### OUTAGE PERFORMANCE OF COOPERATIVE COGNITIVE RELAY NETWORKS

By Nusrat Ahmed Surobhi

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### VICTORIA UNIVERSITY School of Engineering and Science

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Signature of Author:

Nusrat Ahmed Surobhi

### VICTORIA UNIVERSITY

Date: September 2009

Author:	Nusrat Ahmed Surobhi	
Title:	Outage Performance of Cooperative Cognitive	
	Relay Networks	
Department:	School of Engineering and S	cience
Degree:	M. Eng. by Research	Year: <b>2010</b>

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### Abstract

This thesis considers the incorporation of cooperative relays into a cognitive radio network. Cognitive radio is a potential solution to the growing scarcity of radio spectrum and the increased demand for wireless services. Cooperative relay networks can help cognitive radios to improve their utilisation by reducing their transmit power. This allows a reduction in their interference footprint and increases their probability of accessing licensed spectrum, improving throughput, and/or coverage. A cognitive relay network model has been analysed to derive the closed-form outage probability expressions for the repetition-based and selection-based protocols. Both decode-and-forward and amplify-and-forward relaying schemes have been employed for these protocols. When the probability of spectrum availability is unity, the cognitive relay behaves as a conventional cooperative relay. An identical and independently distributed slow fading Rayleigh channel model has been assumed in the analysis. The outage probability expressions are valid for arbitrary signal-tonoise ratios. This is an improvement on the previously published work which was limited to high signal-to-noise ratio regimes.

The derived expressions are generic and validated by simulations for a specified scenario. If the probability of spectrum availability is 0.7, then the introduction of cognitive relay gains more than 5 dB equivalent signal-to-noise ratio improvement over the non-relay case. A further gain of up to 12 dB is possible if the probability of spectrum availability increases to unity. Selection-based relaying scheme outperformed the repetition-based relaying scheme.

The simulation results exactly match the analytical results for the decode-andforward relaying scheme. However, for the amplify-and-forward relaying scheme, the simulation results are a tight upper bound at low signal-to-noise ratios (0 dB-10 dB) and match exactly at medium to high signal-to-noise ratios.

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### List of Publications

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# Acronyms

Acronyms	Definition
3G	third generation
4G	fourth generation
AC	alternating current
ACMA	australian communication and media authority
AF	amplify-and-forward
AM	amplitude modulated
AWGN	additive white gaussian noise
BPSK	binary phase shift keying
CDF	cumulative density function
CDMA	code division multiple access
CROWNCOM	conference on cognitive radio oriented wireless networks
	and communications
CSI	channel state information
DF	decode-and-forward
DySPAN	dynamic spectrum access networks
e2e	end-to-end
EGC	equal gain combining
FCC	federal communication commission
$\mathrm{FM}$	frequency modulated
GSM	global system for mobile communication
IEEE	institute of electrical and electronics engineers
MAC	media access control

MIMO	multiple input multiple output
MQAM	multilevel quadrature amplitude modulation
MRC	maximal ratio combining
MGF	moment generating function
NOI	notice of inquiry
NPRM	notice of proposed rule making
OFDMA	orthogonal frequency division multiple access
PDA	personal digital assistant
PDF	probability density function
PSD	power spectral density
QoS	quality of service
QPSK	quadrature phase shift keying
$\operatorname{RF}$	radio frequency
R-D	relay-destination
RV	random variable
$\mathbf{SC}$	selection combining
SC-FDMA	single carrier-frequency division multiple access
SNR	signal-to-noise ratio
S-R-D	source-relay-destination
S-R	source-relay
TDMA	time division multiple access

$\mathrm{TV}$	tele-vision
UHF	ultra high frequency
VHF	very high frequency
WRAN	wireless regional area networks
WWW	world wide web

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# Chapter 1 Introduction

### 1.1 Cognitive Radios

The wireless communications have witnessed a revolutionary rise in applications and consumers over the past few years. The demand for inexpensive but high speed data services, such as wireless Internet access with rich video content has driven the wireless communications towards high quality and high speed wireless communication services. Due to the 'any time in any where' flexibility of the wireless communications, the consumer demands are growing exponentially resulting in an increase in the demand for the radio spectrum [1].

The evolution of high quality and high speed wireless communications has expanded the demands for radio spectrum at a phenomenal rate [2]. This is why most of the frequencies have already been allocated and the bandwidth has become very expensive. Hence, radio spectrum has become the most valuable and limited natural resource in wireless communication. Moreover, with the emergence of a large number of new applications (a summary of the applications is presented in Table 1.1) [3], the compelling need for wireless Internet access and high speed data network, the demand for radio spectrum is expected to grow even more in the upcoming years.

Due to the inadequate radio spectrum and growing demands, accommodating new applications and users in the radio spectrum band has become a challenging problem for regulatory bodies. The reason behind this inadequacy is not only due

Frequency bands	Applications	
$3 - 30 \; {\rm Hz}$	submarine communications	
30 - 300  Hz	AC power grids $(50-60 \text{ Hz})$	
300 - 3000  Hz	Mine communications	
3-30 KHz	Ultra sound applications	
30 - 300  KHz	AM radio	
300 - 3000  KHz	Aviation	
3-30 MHz	Short wave radio, sky wave propagation	
30 - 300  MHz	FM radio, Television broadcast	
300 – 3000 MHz	Television broadcast	
$3-30 \mathrm{~GHz}$	Wireless networking, Satellite communications	
30 - 300  GHz	Satellite communications, Advanced weapon systems	

Table 1.1: Accommodated applications in different frequency bands [3].

to the growing demand for it, but also due to the conventional spectrum allocation methods. In the conventional spectrum allocation, the radio spectrum is divided into channels and licensed to the telecommunication providers, Internet providers, corporations and individuals as primary users [2]. Licensing of the radio spectrum is done by the government regulatory bodies (i.e, Federal Communication Commission (FCC) in the United States, Ofcom in the United Kingdom and Australian Communications and Media Authority (ACMA) in Australia and in many other countries in a similar way), which prohibits unlicensed applications or consumers to use that spectrum band. Figure 1.1 presents the current radio spectrum allocation chart of Australia by ACMA updated in January, 2009. It is noticed in the Figure 1.1 that the only two unallocated spectrum bands are found from 3 KHz to 9 KHz and from 275 GHz to 300 GHz [4]. It is anticipated that more applications and users will demand these 'congested' spectrum bands. Although there are minute differences, this scenario is more or less similar for other countries as well.

Surprisingly, practical measurements have shown that most of these licensed channels used by the primary users do not transmit most of the time. The Figure 1.2 shows a snapshot of the utilization in the frequency band (1 MHz to 1 GHz)



Figure 1.1: Allocation of radio spectrum, Australia.



Figure 1.2: Utilization of radio spectrum in Melbourne, Australia.

measured at the Victoria University in Melbourne, Australia. The measurement in Figure 1.2 shows that most of the frequency band remained unutilized (in blue) at the time of observation.

This underutilization, coupled with high demand from other potential users, is creating an insufficient use of the available radio spectrum [5]. Reducing the width of the spectrum guard band to minimum can be a rudimentary solution to vacate new spaces in the spectrum band for primary users. A guard band is an unused band between the radio spectrum bands to avoid interference in conventional spectrum allocation. The minimum width of the guard band should guarantee the least interference to the radio spectrum bands. Hence, there is an upper limit of users that can be fitted into a given guard bandwidth. In the Figure 1.3, a new primary user has been accommodated by reducing the guard band. The propagation characteristics also determine the finite frequencies in the radio spectrum bands that can be allocated to a specific application and user.

Also, many more radio spectrum users could be accommodated if the unutilized radio spectra (i.e, in 300-500 MHz and 600-900 MHz in Figure 1.2) licensed to the primary user were utilized under spatio/temporal opportunities [6]. Such a wireless technology named 'cognitive radio' has been recently proposed by Mitola [7].



Figure 1.3: Guard band utilization to accommodate new applications and users.

'Cognitive radio' is a wireless technology that can be employed to sense, recognize and utilize the unutilized radio spectrum wisely at a given time [8]. The main characteristic of a cognitive radio is its inherent intelligence that allows sensing all possible radio spectra before it makes an intelligent decision on how and when to make use of a particular sector of the spectrum for communications. The additional radio spectra users are named as cognitive users [9].

A discussion on cognitive radio and FCC's initiatives and efforts to promote it for wireless communication applications will be presented in the following subsections. Also, a broad classification, characteristics and functions of cognitive radio will be discussed.

### 1.1.1 Background on Cognitive Radio

Cellular systems, wireless local area systems, satellite systems, paging systems, bluetooth, ultra wideband systems, *ZigBee* systems and many more wireless applications have initiated an exponential growth in wireless communications. The multi-media based applications introduced by the Internet and the world wide web (WWW) have made wireless communications extensively popular. At present, wireless communication is moving forward to the fourth generation (4G, is also popularly known as the

Parameter	3G	4G
Frequency bands	$1.8 - 2.5 \mathrm{GHz}$	2-8  GHz
Data rate	Up to 2 Mbps (384 kbps deployed)	Up to 100 Mbps
Technologies	CDMA	OFDMA(uplink) and SC-
		FDMA(downlink)
Network capacity	Less number of simultaneous users	Higher number of simulta-
		neous users
Radio interfaces	Fixed radio interfaces	Adaptive radio interfaces

Table 1.2: A comparison between 3G and 4G wireless communication.

next generation). These 4G systems are expected to replace the existing third generation (3G) wireless communications and will provide complete and secure voice, data and streamed multi-media applications.

The Table 1.2 presents a comparison between 3G and 4G wireless communication in terms of frequency bands, data rate, available technologies etc. The table shows the expected frequency bands and data rate for the 4G wireless communication is much higher than the 3G wireless communication [3]. Providing the required frequency bands and data rate to the 4G wireless communication has become challenging due to the adopted conventional spectrum allocation methods. The dictated government policies on the licensed spectrum bands makes the task even more complicated. However, the scarcity of the radio spectrum has been found artificial because practical measurements have shown that the spectrum remains unutilized at most times. Hence, to optimize the demand for the radio spectrum and utilize the unutilized licensed spectrum, cognitive radio was proposed by Mitola [10].

Mitola's definition of cognitive radio is [10]:

"The term cognitive radio identifies the point at which wireless personal digital assistants (PDAs) and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to:

• (a) detect user communications needs as a function of use context, and



Quantized channel capacity

Figure 1.4: Haykin's model of a cognitive radio.

• (b) to provide radio resources and wireless services most appropriate to those needs."

This definition of cognitive radio considers a high level of awareness to employ intelligence in the choice of the radio spectrum band, air interface, or protocol to higher-level tasks of planning, learning, and evolving new upper layer protocols [8].

Later, Haykin in [9] described the cognitive radio as an intelligent wireless communication system that is aware of its surrounding environment. He also mentioned two primary objectives of cognitive radio, namely:

- highly reliable in communication wherever and whenever needed.
- efficient in utilizing the radio spectrum.

The basic model of cognitive radio as described in [9] is presented in Figure 1.4. In this model, the cognitive radio:

• observes the radio environment (i.e., outside world) on a continuous time basis to analyse the environment by empowering all users' receivers.

- learns from the environment and adapts the performance of each transceiver to statistical variations in the incoming radio frequency (RF) stimuli.
- estimates the channel and predicts the network model to facilitate the transmission.
- controls the transmit power and manages the spectrum (i.e, through spectrum hole detection) and allocates allows the transmission.

Another popular definition of cognitive radio from FCC is [11]:

"A cognitive radio is a radio that can change its transmitter parameters (i.e, transmit power) based on interaction with the environment in which it operates." The cognitive radio also allows the cognitive users to share the spectrum on an opportunistic basis. So, in 2004 FCC defined the cognitive radio as a device that can borrow the licensed spectrum when required without generating harmful interference to the licensed users [12].

All the above definitions of cognitive radio share three major common points:

- Sensing for available unoccupied primary spectrum bands intelligently.
- Allowing the cognitive users to use those bands efficiently.
- Causing no/minimum interference to the primary user.

Hence, a cognitive radio intelligently learns the environment to sense the available unoccupied radio spectrum bands, adapts the environment to allow transmission and does not create harmful interference to the primary users.

The research on cognitive radio is still in its infancy. But, it has attracted significant interest of both academia and industry since it has been introduced in 1999 [13]. This can be observed from the increasing number of publications, IEEE conferences specially on the cognitive radio (i.e., DySPAN, CROWNCOM), number of special issues of journals and etc.

In 2002, FCC's spectrum policy report on licensed spectrum utilization triggered the following questions:

- (i) how to open up the unutilized spectrum?
- (ii) should the spectrum be licensed or unlicensed?

In the same year, FCC stated in a notice of inquiry (NOI) named 'Additional spectrum for unlicensed devices below 900 MHz and in the 3 GHz' [14, 15] that an unlicensed device can only transmit if it can identify an unutilized frequency band. This NOI also considered the possibility of sharing TV bands with the unlicensed users.

In 2003, FCC introduced an interference temperature model in another NOI and in a notice of proposed rule making (NPRM) named 'Establishment of an interference temperature metric'. Interference temperature metric quantifies and manages the upper bound of the interference caused to the primary users by the unlicensed devices [16]. FCC issued another NPRM named 'Facilitating opportunities for flexible, efficient and reliable spectrum use employing cognitive radio technologies' in the same year in which FCC intended to promote an advanced technology for wireless communication. The cognitive radio offered to be that possible advanced technology by providing a more intelligent system for allocating spectrum that can dramatically increase the amount of available spectrum. In this NPRM FCC proposed that TV channels 5–13 in the VHF band and 14–51 in the UHF band could be used for fixed broadband access systems.

The standardization of the cognitive radio was carried by the IEEE in parallel with the FCC. Sevension in 2004 prepared a document named 'In reply to comments of IEEE 802.18' which indicated that IEEE 802.18 supports the opportunistic use of the licensed spectrum bands on a non-interfering basis [17]. Recently Carl. R. Sevension overviewed the newly developed IEEE 802.22 (wireless regional area networks) WRAN standard [18]. IEEE 802.22 WRANs are designed to operate in the TV broadcast bands while ensuring that no harmful interference is caused to the

incumbent operation (i.e., digital TV and analog TV broadcasting) and low-power licensed devices such as wireless microphones.

#### 1.1.2 Classifications and Characteristics

The cognitive radio can be classified based on different parameters (part of spectrum band in use, interference etc). The chart in Figure 1.5 presents a summary of the classifications of cognitive radio. Depending on the utilization of the spectrum band, the cognitive radio can be broadly classified as:

- Ideal cognitive radio: The ideal cognitive radio [10] is considered as a 'genie'. It knows the operating parameters of all radios in its environment and can make a fully informed decision on how to make the best use of any unutilized spectrum bands. This is a hypothetical scenario but it helps in understanding the theme and operation of cognitive radio.
- Spectrum sensing cognitive radio: Spectrum sensing cognitive radio is a special case of the ideal cognitive radio. Such a cognitive radio just observes primary spectrum bands before the transmission [12]. Spectrum sensing cognitive radio seems to be more realistic than ideal cognitive radio.

Based on the parts of the spectrum available for access, the cognitive radio system can be divided into:

- Licensed band cognitive radio: A cognitive radio system capable of using the spectrum bands assigned to the licensed users is called a licensed band cognitive radio system [19].
- Unlicensed band cognitive radio: An unlicensed cognitive radio is allowed to use only the unlicensed part of the spectrum bands [20].

