0.5$, $d_3 = 0.4$, $n = 4$, and various rates of secondary users at 30 dB SNR.

However, a suitable value of μ should be selected between its lower and upper values to meet system requirements for both users. For instance, in the case of Rst = 1, one should choose $0.15 \leq \mu \leq 0.25$. Otherwise, if $\mu < 0.15$ is chosen, the outage performance of the primary users with spectrum sharing would even be worse than that of direct transmission without spectrum sharing, and therefore, the primary system would not be willing to allow spectrum sharing. On the other hand, if $\mu > 0.25$, the secondary relay node cannot obtain any chance to send its messages at the target data rate and is therefore not motivated to assist the primary system. The main advantage of this ANC protocol is that, as long as μ is adequately selected, lower outage probability can be obtained for the secondary user while at the same time maintaining the quality of the primary users.

To illustrate the effect of the distance between secondary users on the gap between lower and upper bounds of outage probability, Figure 4.3 illustrates the lower and upper bounds of the secondary outage as a function of the split factor for two secondary target rates.

The figure reveals that the gap between lower and upper bounds on the outage probability opens with decreasing secondary user distance.

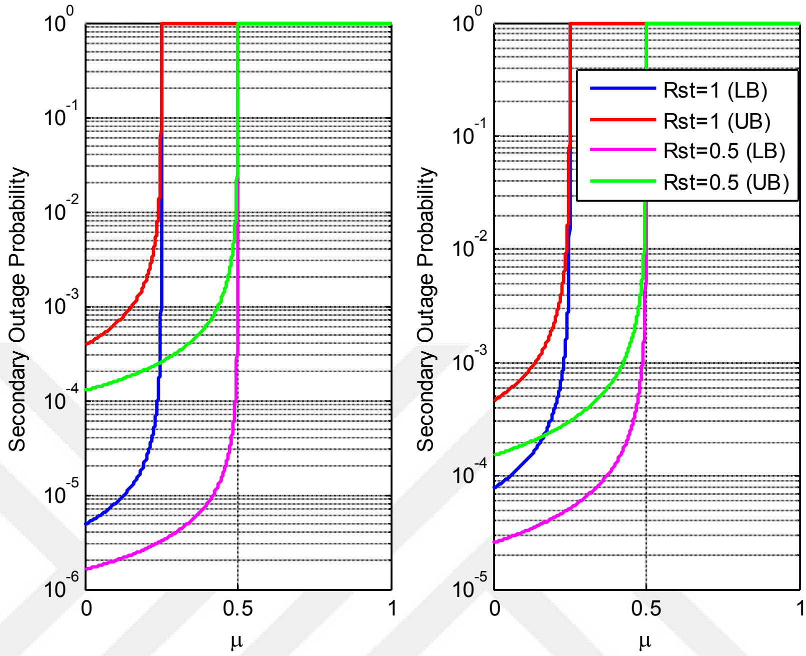

Figure 4.3. Outage probability for the secondary user with $d_1 = d_2 = 0.5, d_3 = 0.2$ (left) $d_3 = 0.4$ (right) for *n*=4.

It would also be interesting to see the influence of path-loss exponents, indicated as *n* in the figures, on the outage probability of secondary users while maintaining the quality of the primary link. Hence, the range of minimum required values of power split factor μ to maintain the quality of the primary link as a function of SNR is shown in Figure 4.4 for various path-loss exponents. It is seen from the figure that higher the degree of the path-loss exponent (higher decay) the less limited the required values power split-factor. Increase on the rate of decay and decrease in the secondary target rate has the same effect on the required value μ. For example, the required value of μ_{min} to maintain the the primary system performance is greater than the maximum usable μ below about 4 dB SNR for *n*=4, implying that the cooperation is not suitable/beneficial for both users below 4 dB. However, this limitation disappears when the path-loss exponent increases or the secondary target rate decreases.