Depending on overlay or underlay approach employed during transmission cognitive radio can be classified as:



Figure 1.5: Classification of a cognitive radio [10, 12, 19, 20, 21, 26].

• Overlay approach [21]: The overlay approach (Figure 1.6) is also known as the interference free approach [22], in which once the spectrum hole is detected, the cognitive users access part of the unoccupied spectrum to transmit their information with virtually no interference to the primary users. The cognitive user can use part of their power for its communication and the remainder of the power to assist primary user's transmission.

This approach has the advantage of not interfering with the primary transmission. However, the major disadvantage of this approach is that the cognitive users are required to sense the spectrum before transmission. Also, cognitive users need to be synchronized with the existing primary users' band.

• Underlay approach [21]: The underlay or interference tolerant approach [22] (Figure 1.7) implements a wideband system. The cognitive users use the radio spectrum at the same time with the primary user possibly employing power allocation or frequency spreading techniques [23]. Hence, the cognitive users

Power density



Figure 1.6: Overlay approach of cognitive radio.

must transmit with low transmit power to operate below the noise floor of the primary users ensuring a tolerable interference to the primary users.

Underlay approach enjoys the flexibility of transmission at any time and doesn't need to be synchronized with the primary users' band. However, the interference power constraints associated with this approach allow only short range communications.

A cognitive radio has the following characteristics which distinguishes it from other wireless communication technologies :

- Flexibility: The ability to change the waveform and configuration of a device [9] is known as flexibility. For an example, a cell tower may operate in the cell band for telephony purposes, but it may change its waveform to get the telemetry during the off-peak. Hence, the same band is flexible enough to be used in two different roles.
- Agility: Agility is the ability of changing the spectrum band in which a device will operate [12]. In the global system for mobile (GSM) communications, mobile phones show their agility in the GSM spectrum bands by operating in two or more bands (i.e, 900 MHz, 1700 MHz and 1900 MHz).

Power density



Figure 1.7: Underlay approach of cognitive radio.

Flexibility and agility together characterize the cognitive radio to be 'adaptive'. This means the cognitive radio can use different waveforms in different bands.

- Perceiving: The ability to observe the state of the existing system including the spectrum bands and the environment [5, 9, 24] makes cognitive radio perceiving. Thus, it allows dynamics in the cognitive radio.
- Networking: Networking is the ability of communicating among multiple cognitive nodes [2]. Thus, it allows the combined sensing and controlling capacity of those nodes. The wireless networking allows the interaction among the group of cognitive radios. These interactions can be useful for sensing an unused spectrum band.

The cognitive radio allows the implementation of the above mentioned characteristics in an environment through the following functions (presented in Figure 1.8 [25, 26]):

• Spectrum sensing: The fundamental challenge of the cognitive radio is to sense the presence/absence of spectrum holes efficiently [21]. Spectrum sensing can be further divided into the following three categories:



Figure 1.8: Functions of a cognitive radio [7, 21, 25, 26].

- Primary signal sensing: A cognitive radio may use any of the following approaches to sense the primary user's signal:
  - \* Energy detection [27].
  - \* Matched filter detection [28].
  - \* Cyclostationary feature detection [29].
- Cooperative sensing: Multiple cognitive users may sense the spectrum hole cooperatively by exchanging their information [28, 30]. Cooperative sensing may use any of the following approaches to sense the spectrum hole:
  - \* Figure 1.9 (a) presents cooperative sensing employing a relay to assist the source-to-destination transmission when the source-to-destination link is under fading/shadowing effects.
  - \* A number of relays in the neighbourhood of the transmitting relay



Figure 1.9: Cooperative sensing approaches.

presented in the Figure 1.9 (b) can sense the spectrum cooperatively for its transmission.

- Interference based detection: Only those spectrum bands are sensed which will create no or minimum interference to the primary user, if they are accessed [26].
- Spectrum management: If more than one spectrum hole is detected in the desired frequency band, the cognitive radio analyses the available radio spectrum bands. Then, it chooses the best frequency among the spectrum bands to ensure the quality of service according to the user's requirements.
- Spectrum mobility: The process of changing of the operational frequency of cognitive radio is called spectrum mobility [7]. Mobility enables the cognitive radio to use the spectrum bands in a dynamic manner by allowing the use of the best available frequency band.
- Spectrum sharing: As the spectrum hole is detected, cognitive radio can share the part of the spectrum bands to transmit its own information. Cognitive radio allows spectrum sharing employing overlay or underlay approach. A dynamic spectrum sharing is employed through the spectrum mobility.

### 1.1.3 Application Areas

A major driving force of any technology is to meet end users' demands. A chart in Figure 1.10 summarizes the broad classifications of cognitive radio applications. The application of cognitive radio can be broadly classified into the following two groups [31]:

- Existing applications where cognitive radio can offer partial or full improvement in the performance.
- New applications where cognitive radio can be beneficial.

Both of the groups may further be classified into four areas of cognitive radio applications as follows :

- Wireless resource optimization applications.
- Communication quality enhancing applications.
- Interoperability enabling applications.
- Service specific applications.

Resource optimization and quality enhancement of wireless applications can be discussed together. Based on the network demands and applications, the cognitive radio can intelligently decide to adapt the more appropriate network protocol. Hence, it optimizes the network resources. While deciding the network protocol, the cognitive radio also reconfigures the network in terms of network capacity to improve the quality of service (QoS) [31].

Interoperability [31] enables the intelligence into the wireless communication applications. An immediate application of the cognitive radio interoperability can be found in military applications. In other application areas, such as in consumer applications, cognitive radio can offer interoperability to the licensed, unlicensed, and semi-licensed spectrum [32] services over diverse networks.



Figure 1.10: Classification of cognitive radio applications after [31].

The service specific applications of cognitive radio technology may include the mobile phones, laptop and fax machine etc [31]. The cognitive radio can help in establishment of a remote home office. This may be helpful in reducing traffic on roads during office hours, office resources and international travel expenses through remote conferencing. The cognitive radio may identify the unutilized spectrum bands from distant places to avoid the congestion of the wireless network at high traffic hours [31]. Cognitive radio can be helpful in realization of the emerging femtocell technology. Femtocell technology can be deployed through cognitive radio to provide a low-cost, low-power (underlay approach) medium of network coverage extension. The cognitive radio can also be implemented in bio-medical applications, traffic controlling, weather fore-casting and many other service specific applications. The IEEE 802.22 standard [18] has proposed the employment of cognitive radio in bringing broadband access to rural areas.
# 1.2 Challenges of Cognitive Radio

The main two challenges to the success of cognitive radio include the primary user detection and the transmission opportunity exploitation [33]. Detection of a primary user actually leads to the detection of a spectrum hole. A spectrum hole is an unoccupied spectrum band which is licensed to the primary user. In the literature, spectrum hole detection is known as the 'spectrum sensing'. The cognitive users can exploit the opportunity of transmission to improve their performance through either overlay approach or underlay approach.

Regardless of the approach employed by the cognitive radio, the inherited fading phenomena of the wireless channels [34], limits the service reliability and coverage of the wireless communication services.

#### 1.2.1 A Potential Solution 'Cooperative Relaying'

A more recent technique named cooperative diversity, exploited by a relay network, has been investigated as an efficient solution to cope with the challenges of the cognitive radio [24, 35]. In a cooperative relay network, the source broadcasts its information via one or a number of intermediate relays along with the direct source to destination transmission. The destination combines the received multiple independent copies of the signal and results in cooperative diversity. A cooperative relay network can be beneficial and effective for implementing the cognitive radio in following ways:

• Spectrum sensing: The spectrum availability to the cognitive users is heterogeneous due to the dynamic traffic of the primary users, the location difference among different users and the opportunistic nature of the spectrum access of the cognitive users [26]. A cooperative relay network can be realized in the cognitive radio environment where a cognitive user acts as the relay to sense the unused spectrum cooperatively with other cognitive users to relay the traffic of the primary/cognitive users (source) [35]. Sometimes, the cognitive users may not use their entire available spectrum due to the low traffic demand. In this case, one cognitive user may act as the relay to other cognitive users (source) to assist their transmission.

In both cases, the cooperative relay network increases the probability of detecting an unused spectrum band for the cognitive users resulting in an improvement in service reliability and coverage extension. Hence, a cooperative relay network can be helpful in spectrum sensing both for the primary users and cognitive users.

- Interference tolerance: The cooperative relay network employs the cooperative diversity to combat with the interference [25]. The source can also choose an appropriate relay route to transmit avoiding the interference (overlay approach) or causing the minimum interference (underlay approach) in the cognitive environment. Thus, cognitive users can assure no/minimum interference to the primary user [5].
- Reliability of service: A cooperative relay network can be extremely effective to cope with the fading phenomena of the wireless communications through the cooperative diversity [36]. It also increases the reliability of the service by guaranteeing the transmission even if the source to destination link is under fade. So, the cognitive users can guarantee the transmission under a fading environment.
- Extension of coverage: The cooperative relay network also expands the network coverage by increasing the source to destination travelling distance for the transmitted signal. This way, the cognitive users become more suitable for a long range transmission.

A cooperative relay network depicted in Figure 1.11 shows the increase in the service reliability and expansion of network coverage. Thus, the cooperative relay



Figure 1.11: Service reliability and coverage extension proposed by cooperative relay network.

network efficiently deals with the challenges of the cognitive radio to improve its performance.

In this research, the operation of a cooperative relay network has been investigated in a cognitive radio environment. The network proposed in this research will be referred to as the 'cognitive relay network'. This network considers overlay transmission approach. A cooperative sensing of the spectrum is also considered for this network.

# **1.3** Contributions

The performance of the proposed cognitive relay network has been analysed specifically in terms of the outage probability based on several practical assumptions. The contributions of the research are mainly divided into two main parts:

• This research derives closed-form analytical expressions of outage probability for the cognitive relay network. In most works, the outage probability has been derived for high signal-to-noise (SNR) regions. But practical systems operate from low to medium SNR regions. This research derives the outage probability that is valid for any arbitrary SNR region. At first, repetition-based decodeand-forward (DF) and amplify-and-forward (AF) cognitive relay networks have been investigated for outage probability evaluation. Repetition-based protocols inherit the problem of bandwidth expansion which can be avoided by selection-based protocols (i.e, the relay with the best transmission channel). Closed-form outage probability expressions of selection-based networks have also been derived for DF and AF relaying schemes and compared with those of the repetition-based networks.

Analytical results are validated through the simulations. It has been observed that for DF relaying protocol the analytical and simulation results match exactly for both repetition-based schemes and selection cooperation. The channel end-to-end SNR for AF relaying scheme is difficult to track mathematically. Hence, an approximate yet accurate approach has been considered to analyse the network. So, the analytical results are lower bounds at the low SNR regions (0 - 10 dB) and match exactly for medium to higher SNR regions with the simulation results for both repetition-based and selection cooperation AF relaying protocol. However, the analyses presented in this work provide tight bounds.

The proposed cognitive relay network shows improved performance in terms of outage probability over the traditional cognitive radio. It has been observed that the network performance does not always improve with the increasing number of relays for the repetition-based networks. This is due to the need of additional time slots for the time division operation in the repetition-based networks. A further enhancement in the performance is found for selectionbased networks over repetition-based networks due to the bandwidth advantage. The increased number of relays always improves the performance of a selection-based network. However, the network performance degrades more in selection-based networks than the repetition-based networks when the spectrum is unavailable.

• The cognitive relay considered in this thesis borrows the spectrum from the primary user opportunistically to transmit its information. Hence, the spectrum may always not be available to the cognitive relays. Unavailability of the spectrum degrades the network performance. This thesis analyses the outage probability of a conventional cooperative relay network to set the benchmark performance for comparison with that of the cognitive relay network. An improvement in performance is shown by employing the cooperative sensing [2] through the relays when the spectrum is not available.

# 1.4 Structure of the Thesis

This thesis is organized as follows:

- Chapter 2 introduces the preliminary concepts of the cooperative relay network and cognitive relay network considered in this thesis. It summarizes the existing state of the art work in these areas to provide the background required to understand the rest of the thesis.
- Chapter 3 presents the proposed system models for the DF and AF cognitive relay network with repetition-based protocols. The spectrum acquisition model and cooperative spectrum sensing have been discussed. Statistical analysis has been presented to evaluate the outage probability.
- Chapter 4 explains the selection criteria for relays in the cognitive relay network. The closed-form expressions of the outage probability have been derived to evaluate network performance for both DF and AF relaying schemes. The analytical results have been validated through the simulation results. Also, the outage probability expressions of the selection-based networks have been

compared to that of repetition-based networks for both DF and AF relaying schemes.

• Chapter 5 concludes this thesis and suggests future possible research directions.

# Chapter 2 Background and Literature Survey

This chapter presents the preliminaries and background of the cooperative relay network. Furthermore, it describes the cognitive relay network considered in the rest of the thesis. The statistics required to calculate the outage probability of the proposed network have also been discussed in this chapter.

# 2.1 Cooperative Relay Network

The main goal of the wireless communications has now become to achieve higher data rates with a larger coverage in transmission as the wireless communications approach to the 4G. The conventional peer-to-peer communications suffer from fading and attenuation adversely [34]. Fading/shadowing effect and attenuation in the wireless network limit the transmission rate and coverage. The solution to these shortcomings is the cooperative diversity which can be realized by the cooperative relay communication. This section reviews the background of the cooperative relay network. Network models, relaying schemes and the combining techniques for the cooperative relay network are also discussed.

The cooperative relay network transmits an independent copy of the same signal via a relay to the destination along with the direct source-destination link. In this thesis, the terms 'direct link transmission' and 'source-to-detination transmission' have been used simultaneously implying the same meaning. Multiple relays can be also be employed to transmit multiple independent copies. Hence, for a cooperative



Figure 2.1: Classical and cooperative models of relay networks.

relay network consisting of M relays, the destination receives M + 1 copies of the transmitted signal. This allows the 'cooperative diversity'. The paths where the signal is obtained are sometimes referred in the literature as 'virtual branches' [37]. However, in a classical relay network, the source transmits only via relays. The Figure 2.1 presents a simplified model of the cooperative relay network and the classical relay network.

#### 2.1.1 Background on Cooperative Relay Networks

The cooperative relay network was introduced by the contemporary leading works of Laneman [38], Erkip and Sendonaris [39]. The work on cooperative relay was based on the previous works on classical relay channels. The classical relay channel was originally examined by van der Meulen [40]. Later, Cover and El Gamal [41] analysed certain discrete memory-less classical relay channels with additive white gaussian noise (AWGN) to determine the channel capacity.

Some pioneering contributions on relaying technique include the work of Schein and Gallager [42], Erkip and Sendonaris [39], Gupta and Kumar [43], Gastpar [44] and Reznik [45]. Kramer and Wijngaarden [46] considered a multiple-access relay channel in which the multiple sources communicate to a single destination by sharing a single relay channel. King [47] and Willems [48] also examined multiple-access relay channels. Sendonaris' work [39, 49] introduced multipath fading into the model



Figure 2.2: Single relay network.

presented in [48, 50]. Work in the references [39, 49] present user cooperation diversity through cooperative relay networks. Multiple antenna operations have been also considered in a cooperative relaying environment [51].

#### 2.1.2 Cooperative Relay Network Model

In this section, a simplified model of the cooperative relay network is presented. This model is based on the three terminal model of the classical relay channel. Unlike in the classical relay network, the cooperative relay network additionally consists of a direct-link between source and destination. Firstly, this section will introduce the cooperative relay network consisting of a single relay. Later, a cooperative relay network with multiple relays will be investigated.

• Single relay network: In Figure 2.2, a single relay is assisting the source to transmit its information to the destination along with the direct-link. The source and the relay are assumed to transmit with the power,  $P_s$  and  $P_r$ . The transmission occurs in two phases as has been assumed in previous literature. The phases are assumed to be orthogonal and thus avoid the interference in the transmission.

In phase one, the source transmits its information to the destination and to the relay. The received signals at the destination and the relay are denoted by  $y_{sd}$  and  $y_{sr}$  respectively. They can be mathematically expressed as :

$$y_{sd} = \sqrt{P_s} h_{sd} x + n_{sd} \tag{2.1}$$

$$y_{sr} = \sqrt{P_s} h_{sr} x + n_{sr} \tag{2.2}$$

In (2.1) and (2.2), x is the transmitted symbol drawn out of a modulation scheme such as BPSK, QPSK or MQAM. The average energy of the symbols has been normalized to  $E[|x|^2] = 1$ . The channel coefficients from sourceto-destination, source-to-relay are denoted by  $h_{sd}$  and  $h_{sr}$  respectively. The channel coefficients have been modelled as complex Gaussian random variables (RVs) with zero-mean and variances  $\lambda_{sd}$  and  $\lambda_{sr}$  respectively leading to the well known flat Rayleigh fading channel. The AWGN noise at the source, relays and the destination are given by  $n_{sd}$  and  $n_{sr}$  respectively. The noise terms are modelled as complex Gaussian RVs with zero-mean and single sided power spectral density (psd)  $N_0$ .

In the phase two, the relay processes the signal and forwards to the destination. The received signal at the destination is  $y_{rd}$  and can be expressed as:

$$y_{rd} = \sqrt{P_r} h_{rd} Z(y_{sr}) + n_{rd} \tag{2.3}$$

In (2.3), relay-to-destination channel coefficients are denoted by  $h_{rd}$ . The channel coefficient has been modelled as complex Gaussian random variable (RV) with zero-mean and variance  $\lambda_{rd}$ . The AWGN noise at the destination is  $n_{rd}$ .

In (2.3),  $Z(\cdot)$  depends on the cooperative relaying scheme implemented at the relay. The operation of  $Z(\cdot)$  related to different cooperative relaying schemes will be discussed in more detail later. In phase two, M number of time slots are required to guarantee the orthogonal transmission and the time division multiple access (TDMA) [38]. The relays can not transmit and receive signals



Figure 2.3: Phases of transmission in cooperative relay network.



Figure 2.4: Serial topology of multiple relay network.

simultaneously because of the half-duplex constraint normally assumed in the literature. Half-duplex systems provide two ways for communications but only one way at a time. Hence, the relays just receive the signal from the source in the first phase. In the second phase, only when the source stops transmission, relays transmit the received signal to the destination. Simultaneous transmission to the destination can be employed through frequency division multiple access at the cost of some bandwidth expansion.

- Multiple relay network: A multiple cooperative relay network may have the following topologies:
  - Serial topology [52]: In a serial topology of the multiple cooperative relay network relays are connected in series with each other as presented in Figure 2.4.
  - Parallel topology [52]: The cooperative relay network with parallel topology consists of parallel relay paths as in Figure 2.5.



Figure 2.5: Parallel topology of multiple relay network.



Figure 2.6: Hybrid topology of multiple relay network.

 Hybrid topology [52]: In this topology, the cooperative relay network consists of both serial and parallel relay paths as presented in Figure 2.6.

This thesis considers parallel cooperative relay network (presented in Figure 2.7), in which the source transmits its information to the destination via M number of relays,  $R_i$ , i = 1, 2, ..., M and through the direct-link in the first phase. The received signals at the destination and the i - th relay are denoted by  $y_{sd}$  and  $y_{sr_i}$  respectively. In the second phase, the relays process the received signal from the source and transmit towards the destination. Now, (2.1), (2.2) and (2.3) can be modified for a multiple relay cooperative network as:

$$y_{sd} = \sqrt{P_s} h_{sd} x + n_{sd} \tag{2.4}$$



Figure 2.7: Multiple relay network.

$$y_{sr_i} = \sqrt{P_s} h_{sr_i} x + n_{sr_i} \tag{2.5}$$

$$y_{rd_i} = \sqrt{P_{r_i}} h_{r_i d} Z(y_{sr_i}) + n_{r_i d}$$
(2.6)

The symbols used in (2.4), (2.5) and (2.6) bear the same meaning as in (2.1), (2.2) and (2.3) for i = 1, 2, ..., M.

### 2.1.3 Cooperative Relaying Schemes

Cooperative relaying schemes are generally categorized as follows and presented in Figure 2.10:

- Fixed cooperative relaying schemes: In fixed cooperative relaying schemes, the channel resources are divided in a fixed (deterministic) manner between the source and the relay. Based on the relaying scheme applied, the processing at the relay (i.e, the operation of Z(·)) becomes different. Two widely used fixed relaying schemes are [38]:
  - DF relaying scheme : In a DF relaying scheme (also known as regenerative relaying), the relay decodes the received signal from the source, re-encodes



Figure 2.8: DF relaying scheme.

it and then retransmits to the destination. If the decoded signal at the relay is presented as  $\hat{x}$ , then the transmitted signal from the relay can be presented as  $\sqrt{P_r}\hat{x}$  [53]. There is a possibility that the relay decodes the signal incorrectly and forwards it resulting in an error propagation. Hence, the decoding at the relay becomes meaningless. For such a scheme, the diversity achieved is one, because the network performance is limited by the worst link from source-to-relay and from source-to-destination. Error correction codes are one way to reduce error in the decoded signals. Laneman [38] proposed that if the SNR of the received signal at the relay exceeds a certain threshold, only then the relay will decode and forward the information to the destination. This constraint reduces incorrect decoding at the relay.

The principal advantage of the DF relaying scheme is not having any amplified noise in the transmitted signal to the destination. The drawbacks of the DF relaying scheme are error propagation at the relay due to the possibility of incorrect decoding of the coded signals and high computation load on the relay nodes.

- AF relaying scheme: For the AF relaying scheme (also known as nonregenerative relaying), the relay scales the revived signal from the source and transmits an amplified version of the signal to the destination. The



Figure 2.9: AF relaying scheme.

amplification is done basically to combat the effect of the fading between the source to relay channel. The relay performs amplification by scaling the revived signal by a factor that is inversely proportional to the received power. The AF relaying can be further divided into:

\* Channel state information (CSI) assisted AF relaying [54]: In the CSI-assisted relaying, the relay employs instantaneous CSI of the source to the relay link to control the gain obtained at relay. Hence, it scales the power of the retransmitted signal. The scaling at the relay is also known as the instantaneous power scaling or variable gain scaling. Hence, the instantaneous transmitted power is always normalized. The amplification factor for the cooperative relay network described by (2.1), (2.2) and (2.3) can be expressed as-

$$G = \sqrt{\frac{P_r}{\left(P_s |h_{sr}|^2 + N_0\right)}}$$
(2.7)

\* Fixed gain relaying [54]: In the blind relaying, relay do not need instantaneous CSI of the the source to relay link at the relay, but scale the the signal with a fixed gain. Hence, this results in variable power at the retransmitted signal and the average transmitted power is normalized. This scaling is also known as the average power scaling or fixed gain scaling. For a cooperative relay network described by (2.1), (2.2) and (2.3), the amplification factor is:

$$G = \sqrt{\frac{P_r}{E\left[\left|y_{sr}\right|^2\right] + N_0}} \tag{2.8}$$

where  $E(\cdot)$  is the expectation operator.

The AF relaying scheme has advantages of simple implementation and low computation load for the relay nodes. The main drawback of the AF protocol is that it amplifies the noise in the signal leading to some performance degradation [53].

All fixed relaying schemes inherit the advantage of easy implementation. However, they suffer from the bandwidth efficiency. This problem can be avoided by using the adaptive relaying schemes. In Figure 2.10, the classification of cooperative relaying schemes has been summarized.

- Adaptive cooperative relaying [38]: As the name implies, adaptive relaying will have channel resources allocated in an adaptive manner. Two major adaptive relaying are [38]: Selection relaying and Incremental relaying.
  - Selection relaying: In the selection relaying [55, 56], the relay node with the highest relay-to-destination channel gain (absolute squared of the complex channel coefficient) is selected by the destination. The relay can be selected among M relays employing DF/AF relaying scheme at the received signal.

The selection relaying offers bandwidth savings. But, the channel fading coefficients are required to be available to the destination for the selection process.

 Incremental relaying: This protocol exploits limited feedback from the destination terminal, i.e., single bit indicating the success or the failure



Figure 2.10: Classification of relaying schemes.

of the direct-link transmission [38]. If the transmission is successful, the relay does not take part in the transmission. In case of the transmission failure, the relay becomes responsible for the transmission.

This method can improve spectral efficiency over fixed and selection relaying. But, because of the feedback procedure there is always a delay in transmission from the source.

#### 2.1.4 Combining Techniques

As in a cooperative relay network, the destination receives multiple independent copies of the same signal. Hence, it results in distributed diversity. Distributed diversity can be effective to mitigate the detrimental effects of channel fading and co-channel interference. Diversity schemes can be categorized as:

- Micro-diversity [57]: This technique helps to mitigate the short-term multipath fading effect.
- Macro-diversity [57]: This technique is designed to combat the long-term multi-path fading effect cased by large obstructions like buildings and trees.

The destination needs to employ a combining technique to combine the diverse received signals. Combining techniques can be classified based on the nature of the



Figure 2.11: Diversity combining techniques.

channel fading as follows (Figure 2.11):

- Pure combining techniques [38]: Pure combining techniques are the well known classical combining techniques such as maximal-ratio-combining (MRC), Equal gain combining (EGC), Selection combining (SC) etc. This thesis deals with the MRC technique and SC techniques only.
  - MRC technique [57]: This is widely used in the repetition-based networks to employ the optimal combining in the absence of the interference. It is optimal in the sense that it yields the best statistical reduction of fading in any linear diversity combiner. The performance of MRC is considered as the 'upper bound' among all possible combining techniques. It needs the knowledge of channel fading parameters, so offers complexity in implementation. The *M* relay cooperative cognitive relay network in Figure 2.12 considers equally likely transmitted signals regardless of the fading statistics of the channels. So, the destination receives multiple independent signals from the source via relays resulting 'virtual branches'. Signals received from the virtual branches are individually weighted and



Figure 2.12: MRC technique.

then added to provide total SNR at the destination as presented with the help of Figure 2.12.

- SC technique: SC technique detects the relay channel with the highest SNR to transmit. Since the output is equal to the output signal of only one of the channels, there is no need to sum the individual channel output. Hence, SC presents the 'lower bound' of the diversity that can be achieved in a system. Though selection cooperation requires some sort of channel knowledge, it results in bandwidth savings. For the network in Figure 2.13, the destination selects the relay with the highest SNR and the available output is the signal transmitted from that selected relay.
- Hybrid combining techniques [38]: Hybrid combining techniques have been proposed recently to meet the complexity constraints of the wideband communication. Generalized combining technique is a widely used hybrid combining technique. However, this work does not deal with hybrid combining techniques.

# 2.2 Cognitive Relay Networks

The advantages offered from the cooperative relays to enhance the traditional cognitive radio's performance have led to the research of how cooperative relays can



Figure 2.13: SC technique.

be brought into the cognitive radio picture. This section discusses a few works that combine cooperative relays and cognitive radios together and provide some interesting results. Several pioneering works studying the combination of cognitive radio and cooperative relay network together include [23, 58, 59, 60, 61].

Several distributed transmit power allocation schemes for cooperative relay assisted cognitive radio employing the underlay approach have been investigated in [23]. In [23], relays re-adjust their power so that they can meet all interference and power constraints to allow a low power transmission. Hence, there is no interference to the primary users.

The performance of a cognitive radio network has been analysed in terms of information theoretic metrics (i.e, channel capacity and achievable rates) in [58]. Three different cognitive radio approaches for single/multiple cognitive user(s) have been studied as follows:

• Interference mitigating approach: In this approach, two users can simultaneously transmit over the same time/frequency slot. The cognitive user will listen to the channel and only transmit if the primary user is not transmitting. However, if a primary is sensed, the cognitive radio can decide on simultaneous transmission. As it will result in interference between the primary and

the cognitive users, work in [58] has shown that the sensed information can be utilized as side information to mitigate the interference.

- Collaborative approach: The approach explains that a cognitive user can act as a relay to collaborate with the primary user when it does not transmit. In this way, a cognitive relay actually improves up the primary transmission.
- Interference avoiding approach: According to the current FCC proposals on opportunistic channel usage, the cognitive radio listens to the wireless channel and determines the unused spectrum parts in either time or frequency slots. Then it adapts its signals accordingly to access the spectrum slot avoiding interference with primary users.

A number of interference avoiding methods have been proposed and investigated in [59] in an ad-hoc cognitive radio environment using multi-hop relays. The interference based methods are as follows:

- Interference avoidance by using media access control (MAC) protocol.
- Use of interference tolerant approach (i.e, underlay approach).
- Interference reduction method (limiting the transmission power of the transmitter of the cognitive radio).
- Interference cancellation by using signal processing.

Cooperative spectrum sensing has been proposed in [60]. One of the cooperative sensing approaches used in [60] allows the cognitive users under shadowing affects to collaborate with other cognitive users cooperatively. In this way, the affected users are assured that the primary user is not transmitting and continues their transmission. The other approach employs cooperative relays to combat shadowing effects by exploiting cooperative diversity. Both cooperative sensing and cooperative transmission have been considered in [61] among secondary users in a cognitive radio network. The cooperative transmission involves a secondary user acting as a relay for a secondary source and even for a primary source. The later will allow the primary user to reduce its transmission power and so increase the transmission opportunity for other secondary users. The cognitive radio network in [60] has proposed cooperative relays to minimize interference to the primary users.

Cooperative sensing in a cognitive radio environment has also been investigated in [2, 6, 24, 27, 30] to enhance the sensing performance of a cognitive radio. A recent work in [33] has explained the impact of cooperative relays in cognitive radio environment for coverage extension and spectrum sensing.

#### 2.2.1 Repetition-Based Cognitive Relay Network

The concept of a repetition-based cluster of cognitive relays has been introduced in [62]. Each cluster contains a number of cognitive relays and a primary source. The relays which do not transmit to the destination can work as neighbour relays to help in sensing the spectrum cooperatively.

The concept of cluster of cognitive relays has been adopted in this thesis to derive the closed-form outage probability for arbitrary SNR. To evaluate the outage probability for DF and AF relaying a few key works have been taken into consideration which relate to the relay network, cooperative relay network and cognitive radio.

To evaluate the closed-form outage probability of proposed DF repetition-based network for arbitrary SNR, this thesis considered the following works:

- The outage probability (valid for only high SNR) of a repetition-based DF relay network [38],
- The outage probability for a cooperative relay network for arbitrary SNR using Moment Generating Function (MGF) approach [63] and

• A recent work presented in [62] which analyses the outage probability of a cognitive relay network valid for high SNR regimes only.