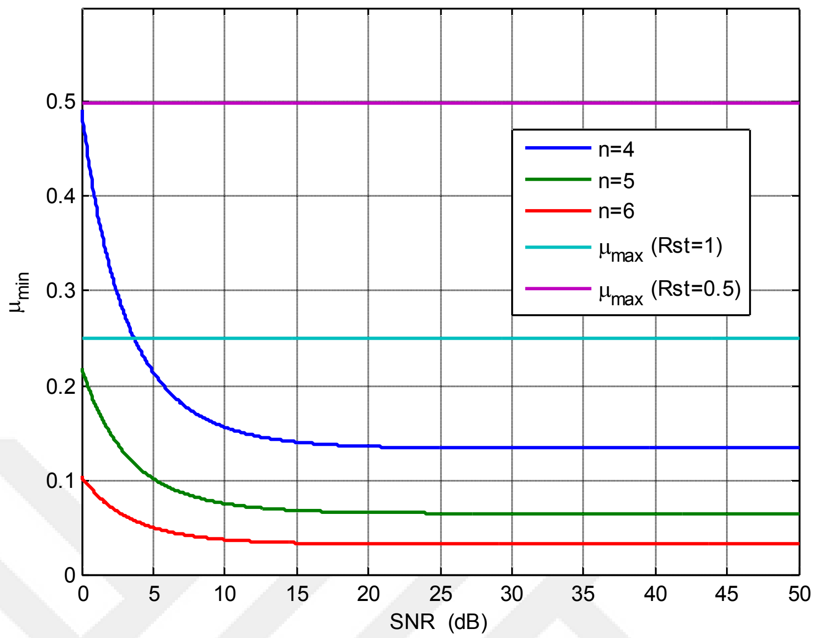

Figure 4.4. Minimum required values of μ to maintain the quality of the primary link for $d_1 = d_2 = 0.5$

The secondary outage probability corresponding to the min required μ (that meets the outage probability of the primary system without cooperation) is illustrated in Figure 4.5 for two values of the secondary target rate. As expected, the outage probability difference between primary and secondary user is greater when the secondary target rate is reduced.

The outage probability for both system at 30 dB SNR as a function of μ is illustrated in Figure 4.6 for various path-losses. It is seen that cooperation is beneficial for both users for the range approximately $0.15 < \mu < 0.5$ for the path-loss exponent n=4 for instance. However, it is explicitly noted that the secondary users can achieve lower outage compared to that of the primary.