To obtain the closed-form outage probability of the proposed AF cognitive relay network for arbitrary SNR, the following works have been taken into consideration:

- The outage probability of a single AF relay network for fading channels [54],
- The outage probability of a single AF relay network in Gamma fading channels [64],
- The outage probability of an AF relaying scheme where multi-relays assist the source to transmit information [38] and
- The outage probability for a repetition-based relay network valid for high SNR regimes [63].

#### 2.2.2 Selection-Based Cognitive Relay Networks

The selection-based relaying scheme is found to be an attractive solution to the drawback of the repetition-based relaying scheme. A repetition-based relaying scheme requires M + 1 time slots for M relays relaying to the destination. This consumes more radio resource i.e. bandwidth. In selection-based relaying, one relay with the largest SNR is allowed to transmit among M relays, resulting in a requirement of only two time slots. Moreover, works in [38, 64] have shown that a full diversity order (which is achievable by the repetition-based network) can still be achieved with the selection-based relaying scheme. Hence, the selection-based relaying scheme does not compromise the signal quality to save the bandwidth.

Selection-based relaying is an adaptive form of relaying that can be realized for both DF and AF relaying schemes. For both DF and AF, the selection-based relaying scheme selects the relay with the largest SNR to transmit. In the literature, the selected relay is often referred to as the 'best' relay. The term 'best' is associated with the relay with the largest SNR on a particular link (i.e relay-destination). In the literature, the selection-based DF relaying has been investigated in [65, 66] over Rayleigh fading channels. The performance of a selection-based DF relay network has been considered in [67] over a Nakagami-m fading channel. For a cooperative selection-based DF relay network, [63] has presented the approximate outage probability valid for high SNR. These results were a significant improvement on the earlier work of [38].

For selection-based AF relaying, works in [54, 68, 69, 70] have been taken into consideration. A harmonic mean approach is employed in [69, 70] to analyse the outage probability of a selection-based relay network. The result presented in [54, 70] contains a first order Bessel function of the second kind. The Bessel function presented in the results can be realized using popular mathematical software such as Mathematica<sup>TM</sup>, Matlab<sup>®</sup>. The Bessel function approach does not lead to the simplification. As a result, it is difficult to obtain the practical insight of the equation. The approximation presented in [64] avoids the Bessel function approach and provides a tight upper bound. A closed-form expression for an AF relay network has been presented in [68] for a cooperative relay network under the Nakagami-*m* relay channel. Both of the expressions in [64, 68] avoid the complexity of the Bessel function and the expressions can be easily computed.

# 2.3 Performance Metrics

This section briefly describes the performance metrics used in this thesis to evaluate the outage probability of the proposed cooperative cognitive relay network.

• Average SNR : One of the most common performance measure metrics used in a wireless communication system is SNR. However, the average SNR is a more appropriate metric for a wireless communication system affected by the fading phenomenon. Here 'average' indicates to the statistical averaging over pdf of the fading [57] channel. Mathematically, if  $\gamma$  represents the instantaneous SNR, then

$$\bar{\gamma} \triangleq \int_0^\infty \gamma p_\gamma(\gamma) d\gamma \tag{2.9}$$

is the average SNR. In (2.9),  $p_{\gamma}(\gamma)$  is the pdf of  $\gamma$ . Average SNR is also useful for a cooperative relay network to combat with fading/shadowing effects.

 Outage probability: Outage probability is another widely used performance measurement metric for a wireless diversity system affected by fading. It is defined as the probability of the instantaneous error probability exceeding a particular value (or the probability of the output SNR, γ) at the destination [57]. The Outage probability is denoted by P<sub>out</sub> and mathematically-

$$P_{out} = \int_0^{\gamma_{th}} p_{\gamma}(\gamma) d\gamma \qquad (2.10)$$

From (2.10) the outage probability can be defined as the cdf of  $\gamma$ . For the slow independent and identically distributed Rayleigh fading channel considered in this work, outage probability can be expressed as the probability that the mutual information of the channel falls below a particular rate at a given SNR. Mathematically,  $P_{out} = \Pr [\gamma < \gamma_{th}]$ .

### 2.4 Summary

This chapter introduced the concept of cooperative relay networks. The cooperative relay schemes and combining techniques available in the technical literature were discussed. The background of cognitive relay network was also presented. The existing key literature on repetition-based cognitive relay networks have been discussed. The preliminaries and existing literature of the selection-based cognitive relay network have also been surveyed. Finally, a short summary of the performance metrics was introduced.

In the next chapter, the proposed repetition-based cognitive relay network model will be presented and analysed. The closed-form outage probability expressions for the DF and AF cognitive relay networks will also be derived in the next chapter. A detailed discussion on the results is included and any analysis is validated by simulations.

# Chapter 3

# Repetition-Based Cognitive Relay Network

This chapter presents the network model of a repetition-based cognitive relay network. The model is then further enhanced in terms of channel and spectrum acquisition models. The performance of a repetition-based cognitive relay network will be analysed to provide a closed-form expressions of outage probability.

# 3.1 Network and Channel Model of Repetition-Based Cognitive Relay Network

Figure 3.1 presents the repetition-based cognitive relay network used in the analysis similar to [62]. This network consists of a source, cluster of relays and a destination. Furthermore, each cluster consists of a primary user, one transmitting relay and other neighbour relays. The transmitting relay is a cognitive relay which depends on the spectrum availability to assist the transmission. The neighbour relays within a cluster help the cognitive relay to sense the available spectrum cooperatively. The transmission from the source to the destination occurs in following steps:

- Broadcast step: In the Broadcast step, the source broadcasts its information to the cognitive relays and to the destination.
- Processing step: The relays process the received signal from the source according to the relaying schemes. Both DF and AF schemes have been used in



Figure 3.1: Repetition-based cognitive relay network.

this thesis. For the DF relaying scheme, the relays decode the received signal and re-encode it for the transmission. This thesis considers an uncoded DF relaying scheme and uses threshold methods. In the threshold method, the SNR of the received signal at the relay is required to exceed a certain predefined threshold to ensure the correct decoding. For the AF relaying scheme, the relays scale the received signal for forwarding it to the destination. The scaling factor is inversely proportional with the power of the received signal.

- Spectrum sensing step: The cognitive relays are dependent on availability of the spectrum for transmission; unlike the cooperative relays that always have spectrum available. Unavailability of spectrum degrades network performance as the relays can not transmit. Cooperative spectrum sensing uses help from neighbour relays within the cluster to improve the probability of acquiring an unused spectrum band, while reducing the probability of interferes with any primary user.
- Forwarding step: Based on the successful acquisition of unused spectrum, the relays forward the processed signal to the destination.



Figure 3.2: Block diagram of an energy detector.

• Combining step: In this step, the destination combines the received signals from the relays and the destination using MRC techniques.

The channels between any nodes (i.e, source to destination, source to relay, relay to destination) are modeled with similar statistics as the cooperative relay channels discussed in detail in Chapter 2.

# 3.2 Spectrum Acquisition Model

The reliability of acquiring spectrum is mostly dependent on the mechanism applied to sense the spectrum. The approach of energy detection [71] to detect an unknown signal is employed in this work. The energy detection method of sensing spectrum is popular because:

- It is less complex than other detection methods in implementation [71].
- It uses the overlay approach for sensing the spectrum, thus causes no interference to the primary users.

The energy detector is also called the primary intuition system as the detector concerns the primary only. However, the performance of the energy detector is susceptible to noise power estimation errors [72]. Under an uncertain noise power, the SNR has to be above a certain threshold to obtain the desired performance.

The Figure 3.2 depicts the block diagram of an energy detector. The input band-pass filter is employed to remove the out-of-band noise by selecting the centre

frequency  $f_c$ , and the bandwidth of interest W. This filter is followed by a squaring device to measure the received energy. Now, an integrate-and-dump device is used to capture the received energy in the observation interval T. The output of the integrator is normalized by a factor,  $\frac{N_0}{2}$  where  $N_0$  is the one-sided noise psd. The normalized output is then compared to the threshold K to decide whether the primary user's signal is present or not.

The goal of spectrum sensing is to determine if a licensed band is occupied by the primary user or not at a given time. Hence, there are only two possible observations: a signal is present  $(\mathcal{H}_1)$  and a signal is absent  $(\mathcal{H}_0)$  resulting a binary hypothesis testing problem.

$$Y_{pr}(t) = \begin{cases} N_{pr}(t) & \mathcal{H}_0 \\ h_{pr}X_p(t) + N_{pr}(t) & \mathcal{H}_1 \end{cases}$$
(3.1)

In (3.1),  $Y_{pr}(t)$  is the signal received by the cognitive user. The amplitude gain of the primary relay channel is  $h_{pr}$  and primary users transmitted signal is  $X_p(t)$ . Furthermore, the AWGN component at the relays is presented by  $N_{pr}(t)$ .

Two important terms related with this hypothesis are : probability of detection,  $P_d$  and false alarm probability,  $P_f$ . The probability of detection of an unoccupied spectrum band protects the primary user from being interfered with. However, the probability of false alarm is the percentage of spectrum bands falsely declared as occupied. However,  $P_f$  can be minimized by regulating  $P_d$  to be always over a threshold value. The threshold criterion required for  $P_d$  can be satisfied by the Y which is the output of the integrator in Figure 3.2.

For the sake of simplicity in calculation, the time bandwidth product, TW is denoted by an integer number, m. In [71], Y has been shown to possess central and non central chi square distributions under  $H_0$  and  $H_1$  respectively. Each of them has 2m degrees of freedom and a non centrality parameter of  $2\gamma$  with  $\gamma$  represents the SNR of Y. So, the pdf of Y under both hypothesis can be written as:

$$f_{Y|H_0}(y) = \frac{y^{m-1}e^{-\frac{y}{2}}}{\Gamma(m)2^m}$$
(3.2)

$$f_{Y|H_1}(y) = \frac{y^{m-1}e^{-\frac{(y+2m\gamma)}{2}}}{\Gamma(m)2^m} {}^0F^1\left(m, \frac{m\gamma y}{2}\right)$$
(3.3)

where  $\Gamma$  is the gamma function and  ${}^{0}F^{1}$  (: ; :) is the confluent hypergeometric limit function ([73], Eq. 3.119). For a non fading channel  $h_{pr}$  is deterministic. Hence, employing the cdf of the central and the non-central chi-square distributions, the probabilities of detection and false-alarm can be re-written as:

$$P_d = \Pr\{Y > K | H_1\} = Q_m\left(\sqrt{2m\gamma}, \sqrt{K}\right)$$
(3.4)

$$P_f = \Pr\{Y > K | H_0\} = \frac{\Gamma(m, \frac{K}{2})}{\Gamma(m)}$$
(3.5)

where  $\Gamma(a,b) = \int_{b}^{\infty} t^{a-1} e^{-t} dt$  is the incomplete gamma function [73] and  $Q_m(:,:)$  is the generalized Marcum Q function as defined in [74]:

$$Q_m(a,b) = \int_b^\infty \frac{x^m}{a^{m-1}} e^{-\frac{x^2+a^2}{2}} I_{m-1}(ax) dx$$
(3.6)

where  $I_{m-1}$  is the (m-1)th order modified Bessel function of the first kind. For a fading channel,  $P_d$  can be defined as:

$$P_d = \int_{\gamma} Q_m \left(\sqrt{2\gamma}, \sqrt{K}\right) f_{\gamma(x)dx} \tag{3.7}$$

where  $f_{\gamma(x)}$  is the pdf of the fading channel. For the Rayleigh channel considered in this thesis,  $\gamma$  has an exponential distribution. Hence, with help of [75] and substituting  $f_{\gamma(x)}$  in (3.7), the average probability of detection, (also denoted as,  $P_d$ ) can be written as:

$$P_{d} = e^{-\frac{K}{2}} \sum_{n=0}^{m-2} \frac{1}{n!} \left(\frac{K}{2}\right)^{n} + \left(\frac{1+\bar{\gamma}}{\bar{\gamma}}\right) \times \left[ e^{-\frac{K}{2(1+\bar{\gamma})}} - e^{\frac{K}{2}} \sum_{n=0}^{m-2} \frac{1}{n!} \left(\frac{K\bar{\gamma}}{2(1+\bar{\gamma})}\right)^{n} \right]$$
(3.8)

where,  $\bar{\gamma}$  is the average SNR.

The probability of false alarm can be expressed as:

$$P_f = Q(m, \frac{K}{2}) \tag{3.9}$$

# 3.3 Cooperative Spectrum Sensing

The reliability of acquiring spectrum can be improved [72] by employing a cooperative spectrum sensing scheme. As discussed in Section 3.1, L-1 relays conduct the joint spectrum sensing for the cognitive transmitting relay in a cluster of L relays. As each sensing relay decides on the presence or absence of the spectrum hole, a combined decision is taken about the availability of spectrum by using any of the following decision rules:

- OR rule [72]: Spectrum is not available for transmission if any of the L-1 sensing relays sense spectrum. The use of OR rule minimises the probability of interfering with the primary user's activity  $(H_1)$ . However, there is also a higher possibility of false alarm resulting in a missed relaying opportunity.
- AND rule [72]: Spectrum is decided not to be available if all of the L 1 sensing relays sense primary user's activity  $(H_1)$ . With the AND rule there are more transmission opportunities but probability of misdetection higher.
- Majority rule [72]: Spectrum is decided to be available for transmission only if a majority of the L-1 sensing relays sense the primary user's activity  $(H_1)$ .

This rule balances between the OR and the AND rule and provides a more realistic result.

This thesis employs the OR rule to take a decision on the spectrum availability since it guarantees the least interference with the primary user. The cooperative probabilities of detection and cooperative probabilities of false alarm are now given as:

$$C_d = 1 - (1 - P_d)^L (3.10)$$

$$C_f = 1 - (1 - P_f)^L \tag{3.11}$$

assuming the channels are independent. In the next section, Section 3.4, to derive the outage outage probability of a cognitive relay network, the cooperative probability of spectrum availability,  $C_d$  has been taken into consideration.

# 3.4 Outage Probability

The closed-form expressions for outage probability of repetition-based DF and AF cognitive relay networks are derived in the following subsections. At first, the outage probability of repetition-based cooperative relay networks will be derived for both relaying schemes to present the benchmark results. The original work in contributions of the thesis are continued in the next four subsections, Subsection 3.4.1, Subsection 3.4.2, Subsection 3.4.3 and Subsection 3.4.4.