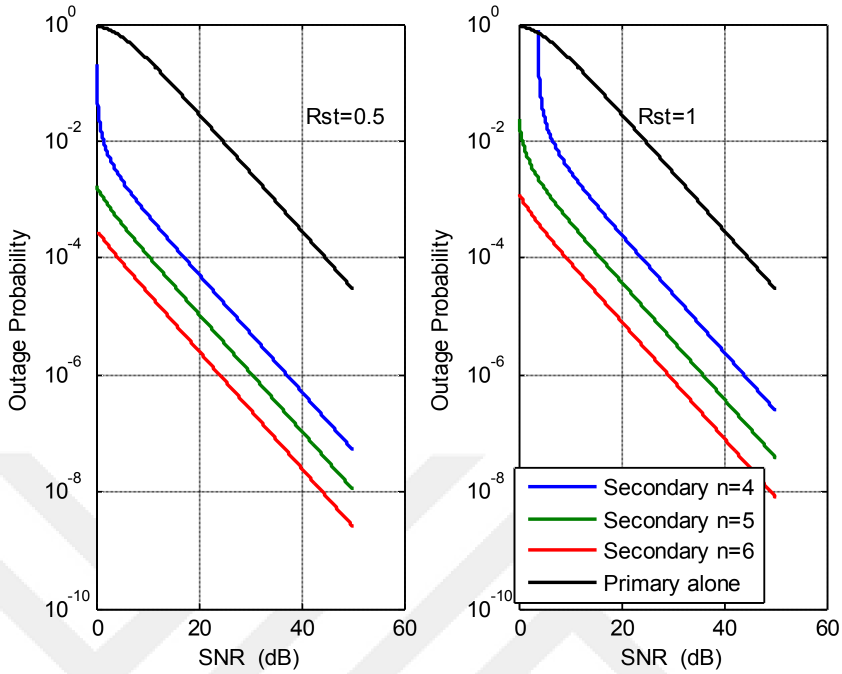

Figure 4.5. Outage probability versus SNR for $d_1 = d_2 = 0.5$, $d_3 = 0.25$

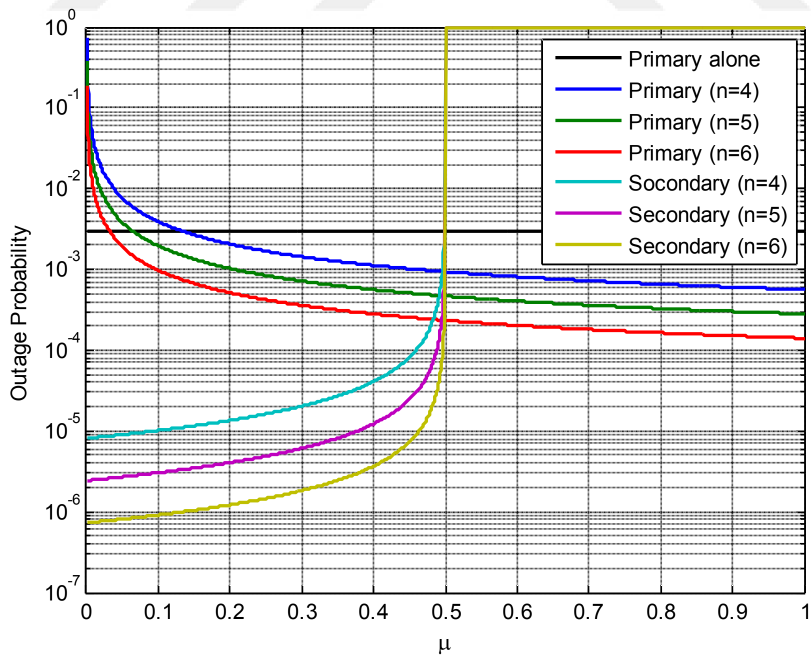

Figure 4.6. Outage probability for the primary and secondary users with $d_1 = d_2 = 0.5$, $d_3 = 0.3, R_{pt} = 1, R_{st} = 0.5$, and various values of attenuation factor n at 30 dB SNR.

By using the extended cognitive channel model as defined in Chapter 3, the secondary outage probability for two different secondary target rate is illustrated in Figure 4.7 compared to its classical counterparts and the primary reference.

In two-state channel settings, as explained above in Chapter 3, secondary users find inactive channels with probability p and communicate until it is required to be freed by primary users, and then communicates through cooperation using ANC with probability (1-p) by splitting its power into two channel states such that the secondary outage probability is minimized. However, power allocated to the channel state-2 for cooperation is again split for relaying the primary message and transmitting secondary data. In Figure 4.7, the outage probability for the classical (one-state) channel and the generalized (two-state) channel is indicated by a superscript (c) and (g), respectively. It is clear that the overall outage probability in a generalized channel is lower compared to that in the classical (one-state) channel.

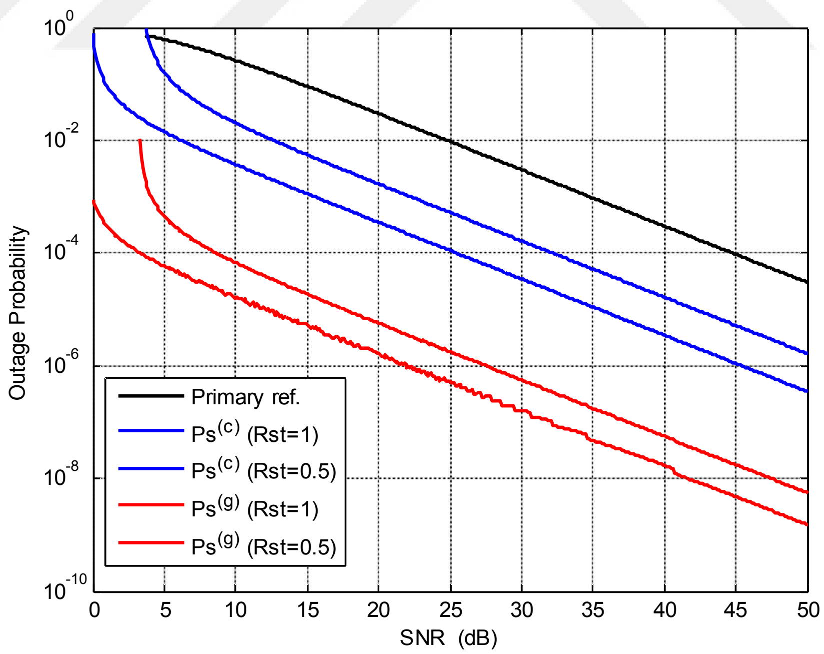

Figure 4.7. Outage probability versus SNR with $d_1 = d_2 = 0.5, d_3 = 0.4,\ n = 4, p = 0.1$

4.2. Coexistence Using ANC with Protocol-2

As seen in Figure 3.3, the only difference from Protocol-1 is that the secondary receiver also overhears primary users. Since the outage probability for the primary users is the same as that in the case of using Protocol-1, the outage probability for only the secondary user is investigated in this section.

In first time slot (or phase), primary users PU1 and PU2 transmit their respective signals concurrently to the relay ST which are also overheard by SR. ST receives the mixed signals from PU1 and PU2, and calculates the appropriate secondary data rate R_4 based on the current channel coefficients of h_1, h_2, h_3, h_4, h_5 and h_6. Therefore, the signals received in the first time slot at ST and SR are given respectively as

$$y_{ST} = \sqrt{P_P}\ h_1 x_2 + \sqrt{P_P} h_2 x_1 + n_{ST} \tag{4.27}$$

$$y_{SR,1} = \sqrt{P_P}\ h_5 x_2 + \sqrt{P_P} h_4 x_1 + n_{SR,1} \tag{4.28}$$

In the second time slot, relay *ST* amplifies and broadcasts the mixture of the primary signals received in the first time slot and its own signal x_s intended for the secondary user *SR*, both of which are linearly combined with μ and 1-μ of the available power at *ST* with appropriate normalization factor $\beta = \sqrt{P_P\ (\Gamma_1 + \Gamma_2) + \sigma^2}$. Here, $\Gamma_i = |h_i|^2$. In the second time slot, the signal received at SR is,

$$y_{SR,2} = h_3\ x_{ST} + n_{SR,2} \tag{4.29}$$

where $x_{ST} = \sqrt{\mu\ Ps}\ \frac{y_{ST}}{\beta} + \sqrt{(1 - \mu\ )Ps}\ x_s$.

$$y_{SR,2} = \sqrt{(1 - \mu)Ps}\ h_3\ x_s + \frac{\sqrt{\mu PpPs}\ h_1 h_3}{\beta} x_2 + \frac{\sqrt{\mu PpPs}\ h_2 h_3}{\beta} x_1 + \frac{\sqrt{\mu Ps}\ h_3}{\beta} n_{ST} + n_{SR,2} \tag{4.30}$$