#### 3.4.1 Decode-and-Forward (DF) Cooperative Relay Networks

The received signal at the destination and the relays from the source is given as:

$$y_{sd} = h_{sd}x + n_{sd} \tag{3.12}$$

$$y_{sr} = h_{sr}x + n_{sr} \tag{3.13}$$

In (3.12) and (3.13),  $h_{sd}$  and  $h_{sr}$  are the source-destination and the source-relay Rayleigh fading channels. The Rayleigh fading channels can be modeled as the circularly symmetric complex RV [76]. Therefore, they can be represented as:

$$h_{sd} = X_{sd} + j Y_{sd} \tag{3.14}$$

$$h_{sr} = X_{sr} + jY_{sr} \tag{3.15}$$

where the real and the imaginary parts of (3.14) and (3.15) are the zero mean, independent and identically distributed Gaussian RVs. It has been shown in [76] that:

$$E[h_{sd}] = E[e^{-j\theta}h_{sd}] \tag{3.16}$$

$$E[h_{sd}] = e^{-j\theta} E[h_{sd}] \tag{3.17}$$

The statistics of a circularly symmetric complex Gaussian RV,  $h_{sd}$  has been shown to be completely specified by the source-destination channel variance,  $\lambda_{sd}$ in [76] as:

$$\lambda_{sd} = E[h_{sd}^{2}] \tag{3.18}$$

The source-relay channel,  $h_{sr}$  can also be described in a similar way with the source-relay channel variance  $\lambda_{sr}$  using (3.18) as:

$$\lambda_{sr} = E[h_{sr}^{2}] \tag{3.19}$$

Furthermore, in (3.12) and (3.13), x is the transmitted signal,  $n_{sd}$  and  $n_{sr}$  are the AWGN noise at the destination and the relay with one-sided psd of  $N_0$ . This thesis assumes that both the source and the relays transmit using unit power.



Figure 3.3: Time slots required for a cooperative relay network with M relays.

In a cooperative relay network for i = 1, 2, ..., M relays, the network requires a total of M + 1 time slots to complete the transmissions as explained in Figure 3.3. Now, the mutual information between the source and each relay is presented as [77]:

$$I_{sr_i} = \frac{1}{M+1} \log_2(1+\gamma_{sr_i})$$
(3.20)

where  $\gamma_{sr_i} = |h_{sr_i}|^2$  presents the instantaneous SNR between the source and the *i*th relay.

To assist the source to destination transmission, the source to relay transmission needs to be reliable enough. That is, when the mutual information of a source to relay channel becomes greater than the target rate,  $\xi$ , the relay is allowed to continue to transmit to the destination. The relays able to meet the targeted rate are defined as a set  $R_s \in i$ . So, the signal received at the destination is:

$$y_{rd} = h_{rd}\hat{x} + n_{rd} \tag{3.21}$$

The relay-destination channel,  $h_{rd}$  can be described in a similar way with the relay-destination channel variance  $\lambda_{rd}$  using (3.18) as:

$$\lambda_{rd} = E[h_{rd}^2] \tag{3.22}$$

The AWGN at the destination is  $n_{rd}$  with one-sided variance of  $N_0$ . Hence the mutual information,  $I_{DF}$  at the destination becomes:

$$I_{DF} = \frac{1}{M+1} \log_2 \left( 1 + \gamma_{sd} + \sum_{R(s)} \gamma_{rd} \right)$$
(3.23)

where  $\gamma_{sd} = |h_{sd}|^2$  and  $\gamma_{rd} = |h_{rd}|^2$  present the instantaneous SNR between the source-destination channel and the relay-destination channel respectively. The outage probability according to the total probability law is:

$$P_{out} = \Pr\left[I_{DF} < R \left| R\left(s\right)\right] \Pr\left[R\left(s\right)\right]$$

$$(3.24)$$

Now the probability of  $\Pr[I_{DF} < R | R(s)] = 1, 2, \dots, M$  is given by:

$$\Pr[\gamma_{sd} + \sum_{i=1}^{M} \gamma_{r_i d}] < 2^{(M+1)R} - 1$$
(3.25)

where R is the pre-defined rate of at the destination which works as a threshold to decide on the outage probability.

To simplify the calculation, we substitute:  $Z_1 = \gamma_{sd}$  and  $Z_2 = \sum_{i=1}^{M} \gamma_{r_id}$  and  $\gamma_{th} = 2^{(M+1)R} - 1$  in (3.25). As discussed earlier, the channels are Rayleigh fading channels and defined as circularly symmetric complex Gaussian RVs. Hence, the pdf of  $Z_1$  is as follows:
$$p_{Z_1}(z_1) = \frac{1}{\lambda_{sd}} e^{-\frac{z_1}{\lambda_{sd}}}$$
(3.26)

The pdf of  $Z_2$  is a well known gamma function with a shape parameter of M and a scale parameter of  $\gamma_{r_id}$ . The scale parameter  $\gamma_{r_id}$  is exponentially distributed with the variance  $\lambda_{r_id}$ . For further simplification of the calculation, this thesis assumes that all source-relay channels have the same fading characteristics ( $\gamma_{sr_1} = \gamma_{sr_2} =$  $\cdots = \gamma_{sr}$ ) and all relay-destination channels have the same fading characteristics ( $\gamma_{r_1d} = \gamma_{r_2d} = \cdots = \gamma_{rd}$ ). The pdf  $p_Z(z)$  where  $Z = Z_1 + Z_2$  can be realized with the help of [78] in:

$$p_Z(z) = \frac{\lambda_{sd}^{M-1}}{(\lambda_{rd} - \lambda_{sd})^M} e^{-\frac{z}{\lambda_{sd}}} - \left(\sum_{j=1}^M \frac{1}{(j-1)!} z^{j-1} \left(\frac{1}{\lambda_{sd}} - \frac{1}{\lambda_{rd}}\right)^{j-M-1}\right) - e^{-\frac{z}{\lambda_{rd}}}$$
(3.27)

Using ([73], eq. (3.381-1)), the cdf,  $F_Z(z)$  can be obtained by integrating  $p_Z(z)$  as in (3.28).

$$F_{Z}(z) = \left(\frac{e^{-\frac{z}{\lambda_{rd}}}}{e^{-\frac{z}{\lambda_{rd}}} - e^{-\frac{z}{\lambda_{sd}}}}\right)^{M}$$

$$\left(1 - \frac{1}{\lambda_{sd}}e^{-\frac{z}{\lambda_{sd}}} - \sum_{j=1}^{M}\frac{\left(\frac{1}{\lambda_{rd}}\right)^{-j}}{\left(\frac{1}{\lambda_{rd}} - \frac{1}{\lambda_{sd}}\right)^{M-j+1}}\left(1 - \left(\sum_{n=0}^{j-1}\frac{(z)^{n}}{(\lambda_{rd})^{n}n!}\right)e^{-\frac{z}{\lambda_{rd}}}\right)\right)$$
(3.28)

An alternative representation for the lower incomplete gamma function,  $\Gamma_L = (a, x)$  as follows [73]:

$$\Gamma_L(a,b) = \int_0^b t^{a-1} e^{-t} dt$$
(3.29)

has been used in this thesis where a is an integer. Finally  $\Pr[|R(s)| = M]$  is as follows:

$$\Pr(|R(s)| = M) = \binom{M}{i} (e^{-\frac{\gamma}{\lambda_{sr}}})^i (1 - e^{-\frac{\gamma}{\lambda_{sr}}})^{M-i}$$
(3.30)

Now substituting (3.28) and (3.30) into (3.24), the outage probability is now straight forward to obtain as:

$$P_{out} = \left(1 - e^{-\frac{\gamma_{th}}{\lambda_{sd}}}\right) \left(1 - e^{-\frac{\gamma_{th}}{\lambda_{sr}}}\right)^M + \sum_{i=1}^M \binom{M}{i} \left(e^{-\frac{\gamma_{th}}{\lambda_{sr}}}\right)^i \left(1 - e^{-\frac{\gamma_{th}}{\lambda_{sr}}}\right)^{M-i} \\ \left(\frac{e^{-\frac{\gamma_{th}}{\lambda_{rd}}}}{e^{-\frac{\gamma_{th}}{\lambda_{rd}}} - e^{-\frac{\gamma_{th}}{\lambda_{sd}}}}\right)^i \left(1 - e^{-\frac{\gamma_{th}}{\lambda_{sd}}} - \sum_{j=1}^i \frac{\left(\frac{1}{\lambda_{rd}}\right)^{-j}}{\left(\frac{1}{\lambda_{rd}} - \frac{1}{\lambda_{sd}}\right)^{1-j}} \left(1 - \left(\sum_{n=0}^{j-1} \frac{\left(\frac{\gamma_{th}}{\lambda_{rd}}\right)^n}{n!}\right) e^{-\frac{\gamma_{th}}{\lambda_{rd}}}\right)\right)$$
(3.31)

The above outage probability expression is both closed-form and generic in what it can be extended to M relays.

#### 3.4.2 Decode-and-Forward (DF) Cognitive Relay Networks

The difference between a cooperative relay and a cognitive relay is that a cognitive relay needs to acquire spectrum before it transmits. As the cognitive relays borrow spectrum from the primary user opportunistically, the spectrum may not always be available for transmission. Hence, the probability of sensing available spectrum needs to be considered. If i is the number of relay nodes being successful in acquiring spectrum opportunistically among M relays, the probability of acquiring available spectrum, P(i) is dependent on  $C_d$ .

$$P(i) = \begin{pmatrix} M \\ i \end{pmatrix} C_d^{\ i} (1 - C_d)^{M-i}$$
(3.32)

Hence, the outage probability of a DF cognitive relay network,  $P_{cog}$  is:

$$P_{cog} = \sum_{i=0}^{M} \mathcal{P}(i) P_{out}$$
(3.33)

The final expression can be presented as follows:

$$P_{cog} = \sum_{i=0}^{M} {\binom{M}{i}} C_d^i (1 - C_d)^{M-i} \left( \left( 1 - e^{-\frac{\gamma_{th}}{\lambda_{sd}}} \right) \left( 1 - e^{-\frac{\gamma_{th}}{\lambda_{sr}}} \right)^M + \sum_{i=1}^{M} {\binom{M}{i}} \left( e^{-\frac{\gamma_{th}}{\lambda_{sr}}} \right)^i \left( 1 - e^{-\frac{\gamma_{th}}{\lambda_{sr}}} \right)^{M-i} \left( \frac{e^{-\frac{\gamma_{th}}{\lambda_{rd}}}}{e^{-\frac{\gamma_{th}}{\lambda_{rd}}} - e^{-\frac{\gamma_{th}}{\lambda_{sd}}}} \right)^i \left( 1 - e^{-\frac{\gamma_{th}}{\lambda_{sd}}} - \sum_{j=1}^{i} \frac{\left( \frac{1}{\lambda_{rd}} \right)^{-j}}{\left( \frac{1}{\lambda_{rd}} - \frac{1}{\lambda_{sd}} \right)^{1-j}} \left( 1 - \left( \sum_{n=0}^{j-1} \frac{\left( \frac{\gamma_{th}}{\lambda_{rd}} \right)^n}{n!} \right) e^{-\frac{\gamma_{th}}{\lambda_{rd}}} \right) \right) \right)$$
(3.34)

#### 3.4.3 Amplify-and-Forward (AF) Cooperative Relay Networks

Equations (3.12), (3.13) present the signal transmitted from the source to the relays and the destination. Due to the nature of end-to-end (e2e) SNR in an AF relay network, a generic expression valid for i = 1, 2, 3, ..., M relays is not possible to obtain [68]. Hence, a two relay network is analysed in this thesis which is considered as a basic form of the multi-relay network and the results presented in the thesis can be extended for M number of relays. The calculation for more than two relays has been avoided in this thesis, as it follows a similar procedure.

The CSI assisted relays in the proposed network receive the information from the source and they scale the signal with a gain, G (as in(2.7)). The signal received at the destination from each relay is:

$$y_{rd} = h_{rd}G(y_{sr}) + n_{rd} (3.35)$$

where  $y_{sr}$  is as in (3.13). Therefore,

$$y_{rd} = h_{rd}G(h_{sr}x + n_{sr}) + n_{rd} ag{3.36}$$

The symbols bear the same meaning and the channels follow the similar characteristics as described in the Subsection 3.4.1. As we assume the noise terms  $n_{sr}$  and  $n_{rd}$  to be AWGN signals with the one-sided psd of  $N_0$ , the equivalent e2e SNR at the destination [54] is:

$$\gamma_{eq} = \frac{[h_{rd}Gh_{sr}]^2}{[(h_{rd}G)^2 + 1]N_0}$$
(3.37)

From (3.37), it has been shown [54] that, the choice of the relay gain defines the equivalent SNR at the destination. In [54], the relay gain is defined as:

$$G^{2} = \frac{E_{r}}{\left|h_{sr_{i}}\right|^{2} + N_{0}} \tag{3.38}$$

The thesis assumes that for AF relaying, the source transmits a signal which has an average power  $(E_r)$  normalized to 1 and changes (3.38) as:

$$G^2 = \frac{1}{\left|h_{sr_i}\right|^2 + 1} \tag{3.39}$$

Therefore, substituting (3.39) into (3.37) and extending for M relays results into the equivalent e2e SNR at the destination [64] SNR as:

$$\gamma_{sum} = \sum_{i=1}^{M} \frac{\gamma_{sr_i} \gamma_{r_i d}}{\gamma_{sr_i} + \gamma_{r_i d} + 1}$$
(3.40)

where  $\gamma_{sr_i}$  and  $\gamma_{r_id}$  present the instantaneous SNR between the source-relay channels and the relay-destination channels respectively. The variance of the sourcerelay and relay-destination channels are represented as  $\lambda_{sr_i}$  and  $\lambda_{r_id}$ . The mutual information at the destination is:

$$I_{AF_i} = \frac{1}{M+1} \log_2 \left( 1 + \gamma_{sd} + \sum_{i=1}^M \frac{\gamma_{sr_i} \gamma_{r_id}}{\gamma_{sr_i} + \gamma_{r_id} + 1} \right)$$
(3.41)

where  $\gamma_{sd}$  presents the instantaneous SNR between the source-destination channel with a variance  $\lambda_{sd}$ . The e2e SNR is difficult to track mathematically. But a bound based approach has been adopted in several recent works. The total SNR can be approximated by its upper bound,  $\gamma_{ub}$  as [54]:

$$\gamma_{e2e} \le \gamma_{ub} = \gamma_{sd} + \sum_{i=1}^{M} \gamma_i \tag{3.42}$$

where,

$$\gamma_{i} = \min\left(\gamma_{sr_{i}}, \gamma_{r_{i}d}\right) \tag{3.43}$$

Now, the performance of the source-relay-destination link is dominated by the worst link between the source-to-relay and relay-to-destination link. The approximate value of SNR is analytically more tractable to derive the pdf and the cdf. The pdf of  $\gamma_i$  is now exponentially distributed and has a closed-form solution. In [64], this approximation is shown to be accurate for medium to high SNR regimes for the generalized Gamma channel in a classical relay scenario. However, this thesis adopts the bound and derives a closed-form outage probability expression at the arbitrary SNR for AF cooperative and cognitive relay networks. The bound is found to be tight enough in low to medium SNR regimes and accurate from medium to high SNR regimes. Now, the mutual information at the destination becomes:

$$I_{AF_{i}} = \frac{1}{M+1} \log_{2} \left( 1 + \gamma_{sd} + \sum_{i=1}^{M} \gamma_{i} \right)$$
(3.44)

As the Rayleigh fading channel is being considered, the pdf of  $\gamma_{sd}$  has the same expression as found in (3.26). Due to the nature of the summation, this thesis first considered the outage probability analysis for M = 1 relay and then for M = 2relays. • When only one relay (M = 1) assists the source, then  $\gamma_i = \gamma_1$ . The cdf of  $\gamma_1$  is:

$$F_{\gamma_1}(\gamma) = 1 - \mathcal{P}(\gamma_{sr_1} > \gamma) \mathcal{P}(\gamma_{r_1d} > \gamma)$$
(3.45)

$$F_{\gamma_1}(\gamma) = 1 - e^{-\left(\frac{1}{\lambda_{sr_1}} + \frac{1}{\lambda_{r_1d}}\right)\gamma}$$
(3.46)