After the reception of $y_{SR,1}$, SR attempts to decode x_1 and x_2, and stores the decoding results if it succeeds. With the prior knowledge about signals x_1 and x_2 received in first time slot contrary to (Yong Li, et. al, 2014), it can use this information to cancel out the mutual interference from the two primary users received in the second time slot. Therefore, the received signal at SR after interference cancellation in the second time slot is,

$$y'_{SR} = \sqrt{(1-\mu)Ps}\, h_3\, x_s + \frac{\sqrt{\mu Ps}\, h_3}{\beta} n_{ST} + n_{SR,2} \quad (4.31)$$

4.2.1. Outage probability for the secondary users

Outage event occurs at the SR when the target transmission rate R_{st} is not achieved. There are four such cases in which the outage is declared. Outage may occur if SR: is able to decode both of the primary signals x_1 and x_2 (event A), or fails decoding x_1 but decodes x_2 (event B), or succeeds decoding x_1 but unable to decode x_2 (event C), or finally is unable to decode x_1 and x_2 both (event D) in the first-phase of the protocol. However, the events C and D are treated as one event (collapsed into D) with probability $P(D) = 1 - P(A) - P(B)$, since the protocol considers cancellation of interference decoded with higher probability. It is assumed that the quality of the link h_5 is better compared to the link h_4. It is noted that if the signal with the strongest link x_2 is not decoded, primary signals are both treated as noise in the second-phase. Defining Ω as the event that the secondary target rate R_{st} is not achieved, the outage probability for secondary system is

$P_{out}^{s} = \Pr(\Omega|A)\Pr(A) + \Pr(\Omega|B)\Pr(B) + \Pr(\Omega|D)\Pr(D)$ which can be found as,

$$P_{out}^{s} = 1 - [\Pr\{R_5 > R_{pt}\}\Pr\{R_4 > R_{pt}\}\Pr\{R_3^{(1)} > R_{st}\} +$$
$$\Pr\{R_5 > R_{pt}\}\Pr\{R_4 < R_{pt}\}\Pr\{R_3^{(2)} > R_{st}\} +$$
$$(1 - (\Pr\{R_5 > R_{pt}\}\Pr\{R_4 > R_{pt}\} + \Pr\{R_5 > R_{pt}\}\Pr\{R_4 < R_{pt}\}))\Pr\{R_3^{(3)} > R_{st}\}] \quad (4.32)$$

where, R_4 and R_5 are the rates achieved between PU2-SR and PU1-SR link, respectively, and R_3 is the rate at SR in second-phase. R_{st} is defined as the target rate of the secondary system. The maximum achievable rate for the secondary user in the first-phase to decode the message of PU1 x_2 is found as

$$R_5 = \frac{1}{2}\log_2\left(1 + \frac{\psi_p|h_5|^2}{\psi_p|h_4|^2 + 1}\right) \tag{4.33}$$

Letting $Z = \frac{\psi_p|h_5|^2}{\psi_p|h_4|^2+1}$, the cumulative distribution function of Z can be obtained as

$$F_Z(z) = 1 - \frac{d_4^n}{d_4^n + d_5^n z} e^{-d_5^n z} \tag{4.34}$$

Then, the probability $\Pr\{R_5 > R_{pt}\}$ can be found as

$$\Pr\{R_5 > R_{pt}\} = \Pr\{Z > \rho_p\} = 1 - F_Z(\rho_p) = \frac{d_4^n}{d_4^n + d_5^n \rho_p} e^{-d_5^n \rho_p} \tag{4.35}$$

where $\rho_p = 2^{2R_{pt}} - 1$. Upon the successful decoding of x_2 and its cancellation from the received signal, the maximum rate achievable in decoding x_1 is found as

$$R_4 = \frac{1}{2}\log_2(1 + \psi_p|h_4|^2) \tag{4.36}$$

Likewise, the probability $\Pr\{R_4 > R_{pt}\}$ can be found as

$$\Pr\{R_4 > R_{pt}\} = e^{-\frac{d_4^n \rho_p}{\psi_p}} \tag{4.37}$$

Probability of successful decoding both primary signals x_1 and x_2 is then

$$\Pr\{R_5 > R_{pt}\}\Pr\{R_4 > R_{pt}\} = \frac{d_4^n}{d_4^n + d_5^n \rho_p} e^{-\left(d_5^n + \frac{d_4^n}{\psi_p}\right)\rho_p} \tag{4.38}$$

Then the remaining probabilities are then

$$\Pr\{R_5 > R_{pt}\}\Pr\{R_4 < R_{pt}\} = \frac{d_4^n}{d_4^n + d_5^n \rho_p} e^{-d_5^n \rho_p} \left(1 - e^{-\frac{d_4^n \rho_p}{\psi_p}}\right) \tag{4.39}$$

However, the computation of the probabilities $\Pr\left\{R_3^{(i)} > R_{st}\right\}, i = 1,\ 2, 3$, in (4.32) is different for each *i*, since the value of R_3 varies depending on the cancellation of the primary signals differing in each case. The signal to noise plus interference ratios for the SR at the end of phase-two

$$\gamma_{3,3}^{(1)} = \frac{(1-\mu)\psi_s\omega_3}{\frac{\mu\,\psi_s\omega_3}{\psi_p(\omega_1+\omega_2)+1}+1} \tag{4.40}$$

$$\gamma_{3,3}^{(2)} = \frac{(1-\mu)\psi_s\omega_3}{\frac{\mu\,\psi_s\omega_3(\psi_p\omega_2+1)}{\psi_p(\omega_1+\omega_2)+1}+1} \tag{4.41}$$

$$\gamma_{3,3}^{(3)} = \frac{(1-\mu)\psi_s\omega_3}{\mu\,\psi_s\omega_3+1} \tag{4.42}$$

Then for each case, the achievable rates are then

$$R_3^{(i)} = \frac{1}{2}\log_2(1+\gamma_i), \quad i = 1,2,3 \tag{4.43}$$

where $\gamma_i = min\left\{\gamma_{1,3}, \gamma_{2,3}, \gamma_{3,3}^{(i)}\right\}$. Here, $\gamma_{1,3}, \gamma_{2,3}$ are the equations in (4.5) and (4.11), respectively. Then, $\Pr\{R_3 > R_{st}\}$ for each line of (4.32) is found as

$$\Pr\left\{R_3^{(i)} > R_{st}\right\} = \Pr\{\gamma_i > 2^{2R_{st}}-1\} = 1 - F_{\gamma_i}(2^{2R_{st}}-1) \tag{4.44}$$

However, as it is challenging to find pdf of γ_i, outage probabilities for the secondary system is analysed though simulation. Figure 4.8 and Figure 4.9, in the first of which the SR nearer to the PU1 compared to that in Figure 4.9, illustrates the outage probabilities of the secondary users for both protocols in comparison with that of primary users as a function of the power split factor. It is observed that there is no noticeable difference between the outage probabilities of secondary users especially in the region of practical importance (μ<0.5) for both protocols, at a fixed SNR. It would also be interesting to see if there exist any significant difference on outage probabilities over a range of SNR values. The outage probabilities are illustrated in Figures 4.10 and 4.11. Again no significant difference is seen in both figures. It is interesting that decoding by SR in the first-phase, and using it in the second-phase to cancel interference does not help reducing its outage probability.