Taking into account the independence of both variables, the outage probability for the single relay assisted AF system is the cdf of  $\gamma_{th_1} = \gamma_{sd} + \gamma_1$  which is defined as  $F_{\gamma_{th_1}}(\gamma_{th})$  and mathematically

$$F_{\gamma_{th_1}}(\gamma_{th}) = \int_{0}^{\gamma_{th}} p_{\gamma_{sd}}(\gamma) F_{\gamma_1}(\gamma_{th} - \gamma) d\gamma \qquad (3.47)$$

Finally, substituting (3.26) and (3.45) into (3.47) and simplifying the integral:

$$P_{out_{1}} = \frac{\frac{1}{\lambda_{sd}} \left(1 - e^{-\left(\frac{1}{\lambda_{sr_{1}}} + \frac{1}{\lambda_{r_{1}d}}\right)\gamma_{th}}\right) - \left(\frac{1}{\lambda_{sr_{1}}} + \frac{1}{\lambda_{r_{1}d}}\right) \left(1 - e^{-\frac{\gamma_{th}}{\lambda_{sd}}}\right)}{\left(\frac{1}{\lambda_{sd}} - \frac{1}{\lambda_{sr_{1}}} - \frac{1}{\lambda_{r_{1}d}}\right)}$$
(3.48)

• When both of the two relays (M = 2) transmit, then  $\gamma_i = \gamma_1 + \gamma_2$ . Since  $\gamma_1$  and  $\gamma_2$  are independent, the pdf of  $\gamma_1 + \gamma_2$  is obtained with help of [68] as:

$$p_{(\gamma_1+\gamma_2)}(\gamma) = \int_{0}^{\gamma} p_{\gamma_1}(x) p_{\gamma_2}(\gamma-x) d\gamma \qquad (3.49)$$

To simplify the calculation, this thesis assumes:  $\gamma_{sr_1} + \gamma_{r_1d} = \gamma_{sr_1d}$  and  $\gamma_{sr_2} + \gamma_{r_2d} = \gamma_{sr_2d}$  for simplification of calculation. By integrating pdf in (3.49), the cdf  $F_{(\gamma_1+\gamma_2)}$  is obtained as:

$$F_{(\gamma_1+\gamma_2)}(\gamma) = \frac{\frac{1}{\lambda_{sr_1d}} \left(1 - e^{-\frac{\gamma}{\lambda_{sr_2d}}}\right) - \frac{1}{\lambda_{sr_2d}} \left(1 - e^{-\frac{\gamma}{\lambda_{sr_2d}}}\right)}{\frac{1}{\lambda_{sr_1d}} - \frac{1}{\lambda_{sr_2d}}}$$
(3.50)

Now, the outage probability for two relays in transmission can be evaluated using (3.51) as:

$$F_{\gamma_{th_2}}(\gamma_{th}) = \int_{0}^{\gamma_{th}} p_{\gamma_{sd}}(\gamma) F_{(\gamma_1 + \gamma_2)}(\gamma_{th} - \gamma) d\gamma$$
(3.51)

Finally the outage probability expression is:

$$P_{out_{2}} = \frac{\frac{\frac{1}{\lambda_{sr_{1}d}}e^{-\frac{\gamma_{th}}{\lambda_{sr_{2}d}}}}{\frac{1}{\lambda_{sd}} - \frac{1}{\lambda_{sr_{2}d}}} - \frac{\frac{1}{\lambda_{sr_{2}d}}e^{-\frac{\gamma_{th}}{\lambda_{sr_{1}d}}}}{\frac{1}{\lambda_{sr_{1}d}} - \frac{1}{\lambda_{sr_{2}d}}} - \frac{\left(\frac{1}{\lambda_{sr_{1}d}} - \frac{1}{\lambda_{sr_{2}d}}\right)}{\frac{1}{\lambda_{sd}} - \frac{1}{\lambda_{sr_{2}d}}}\right) \frac{\left(1 - e^{-\frac{\gamma_{th}}{\lambda_{sd}}}\right)}{\left(\frac{1}{\lambda_{sd}} - \frac{1}{\lambda_{sr_{2}d}}\right)\left(\frac{1}{\lambda_{sd}} - \frac{1}{\lambda_{sr_{1}d}}\right)}}{\lambda_{sd} \left(\frac{1}{\lambda_{sr_{1}d}} + \frac{1}{\lambda_{sr_{2}d}}\right)}$$
(3.52)

#### 3.4.4 Amplify-and-Forward (AF) Cognitive Relay Networks

For the AF cognitive relay network, the outage probability can be obtained in a similar way as Subsection 3.4.2 for the DF cognitive relay networks. The outage probability can be presented according to (3.33) as:

• Single relay cognitive network (M = 1):

$$P_{cog_{1}} = \sum_{i=0}^{M} \left( \binom{M}{i} C_{d}^{i} (1 - C_{d})^{M-i} \right) \frac{1}{\lambda_{sd} \left( \frac{1}{\lambda_{sd}} - \frac{1}{\lambda_{sr_{1}}} - \frac{1}{\lambda_{r_{1}d}} \right)} \left( \left( \left( 1 - e^{-\left(\frac{1}{\lambda_{sr_{1}}} + \frac{1}{\lambda_{r_{1}d}}\right)\gamma_{th}} \right) - \left( \frac{1}{\lambda_{sr_{1}}} + \frac{1}{\lambda_{r_{1}d}} \right) \left( 1 - e^{-\frac{1}{\lambda_{sd}}\gamma_{th}} \right) \right)$$

$$(3.53)$$

• Two relay cognitive network (M = 2):

$$P_{cog_{2}} = \sum_{i=0}^{M} \left( \binom{M}{i} C_{d}^{i} (1 - C_{d})^{M-i} \right) \frac{1}{\lambda_{sd} \left( \frac{1}{\lambda_{sr_{1}d}} + \frac{1}{\lambda_{sr_{2}d}} \right)} \left( \frac{\frac{1}{\lambda_{sr_{2}d}} - \frac{\gamma_{th}}{\lambda_{sr_{2}d}}}{\frac{1}{\lambda_{sd}} - \frac{1}{\lambda_{sr_{2}d}}} - \frac{\frac{1}{\lambda_{sr_{2}d}} - \frac{\gamma_{th}}{\lambda_{sr_{1}d}}}{\frac{1}{\lambda_{sd}} - \frac{1}{\lambda_{sr_{2}d}}} - \frac{\frac{1}{\lambda_{sr_{2}d}} - \frac{1}{\lambda_{sr_{2}d}}}{\frac{1}{\lambda_{sd}} - \frac{1}{\lambda_{sr_{1}d}}} - \frac{\frac{1}{\lambda_{sr_{2}d}} - \frac{1}{\lambda_{sr_{2}d}}}{\frac{1}{\lambda_{sd}} - \frac{1}{\lambda_{sr_{2}d}}} - \frac{\frac{1}{\lambda_{sr_{2}d}} - \frac{1}{\lambda_{sr_{2}d}}}{\frac{1}{\lambda_{sd}} - \frac{1}{\lambda_{sr_{1}d}}}} - \frac{\frac{1}{\lambda_{sr_{2}d}} - \frac{1}{\lambda_{sr_{2}d}}}{\frac{1}{\lambda_{sd}} - \frac{1}{\lambda_{sr_{2}d}}} - \frac{1}{\lambda_{sr_{2}d}} - \frac{1}{\lambda_{sr_{2}d}}} - \frac{1}{\lambda_{sr_{2}d}} - \frac{1}{\lambda_{sr_{2}d}}} - \frac{1}{\lambda_{sr_{2}d}} - \frac{1}{\lambda_{sr_{2}d}} - \frac{1}{\lambda_{sr_{2}d}}}{\frac{1}{\lambda_{sr_{2}d}} - \frac{1}{\lambda_{sr_{2}d}}} - \frac{1}{\lambda_{sr_{2}d}} - \frac{1}{\lambda_{sr_{2}d}} - \frac{1}{\lambda_{sr_{2}d}}} - \frac{1}{\lambda_{sr_{2}d}} - \frac{1}{\lambda_{sr_{2}d}} - \frac{1}{\lambda_{sr_{2}d}}} - \frac{1}{\lambda_{sr_{2}d}} - \frac{1}{\lambda_{sr_{2}d}}} - \frac{1}{\lambda_{sr_{2}d}} - \frac{1}{\lambda_{sr_{2}d}}} - \frac{1}{\lambda_{sr_{2}d}} - \frac{1}{\lambda_{sr_{2}d}} - \frac{1}{\lambda_{sr_{2}d}}} - \frac{1}{\lambda_{sr_{2}d}} - \frac{1}{\lambda_{sr_{2}d}}} - \frac{1}{\lambda_{sr_{2}d}} - \frac{1}{\lambda_{sr_{2}d}} - \frac{1}{\lambda_{sr_{2}d}} - \frac{1}{\lambda_{sr_{2}d}}} - \frac{1}{\lambda_{sr_{2}d}} - \frac{1}{\lambda_{sr_{2}d}}} - \frac{1}{\lambda_{sr_{2}d}} - \frac{1}{\lambda_{sr_{2}d}} - \frac{1}{\lambda_{sr_{2}d}}} - \frac{1}{\lambda_{sr_{2}d}} - \frac{1}{\lambda_{sr_{2}d}} - \frac{1}{\lambda_{sr_{2}d}}} - \frac{1}{\lambda_{sr_{2}d}} - \frac{1}{\lambda_{sr_$$

#### **3.5** Results and Discussions

This section presents the outage probability for the cooperative and the cognitive networks with DF and AF relaying schemes respectively. The networks are assumed to have slowly faded independent and identically distributed Rayleigh channels. The presented results are valid for arbitrary SNR. Hence, the network can be realized for a practical model of cooperative/cognitive relays. Although the results are presented for up to M = 3 relays in the networks, they can be extended for an arbitrary number of relays. For all figures below, lines (both solid and dashed) indicate analytical results and markers indicate simulation results.

A comparison of outage probability for DF cooperative relay networks is presented in Figure 3.4. Figure 3.5 presents the comparison of outage probability for DF cognitive relay network at a spectrum acquisition probability of  $C_d = 0.7$ . The outage probability in this case is much higher than that of cooperative relay networks. The higher outage probability is the indication of performance degradation due to the unavailability of the spectrum. The outage probability improves if the spectrum can be acquired with a higher probability. Hence, the performance of the cognitive relay network is entirely dependent on the acquisition of the spectrum.

A comparison of the outage probability of the DF cooperative and cognitive relay networks has been presented for  $C_d = 0.7$  in Figure 3.6. At an outage probability of  $10^{-3}$ , cognitive networks have an equivalent SNR loss of 10 dB, 10.5 dB and 10



Figure 3.4: Comparison of outage probability of DF cooperative relay networks  $(C_d = 1.0)$ .



Figure 3.5: Comparison of outage probability of DF cognitive relay networks ( $C_d = 0.7$ ).



Figure 3.6: Comparison of outage probability of DF cooperative  $(C_d = 1.0)$  and cognitive relay networks  $(C_d = 0.7)$ .



Figure 3.7: Outage probability of DF cognitive relay network for M = 1 relay with different  $C_d$ . The curves correspond to  $C_d = 0$  and  $C_d = 1$  represent no relays in transmission and cooperative relay network respectively.



Figure 3.8: Comparison of outage probability of AF cooperative relay networks  $(C_d = 1.0)$ .

dB compared to the cooperative networks for M = 1, 2 and 3 relay(s) respectively.

The performance of a cognitive relay network can be improved by incorporating a higher  $C_d$  as presented in Figure 3.7 for M = 1 relay. At the outage probability of  $10^{-3}$ , there is an equivalent SNR gain of 8 dB, when  $C_d$  improves from 0.7 to 0.9. With even higher  $C_d$ , the benchmark performance ( $C_d = 1.0$ ) can be achieved. An interesting observation found from Figure 3.6 and Figure 3.7 is that there is an equivalent SNR gain of 5 dB at  $C_d = 0.7$  for the same outage probability compared to the non-relay case,  $C_d = 0$ . The simulation results match the analytical results exactly for DF relaying scheme.

A comparison of outage probability of AF cooperative relay networks are presented in Figure 3.8. The outage probability for the AF cognitive relay networks has been compared for  $C_d = 0.7$  in Figure 3.9. Figure 3.9 exhibits a significant change in the outage probability compared to the cooperative AF cooperative relay networks.

For  $C_d = 0.7$ , the outage probability of AF cooperative and cognitive relay



Figure 3.9: Comparison of outage probability of AF cognitive relay networks ( $C_d = 0.7$ ).



Figure 3.10: Comparison of outage probability of AF cooperative  $(C_d = 1.0)$  and cognitive relay  $(C_d = 0.7)$  networks.



Figure 3.11: Outage probability of AF cognitive relay network for M = 1 relay with different  $C_d$ . The curves correspond to  $C_d = 0$  and  $C_d = 1$  represent no relays in transmission and cooperative relay network respectively.

network have been compared in Figure 3.10. At an outage probability of  $10^{-3}$ , there is an equivalent SNR loss of 11 dB, 11.5 dB and 12 dB in AF cognitive networks compared to the AF cooperative networks for M = 1, 2 and 3 relay(s). Lastly, an improvement of performance for M = 1 relay has been presented in Figure 3.11 with the higher probability of spectrum availability. As  $C_d$  increases from 0.7 to 0.9, the AF cognitive relay network achieves an equivalent SNR gain of 8 dB. This Figure also exhibits that the AF cognitive relay network has an equivalent SNR gain of 5 dB compared to the non-relay scenario,  $C_d = 0$ . As this thesis adopts the bound based approach, the simulation result is an upper bound for lower SNR region (0 - 10) dB and matches exactly for medium to high SNR. Hence, the bound presented is tight and a good approximation of the actual results in low SNR regimes.

From the Figures (Figure 3.4, Figure 3.5, Figure 3.8 and Figure 3.9), it has been observed that more relays in the network does not always reduce (specially at low SNR) the outage probability for repetition-based relaying. Due to the time division fashion, in which the protocols operate and unavailability of the spectrum, increasing numbers of transmitting relays can increase the outage probability.

The evaluated outage probability expressions of the repetition-based network can be realized more practically as they are valid at arbitrary SNR. The previous work in [38], [62] and [63] were only valid for the high SNR regime. Unlike [63], this research has utilized pdf based approach to evaluate the outage probability expressions. The pdf based approach avoids hypergeometric functions and can be easily translated into other performance metrics, i.e bit error rate. The outage probability expressions of AF repetition-based network are realized for multiple relay networks where the work in [54] and [64] only realize a single relay network.

#### 3.6 Summary

In this chapter, a detailed discussion on the repetition-based cognitive relay network model has been included. The energy detection model for sensing an available spectrum band has been included for clarification. The closed-form outage probability expressions of DF and AF cognitive relay network have been derived for arbitrary SNR. The performance the cognitive relay networks has been compared to that of cooperative relay networks. DF and AF cognitive relay networks face an equivalent SNR loss of up to 10.5 dB and 12 dB for  $C_d = 0.7$  at a given outage probability. However, the networks achieve an equivalent SNR gain of 5 dB compared to no relay in the transmission at all. As  $C_d$  increases, the gain also increases resulting a lower outage probability. For repetition-based relay networks, specially at low SNR regimes the increase of number of relays does not improve the outage probability. Simulation results and discussions are also presented to validate the numerical analyses.