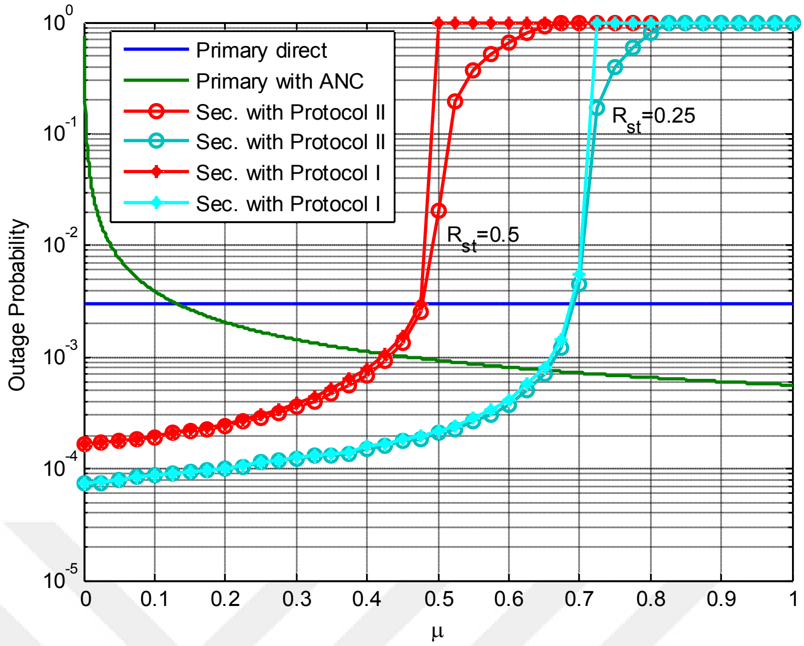

Figure 4.8. Outage probabilities for the primary and secondary users with $d_1 = d_2 = 0.5$, $d_3 = 0.4$, $n = 4$, $R_{pt} = 1$, $R_{st} = 0.5$, and $R_{st} = 0.25$ at 30 dB SNR.

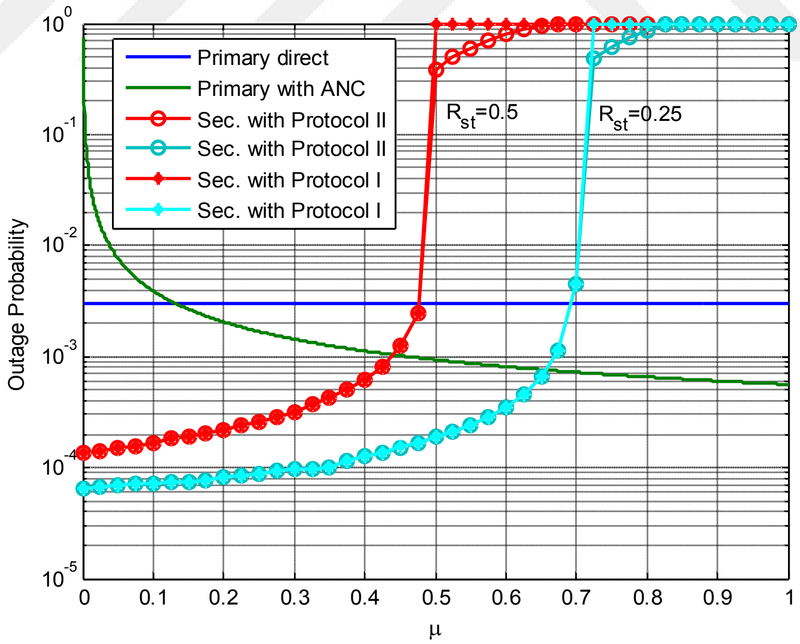

Figure 4.9. Outage probabilities for the primary and secondary users with $d_1 = d_2 = 0.5$, $d_3 = 0.1$, $n = 4$, $R_{pt} = 1$, $R_{st} = 0.5$, and $R_{st} = 0.25$ at 30 dB SNR.

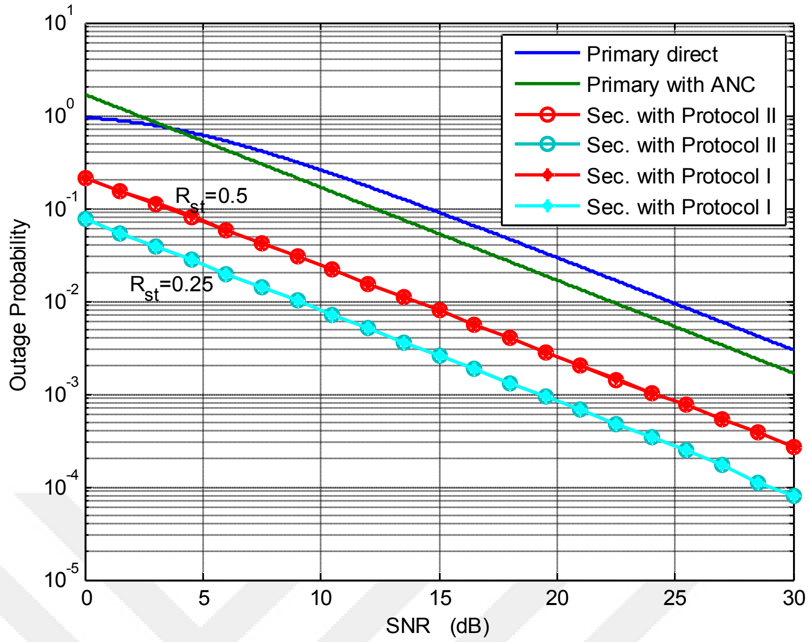

Figure 4.10. Outage probability versus SNR with $d_1 = d_2 = 0.5, d_3 = 0.1,\ n = 4,\ \mu = 0.25$.

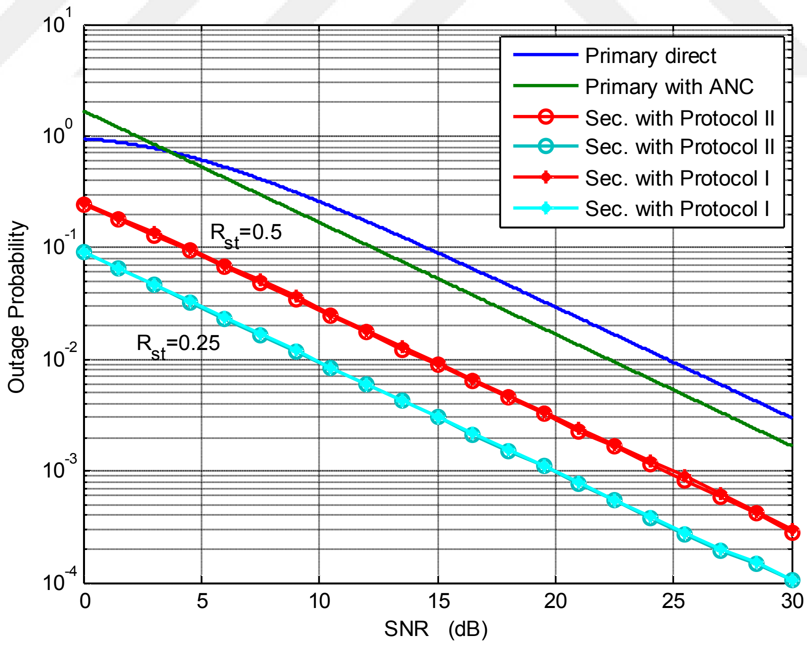

Figure 4.11. Outage probability versus SNR with $d_1 = d_2 = 0.5, d_3 = 0.4,\ n = 4,\ \ \mu = 0.25$.

5. CONCLUSION

In this thesis, the use of analog network coding for the spectral coexistence of primary and secondary users in flat Rayleigh fading through cooperative amplify and forward two-way relaying has been investigated, assuming 2x2 overlay all SISO radio network. The system has been analysed in terms of outage probabilities under two scenarios. Assuming cognitive spectrum sensing, outage probability has also been obtained for the secondary users by generalizing the transmission to the case in which spectrum holes may also be available with some probability. In this way, outage probability for the secondary users improves. It has been found that there is no noticeable difference between the outage probabilities of secondary users under the two transmission protocols considered.

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