In the next chapter, the proposed selection-based cognitive relay network model will be presented. The chapter will explain the selection criteria for relays. The closed-form expressions of the outage probability for selection-based networks will be derived in the chapter. A discussion on the results will also be included. Simulation results will be presented to support the analytical results.

# Chapter 4

# Selection-Based Cognitive Relay Network

A limitation of the repetition-based relaying protocol is the bandwidth expansion due to the time division protocol used in the transmission. As an alternative, works in [63, 79] presented a selection-based relaying scheme where a single relay with the largest SNR is chosen for transmission. Therefore, this relaying technique has a prelog term of  $\frac{1}{2}$  in (3.23) and (3.41) for DF and AF relaying schemes respectively. In this chapter, the performance of the selection-based relaying scheme with cognitive radio is studied by providing the closed-form expressions for the outage probability.

## 4.1 Network Model of Selection-Based Cognitive Relay Network

Figure 4.1 presents the selection-based cognitive relay network. The transmission in the network follows the broadcast step in which the source broadcasts the information to the destination and the relays. After the broadcast step, the relays process the received signal in the processing step. The relays then enter into the spectrum sensing step to obtain available spectrum for transmission.

The best relay is selected in the selection step. To select the best relay, the destination needs to have CSI. The spectrum is then sensed for the best relay in the spectrum sensing step. Only if the spectrum is available, the best relay is allowed to



Figure 4.1: Selection-based cognitive relay network.

enter into the forwarding step. In the forwarding step, the best relay forwards the processed information to the destination and the destination combines the signals received from the best relay and the source in the combining step.

## 4.2 Selection Criterion

The criterion for selection of the best relay is different for DF and AF relaying schemes. They will be discussed in this section.

DF Relaying: For DF relaying, the best relay is selected among the set of decoding relays. The destination selects the strongest relay-to-destination (R-D) channel based on the instantaneous SNR to select the best relay. Hence, the best relay is with :

$$\gamma_{max} = \arg \max(\gamma_{r_{R(s)}d}) \tag{4.1}$$

where  $\gamma_{r_{R(s)}d}$  is the SNR for the relay-destination link and R(S) includes the relaying set.

- AF Relaying: In AF relaying, the best relay can be selected based on the following criteria:
  - Source-relay-destination (S-R-D) channel: To select the best relay depending on the maximum instantaneous e2e SNR of the S-R-D link is actually to select the relay with maximum  $\gamma_i$  presented in (3.43). This selection is also known as cascaded selection. Hence, the selection criterion can be expressed as:

$$\gamma_{s_{s-r-d}} = \max\left(\gamma_i\right) = \max\left(\min\left(\gamma_{sr_i}, \gamma_{r_id}\right)\right) \tag{4.2}$$

The performance of the  $\gamma_{s_{s-r-d}}$  is dominated by the worst link between the source-relay and relay-destination channel.

- Source-relay (S-R) channel: This is also known as partial relay selection as only the S-R channel is taken into consideration. The partial relay selection based on the S-R CSI can prolong the life time of a resourceconstrained wireless network [70]. So, (4.2) can be written as:

$$\gamma_{s_{s-r}} = \min\left(\max(\gamma_{sr_i}), \gamma_{r_id}\right) \tag{4.3}$$

Due to the impact of the source-relay link on the relay-destination link of the CSI assisted AF relays, selection of the best relay-destination (R-D) link results in a similar performance as the selection of the best sourcerelay channel. So, selection of the R-D link for analysing the outage probability has been omitted.

#### 4.3 Outage Probability

In this section, the closed-form outage probability of the selection-based DF and AF cooperative relay networks are derived to present the benchmark results. Then, the outage probability of a selection-based DF and AF cognitive relay network has been derived. The following four subsections represent the contributions of the thesis.

#### 4.3.1 Decode-and-Forward (DF) Selection-Based Cooperative Relay Networks

For a cooperative relay network with selection relaying, the signals received at the destination and relays are given in (3.12) and (3.13). When the best relay is selected, the relay retransmits to the destination following (3.21). At the destination the mutual information of the transmitted signals for the selection-based relaying scheme is obtained as follows by modifying (3.23) for M = 1.

$$I_{DF_{sel}} = \frac{1}{2} \log_2 \left( 1 + \gamma_{sd} + (\gamma_{r_{R(s)}d}) \right)$$

$$(4.4)$$

Regardless of the number of relays presented in the network, only the best relay is selected for transmission, M is always one and results in a pre-log term of  $\frac{1}{2}$ .

Conditioned on the decoding set  $\Pr[I_{DF_{sel}} < R || R(s) | = 1, 2, ..., M]$ , the outage probability is

$$P_{out} = \Pr\left[I_{DF_{sel}} < R \left| R\left(s\right)\right] \Pr\left[R\left(s\right)\right]$$

$$(4.5)$$

The probability of  $\Pr\left[I_{DF_{sel}} < R | R(s)\right] = 1, 2, \dots, M$  is given by:

$$\Pr[\gamma_{sd} + \max(\gamma_{r_{R(s)}d})] < 2^{2R} - 1 \tag{4.6}$$

For simplicity of the calculation,  $Z_1 = \gamma_{sd}$ ,  $Z_2 = \max(\gamma_{r_{R(s)}d})$  and  $\gamma_{th} = 2^{2R} - 1$ are substituted in (4.6). The cdf of the RV Z is defined as  $Z = Z_1 + Z_2$ . The pdf of  $Z_1$  is as in (3.26). The cdf of  $Z_2$  is exponentially distributed with the variance  $\lambda_{r_{R(s)}d}$ ,  $R_s = 1, 2, \dots M$ . For sake of simplicity, this thesis assumes that all sourcerelay channels have the same fading characteristics ( $\gamma_{sr_1} = \gamma_{sr_2} = \dots = \gamma_{sr}$ ) and all relay-destination channels have the same fading characteristics ( $\gamma_{r_1d} = \gamma_{r_2d} = \dots = \gamma_{rd}$ ). Hence, the cdf of  $Z_2$  is given by:

$$F_{Z_2}(z) = (1 - e^{-\frac{z}{\lambda_{rd}}})^M$$
(4.7)

Using the binomial theorem (4.7) can be re-written as:

$$F_{Z_2}(z) = \sum_{i=0}^{M} \left(-1\right)^i \left(\begin{array}{c}M\\i\end{array}\right) e^{-i\frac{z}{\lambda_{rd}}}$$

$$(4.8)$$

Taking into account that  $Z_1$  and  $Z_2$  are independent RVs, the cdf of  $F_Z$  can be expressed with help of [68] as:

$$F_Z(z) = \int_0^z F_{Z_2}(z-x)p_{Z_1}(x)dx$$
(4.9)

where  $p_{Z_1}(x)$  is the pdf of the  $Z_1$ . Therefore,

$$F_Z(z) = \frac{1}{\lambda_{sd}} \sum_{i=0}^M \left(-1\right)^i \left(\begin{array}{c}M\\i\end{array}\right) e^{-i\frac{z}{\lambda_{rd}}} \int\limits_0^z e^{-\left(\frac{1}{\lambda_{sd}} - \frac{i}{\lambda_{rd}}\right)x} dx \tag{4.10}$$

After simplifying the integral, (4.10) becomes

$$F_Z(z) = \frac{1}{\lambda_{sd}} \sum_{i=0}^M \left(-1\right)^i \begin{pmatrix} M \\ i \end{pmatrix} \frac{e^{-\left(\frac{1}{\lambda_{sd}} - \frac{i}{\lambda_{sr}}\right)x}}{\frac{1}{\lambda_{sd}} - \frac{i}{\lambda_{rd}}}$$
(4.11)

 $\Pr[R(s)]$  can be found from (3.30). Hence, substituting (4.11) and (3.30) into (4.5), the final expression of outage probability for selection-based DF cooperative relay network is obtained as follows:

$$P_{out} = \sum_{i=0}^{M} \binom{M}{i} \left(e^{-\frac{\gamma_{th}}{\lambda_{sr}}}\right)^{i} \left(1 - e^{-\frac{\gamma_{th}}{\lambda_{sr}}}\right)^{M-i} \frac{1}{\lambda_{sd}} \sum_{n=0}^{i} \left(-1\right)^{n} \binom{i}{n} \frac{e^{-\left(\frac{1}{\lambda_{sd}} - \frac{n}{\lambda_{sr}}\right)\gamma_{th}}}{\frac{1}{\lambda_{sd}} - \frac{n}{\lambda_{sr}}}$$

$$(4.12)$$

#### 4.3.2 Decode-and-Forward (DF) Selection-Based Cognitive Relay Networks

The outage probability for the selection-based cognitive relay network can be obtained by including the effect of the probability of acquiring spectrum,  $C_d$  using (3.33). As the performance of the cognitive relay is dependent on the spectrum acquisition, the selected relay can not transmit until it acquires the spectrum. So, finally the outage probability including the probability of acquiring the spectrum is:

$$P_{cog} = \sum_{i=0}^{M} {\binom{M}{i}} C_d^i (1 - C_d)^{M-i}$$

$$\left(\sum_{i=0}^{M} {\binom{M}{i}} (e^{-\frac{\gamma_{th}}{\lambda_{sr}}})^i (1 - e^{-\frac{\gamma_{th}}{\lambda_{sr}}})^{M-i} \frac{1}{\lambda_{sd}} \sum_{n=0}^{i} (-1)^n {\binom{i}{n}} \frac{e^{-(\frac{1}{\lambda_{sd}} - \frac{n}{\lambda_{sr}})\gamma_{th}}}{\frac{1}{\lambda_{sd}} - \frac{n}{\lambda_{sr}}}\right)$$

$$(4.13)$$

#### 4.3.3 Amplify-and-Forward (AF) Selection-Based Cooperative Relay Networks

For AF selection cooperative relaying, the source sends the signal to the relays and the destination as in (3.12) and (3.13). The relay amplifies the signal and sends to the destination according to (3.35). Based on the selection criteria, the mutual information at the destination is expressed as:

• For S-R-D link selection criterion:

$$I_{AF_{sel}} = \frac{1}{2} \log_2 \left( 1 + \gamma_{sd} + \left( \gamma_{s_{s-r-d}} \right) \right) \tag{4.14}$$

• For S-R link selection criterion:

$$I_{AF_{sel}} = \frac{1}{2} \log_2 \left( 1 + \gamma_{sd} + \left( \gamma_{s_{s-r}} \right) \right) \tag{4.15}$$

For simplicity of the calculation, the outage probability of a selection-based AF cooperative relay network has been derived for M = 2 relays. In a similar way, the results can be extended to an arbitrary number of relays. For simplicity of calculation,  $\frac{1}{sr_1d} = \frac{1}{sr_1} + \frac{1}{r_1d}$ ,  $\frac{1}{sr_2d} = \frac{1}{sr_2} + \frac{1}{r_2d}$  and  $\frac{1}{sr_Td} = \frac{1}{sr_1} + \frac{1}{r_1d} + \frac{1}{sr_2} + \frac{1}{r_2d}$  are assumed. For the two relay network with the help of [69, 70], the cdf of (4.2) and (4.3) can be found as:

• For S-R-D selection criterion:

$$F_{\gamma_{s_{s-r-d}}}(\gamma) = \left(1 - e^{-\frac{\gamma}{\lambda_{sr_1d}}} - e^{-\frac{\gamma}{\lambda_{sr_2d}}} + e^{-\frac{\gamma}{\lambda_{sr_Td}}}\right)$$
(4.16)

• For S-R selection criterion:

$$F_{\gamma_{s_{s-r}}}(\gamma) = \left(1 - e^{-\frac{\gamma}{\lambda_{sr_1d}}} - e^{-\frac{\gamma}{\lambda_{sr_2d}}} \left(1 - e^{-\frac{1}{\lambda_{r_1d}}\gamma}\right)\right)$$
(4.17)

where,  $\gamma_{sr_i}$  and  $\gamma_{r_id}$  are exponentially distributed with the parameters  $\lambda_{sr_i}$  and  $\lambda_{r_id}$ .

The outage probability for a selection-based cooperative relay network can now be obtained following a similar equation as (3.47). Final expressions of outage probability are presented in the following equations:

• For S-R-D selection criterion:

$$P_{out} = 1 - e^{-\frac{\gamma_{th}}{\lambda_{sd}}} - \lambda_{sr_2}\lambda_{r_2d}\frac{e^{-\frac{\gamma_{th}}{\lambda_{sr_2d}}} - e^{-\frac{\gamma_{th}}{\lambda_{sd}}}}{\lambda_{sr_2}(\lambda_{r_2d} - \lambda_{sd}) - \lambda_{r_2d}\lambda_{sd}} - \frac{\lambda_{sr_1}\lambda_{r_1d}}{\lambda_{sr_1}(\lambda_{r_1d} - \lambda_{sd}) - \lambda_{r_1d}\lambda_{sd}}} \left(e^{-\frac{\gamma_{th}}{\lambda_{sr_2d}}} - e^{-\frac{\gamma_{th}}{\lambda_{sd}}}}\right) + \frac{\lambda_{sr_1}\lambda_{r_1d}\lambda_{sr_2}\lambda_{r_2d}\left(e^{-\frac{\gamma_{th}}{\lambda_{sd}}} - e^{-\frac{\gamma_{th}}{\lambda_{sd}}}\right)}{\lambda_{sr_1}\lambda_{sr_2}\lambda_{r_2d}\lambda_{sd} + \lambda_{sr_1}(\lambda_{sr_1}\lambda_{sr_2}\lambda_{sd} + \lambda_{r_2d}(\lambda_{sr_2}\lambda_{sd} + \lambda_{sr_1}(\lambda_{sr_2}\lambda_{sd} - \lambda_{sr_2})))}$$

$$(4.18)$$

• For S-R selection criterion:

$$P_{out} = 1 - e^{-\frac{1}{\lambda_{sd}}\gamma_{th}} - \lambda_{sr_1}\lambda_{r_1d}\frac{e^{-\frac{\gamma_{th}}{\lambda_{sd}}} - e^{-\frac{\gamma_{th}}{\lambda_{sr_1d}}}}{\lambda_{sd\lambda_{sr_1d}} - \lambda_{sr_1}\lambda_{r_1d}} - \lambda_{sr_2}\lambda_{r_2d}\frac{e^{-\frac{\gamma_{th}}{\lambda_{sd}}} - e^{-\frac{\gamma_{th}}{\lambda_{sr_2d}}}}{\lambda_{sd\lambda_{sr_2d}} - \lambda_{sr_2}\lambda_{r_2d}\lambda_{sr_2d} - \lambda_{sr_2}\lambda_{r_2d}} + \frac{\lambda_{sr_2}\lambda_{r_1d\lambda_{r_2d}}\left(e^{-\frac{\gamma_{th}}{\lambda_{sd}}} - e^{-\frac{\gamma_{th}}{\lambda_{sr_2d}}}\right)}{\lambda_{sd}(\lambda_{sr_2}\lambda_{r_2d} + \lambda_{r_1d}\lambda_{sr_2d}) - \lambda_{sr_2}\lambda_{r_1d}\lambda_{r_2d}}$$

$$(4.19)$$

#### 4.3.4 Amplify-and-Forward (AF) Selection-Based Cognitive Relay Networks

Outage probability for the selection-based AF cognitive relay network is also dependent on the availability of the spectrum. Although the relay is being selected for transmission, transmission does not occur if the spectrum is not available. Hence, the performance of the network degrades. The outage probability of the selectionbased AF cognitive relay network can easily be obtained using (3.33) as in Chapter 3.

• For S-R-D selection criterion:

$$P_{cog} = \sum_{i=0}^{M} {\binom{M}{i}} C_d^i (1 - C_d)^{M-i} \left( 1 - e^{-\frac{\gamma_{th}}{\lambda_{sd}}} - \lambda_{sr_2} \lambda_{r_2d} \frac{e^{-\frac{\gamma_{th}}{\lambda_{sr_2d}}} - e^{-\frac{\gamma_{th}}{\lambda_{sd}}}}{\lambda_{sr_2} (\lambda_{r_2d} - \lambda_{sd}) - \lambda_{r_2d} \lambda_{sd}} \right. \\ \left. + \frac{\lambda_{sr_1} \lambda_{r_1d} \lambda_{sr_2} \lambda_{r_2d}}{\lambda_{sr_1} \lambda_{sr_2} \lambda_{sd} + \lambda_{sr_1} (\lambda_{sr_1} \lambda_{sr_2} \lambda_{sd} + \lambda_{r_2d} (\lambda_{sr_2} \lambda_{sd} + \lambda_{sr_1} (\lambda_{sd} - \lambda_{sr_2})))} \left( e^{-\frac{\gamma_{th}}{\lambda_{sd}}} - e^{-\frac{\gamma_{th}}{\lambda_{sr_Td}}} \right) \\ \left. - \frac{\lambda_{sr_1} \lambda_{r_1d}}{\lambda_{sr_1} (\lambda_{r_1d} - \lambda_{sd}) - \lambda_{r_1d} \lambda_{sd}} \left( e^{-\frac{\gamma_{th}}{\lambda_{sr_2d}}} - e^{-\frac{\gamma_{th}}{\lambda_{sd}}} \right) \right)$$

$$(4.20)$$

• For S-R selection criterion:

$$P_{cog} = \sum_{i=0}^{M} \binom{M}{i} C_{d}^{i} (1-C_{d})^{M-i} \left( 1 - e^{-\frac{1}{\lambda_{sd}}\gamma_{th}} - \lambda_{sr_{1}}\lambda_{r_{1}d} \frac{e^{-\frac{\gamma_{th}}{\lambda_{sd}}} - e^{-\frac{\gamma_{th}}{\lambda_{sr_{1}d}}}}{\lambda_{sd\lambda sr_{1}d} - \lambda_{sr_{2}}\lambda_{r_{2}d} \frac{e^{-\frac{\gamma_{th}}{\lambda_{sd}}} - e^{-\frac{\gamma_{th}}{\lambda_{sr_{2}d}}}}{\lambda_{sd\lambda sr_{2}d} - \lambda_{sr_{2}}\lambda_{r_{2}d}} + \lambda_{sr_{2}}\lambda_{r_{1}d}\lambda_{r_{2}d} \frac{\left(e^{-\frac{\gamma_{th}}{\lambda_{sd}}} - e^{-\frac{\gamma_{th}}{\lambda_{sr_{2}d}}}\right)}{\lambda_{sd}\left(\lambda_{sr_{2}}\lambda_{r_{2}d} + \lambda_{r_{1}d}\lambda_{sr_{2}d}\right)}\right)}$$

$$(4.21)$$

#### 4.4 **Results and Discussions**

This section presents the results of selection-based cooperative and cognitive relay networks for DF and AF relaying. Figure 4.2 compares the outage probability of the repetition-based and the selection-based cooperative DF networks for M = 2and 3 relays. There is an equivalent SNR gain of 7 dB and 11 dB in selectionbased protocol for M = 2 and M = 3 relays respectively at an outage probability of  $10^{-3}$  compared to the repetition-based relaying. Figure 4.3 compares the outage probability of the repetition-based and selection-based cognitive DF relay network for  $C_d = 0.7$ . Even with this lesser probability of spectrum availability, the selectionbased cognitive networks have an equivalent SNR gain of 4 dB and 7 dB more for M = 2 and 3 relays respectively at an outage probability of  $10^{-3}$ . Figure 4.4 shows that there is a significant equivalent SNR gain of 10 dB for above statistics compared to the non-relay case. A further gain of 20 dB can be obtained as  $C_d$  approaches to 1.

Figure 4.5 presents a comparison of the outage probability among the repetitionbased, S-R selection-based and S-R-D selection-based cooperative relay networks for M = 2 and 3 relays. Unfortunately, S-R-D selection-based relaying gains only up to 2 dB of equivalent SNR at an outage probability of  $10^{-3}$  for M = 2 relays. There is a penalty of another 1 dB for the S-R selection-based network. As the number of relays in the network increases to 3, the S-R-D selection-based network gains an equivalent SNR of 6 dB. There is a similar penalty for S-R selection-based relaying



Figure 4.2: Comparison of outage probability between repetition and selection-based DF cooperative relay network ( $C_d = 1.0$ ).



Figure 4.3: Comparison of outage probability between repetition and selection-based DF cognitive relay network ( $C_d = 0.7$ ).



Figure 4.4: Improvement of outage probability with improvement of  $C_d$  for DF selection-based cognitive relay network.  $C_d = 0$  represents a non-relay scenario and  $C_d = 1$  represents the cooperative network.



Figure 4.5: Comparison of outage probability between selection-based and repetition-based AF cooperative relay network  $(C_d = 1.0)$ .



Figure 4.6: Comparison outage probability between selection-based and repetitionbased AF cognitive relay network ( $C_d = 0.7$ ).



Figure 4.7: Performance improvement of selection-based AF cognitive relay network with improved  $C_d$ .  $C_d = 0$  represents a non-relay scenario and  $C_d = 1$  represents the cooperative network.

resulting the equivalent SNR gain to 5 dB. This reason behind the penalty is that the performance of an AF relay network is dependent on both the source-relay and the relay-destination links. For AF cognitive relay network, the outage probability of selection-based networks have been compared with the repetition-based cognitive relay network for the probability of spectrum acquisition of  $C_d = 0.7$  in Figure 4.6. The cognitive selection-based networks faces an equivalent SNR loss of 5 dB and 9 dB for M = 2 and 3 relays compared to the repetition-based networks. This Figure also indicates that there is a higher loss of equivalent SNR for cognitive selection-based networks than that of repetition-based networks. Figure 4.7 presents an improvement of the performance of the selection-based network with the improvement of  $C_d$ . There is an equivalent SNR gain of 10 dB at  $C_d = 0.7$  compared to the non-relay case. Moreover, another 20 dB equivalent SNR gain can be obtained as  $C_d$  increases to 1.0.

The outage probability expressions of DF selection-based network can be realized for arbitrary SNR which is an improvement over work in [63]. For AF selectionbased networks, the outage probability expressions achieve a tighter bound than work in [64].

#### 4.5 Summary

The selection-based cognitive relay network has been analysed for both DF and AF relaying schemes to obtain closed-form outage probability expressions. The selection criteria employed in the networks have been discussed in detail. In DF relaying scheme, the best relay is selected based on the strongest relay-destination link as the first link doesn't have any impact on the signal sent to the destination. However, for AF relaying, as the relay-destination link always has an impact on the source-relay link, the best way to select a relay is to select the best S-R-D link. In special cases, the selection can also be made based on S-R links with a small penalty in the network performance. It has also been shown how the selection cooperation

leads to bandwidth saving. However, when the spectrum is not available selectionbased relay networks result in a higher outage probability leading to a more degraded network performance than the repetition-based relay networks.

In the next chapter, a conclusion will be drawn on the work presented in this thesis. Also, a number of proposals will be made for further scopes of research in the work.

# Chapter 5 Conclusion and Further Research

## 5.1 Conclusions

Cognitive radio technology is an emerging concept in wireless communications. The cognitive radio technology has the potential to overcome radio spectrum scarcity and serve the increasing demand of the radio spectrum. However, to do so, cognitive radio has to meet the challenge of acquiring unutilized spectrum bands or partially utilized spectrum bands with limited interference to the primary user. In order to cope with the challenge, cooperative relay networks are considered as a key technology. A cognitive relay can extend the network coverage and reduce transmit power. The lower transmit power minimizes the interference to the primary as well as other co-channel users.

This work studied the performance of several cooperative relay networks in a cognitive radio environment. The main contributions were:

• The derivation of closed-form and generic expressions for the outage probability of repetition-based and selection-based decode-and-forward cognitive relay networks. This work was published in IEEE International Conference on Communications (ICC) at Cognitive and Cooperative Wireless Networks Workshop, 2008 [77].

- The development of closed-form outage probability expressions for repetitionbased and selection-based amplify-and-forward cognitive relay networks. Although, these expressions did not have a generic form, they could be intuitively extended for an arbitrary number of relays by repeating the procedure (3.43). This work was published at IEEE International Conference on Signal Processing and Communications Systems (ICSPCS), 2008 [80].
- As a special case, the closed-form outage probability expressions for decodeand-forward and amplify-and-forward cooperative relay networks were obtained. This special case was used as a benchmark for comparing the performance of different cognitive relay networks [77, 80].
- All outage probability expressions were valid for arbitrary signal-to-noise ratios. Previous works in the literature were only valid for high signal-to-noise ratio regimes.

Chapter 1 presented the motivation for the problems considered and analysed in the thesis. The contributions of the thesis were also presented in brief.

Chapter 2 introduced the preliminaries and the background information on cognitive radio and cooperative relay networks. One of the major problems of radio spectrum allocation today is it only allows access to the licensed users even if the spectrum remains unutilized most of the time. FCC's report on licensed spectrum utilization showed that only a 10% of the licensed spectrum bands are in use at any given time. Since the FCC initiated a number of 'notices of inquiry' and 'notices of proposed rule making', cognitive radio came into the picture to utilize the unutilized/underutilized spectrum bands efficiently. The chapter described the overlay and underlay spectrum access approach to cognitive radio. This thesis was concerned with the overlay method. The challenges of making cognitive radio more practical and effective were addressed by introducing cooperative relays into the system. Then followed, a detailed discussion on fixed and adaptive relaying protocols, including 'decode-and-forward' and 'amplify-and-forward'. Cooperation requires combining at the destination, and the chapter concluded with a review of these methods.

Chapter 3 investigated the inclusion of cognitive radio operation into a parallel cooperative multi-relay network. The closed-form expressions of repetition-based decode-and-forward (3.33) and amplify-and-forward (3.53, 3.54) cognitive relay networks were derived for arbitrary signal-to-noise ratio in this chapter. The following interesting observations were found from the results:

- As expected, the outage probability for cognitive relays was much higher than that of cooperative relays because of the latter guaranteed spectrum availability. At a given outage probability of  $10^{-3}$  and probability of spectrum acquisition  $C_d = 0.7$ , the cognitive decode-and-forward relay network performance degraded up to 10.5 dB compared to the cooperative network. In the case of amplify-and-forward the loss was up to 12 dB.
- Even though, cognitive relay networks faced up to a 12 dB loss in performance, there was a significant performance gain of more than 5 dB, compared to the case when there was no relay at all (Figure 3.7, Figure 3.11).
- Repetition-based relay networks did not necessarily reduce outage probability as the number of relays was increased. At the low signal-to-noise ratios the outage probability was particularly sensitive to the need for additional time slots in the time division protocol.

Chapter 4 derived the closed-form outage probability expressions of selectionbased decode-and-forward (4.13) and amplify-and-forward (4.20, 4.21) cognitive relay networks. From these results, the following observations were made:

• The equivalent signal-to-noise ratio of the cooperative selection-based decodeand-forward network ( $C_d = 1.0$ ) was up to 11 dB lower than that of the repetition-based network for the same outage probability.

- The improvement reduced as the probability of the spectrum availability dropped. At  $C_d = 0.7$ , the improvement was up to 7 dB.
- Unexpectedly, amplify-and-forward networks had no significant benefit (2 dB or less) from moving to selection-based operation for a M = 2 relay network. However, there is a significant equivalent SNR gain of up to 6 dB as the number of relays increases to 3.
- Selection-based cognitive relay networks were more sensitive to the loss of spectrum than were the repetition-based networks. If the spectrum was unavailable for the selected relay, then there was no transmission (in this work, the nearest optimum/second best relay was not allowed to transmit). The equivalent signal-to-noise ratio loss was 3 dB more for the selection-based networks when  $C_d$  reduced from 0.9 to 0.7 (Figure 3.7, Figure 3.11, Figure 4.4, Figure 4.7).
- Unlike repetition-based network, the larger the number of relays in a network, the better the selection-based relay network performed.

Analytical results of both Chapter 3 and Chapter 4 were validated through the simulations. For decode-and-forward relaying scheme, the simulation results exactly matched the analytical results. However, for amplify-and-forward relaying scheme, the simulation results were a tight upper bound for low signal-to-noise ratio ((0-10) dB) and matched exactly at medium to high signal-to-noise ratios.

Table 5.1 summarizes the derived outage probability expressions in Chapter 3 and Chapter 4. The equation number indicates the final outage probability expression.

## 5.2 Further Research

This thesis opens up a number of research problems that can be analysed. A few of the possible extensions and scope of this work are as follows:

No.	Network Model	Relaying Scheme	Outage Probability Expression
1	Cooperative	DF	(3.31)
2	Cognitive	DF	(3.34)
3	Cooperative	AF	(3.48), (3.52)
4	Cognitive	AF	(3.53), (3.54)
5	Cooperative	Selection-Based DF	(4.12)
6	Cognitive	Selection-Based DF	(4.13)
7	Cooperative	Selection-Based AF	(4.18), (4.19)
8	Cognitive	Selection-Based AF	(4.20), (4.21)

Table 5.1: A summary of derived outage probability expressions.

- This work has many operational assumptions. For example, the relays know the channel gain they are using as well as the channel gain associated with the other relays. How this knowledge is shared has not been considered. However, what is for sure, this will add additional overheads into the system. One important future work would be to include these overheads by introducing media access protocol. The results would then be more practically meaningful.
- The cognitive relay network presented in this work was based on the Rayleigh fading channel. Future work could include other practical propagation models such as Nakagami or Rician fading.
- Other relaying protocols, for example incremental relaying and less complex combining techniques such as EGC can be considered in these networks. The incremental relaying protocol exploits a limited feedback from the destination terminal, i.e., a single bit indicating the success or the failure of the direct transmission. A relay is only added whenever the source-destination link fails to transmit. This method can improve spectral efficiency over repetition-based and selection-based relaying. In the EGC method, the destination adds signals together using equal weights.
- Adaptive modulation techniques can be introduced. If the link between any

two nodes is strong, then modulation techniques like 16–QAM can be used. When the link is weak the modulation techniques can be switched to the robust BPSK modulation.

- An interesting extension of this work is to analyse cognitive relaying in an underlay environment dealing with power distribution to avoid or minimize the interference created to the primary user.
- Another interesting scope of this work is to extend it using the concept of multiple input multiple output (MIMO) relaying in a cognitive environment.

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