Exploiting the Direct Communication Link for Enhancing Effective Capacity Performance of Cognitive Radio Relay Networks

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Abstract

Nowadays, cognitive radio (CR) is a promising concept to improve the radio spectrum exploitation. CR has tremendous ability to enhance spectrum efficiency by allowing secondary users (SUs) to access licensed radio spectrum resource which is currently not being used by primary users (PUs). One basic challenge of that paradigm is securing the quality of service (QoS) of the primary link transmission while increasing the rate of the secondary links transmission.

Cooperative relaying is an encouraging technology which offers the opportunity to maximize the transmission diversity gain significantly in the rapid development growth of wireless communication which contains cognitive radio networks. On the other hand, effective capacity (EC) which is designed to provide a maximum constant arrival rate that a statistical wireless channels can support while satisfying statistical QoS requirements.

In this thesis, the performance enhancement analysis of cognitive radio relay network (CRRN) by exploiting the direct communication link has been investigated in Rayleigh fading channel where peak interference power constraint is taken into consider. A spectrum sharing technique is considered in this thesis where a restriction of spectrum sharing is applied by the PUs. Here, an SU can coexist simultaneously with the PU for transmitting data as long as a certain threshold on the peak interference power applied on the primary receiver is not overstepped by the SUs transmission. In addition, it is supposed that there are multiple intermediate relay nodes available to transmit their signal to the destination along with a direct communication link for secondary transmission. Moreover, the SU transmission has to meet a random delay QoS constraint. By providing this QoS constraint, the maximum arrival data rate of SUs can be achieved with small error of probability. Specifically, this thesis also acquires closed-form expressions of EC for CRRN. It is evident that if the channel quality and the interference threshold set by the PU are changed, then the capacity of the channel is also to be changed. In addition, it is also verified that the direct communication link together with multiple relay nodes has significantly higher capacity gains compare to non-direct communication link for CRRN. Matlab simulations are presented to find out theoretical results and Monte-Carlo simulations are carried out to support these numerical results. Both the simulation results and the analytical results match very well.

Keywords: Cognitive Radio, Quality of Service (QoS), Effective Capacity, Cooperative Relaying, Cognitive Relay Networks, Peak Interference Power Constraint, Delay QoS Constraint.

This Thesis is Dedicated

to

My Parents

and

Teachers

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List of Abbreviations

AF	Amplify-and-Forward
ATM	Asynchronous Transfer Mode
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
CC	Cooperative Communication
CDF	Cumulative Distribution Function
CR	Cognitive Radio
CRN	Cognitive Relay Networks
CRRN	Cognitive Radio Relay Network
CSI	Channel State Information
CU	Cognitive User
DF	Decode-and-Forward
DSA	Dynamic Spectrum Access
EB	Effective Bandwidth
EC	Effective Capacity
FCC	Federal Communications Commission
i.i.d.	Independent and Identically Distributed
OSA	Opportunistic Spectrum Access

PDF	Probability Density Function
PLCM	Physical Layer Channel Model
PN	Primary Network
PR	Primary Receiver
PT	Primary Transmitter
PU	Primary User
QoS	Quality of Service
RF	Radio Frequency
SN	Secondary Network
SNR	Signal to Noise Ratio
SU	Secondary User

Chapter 1: Introduction

1.1 Introduction

In modern society, radio frequency (RF) spectrum is one of the most scarce and natural resources. RF spectrum demand has extended significantly during the last two decades, because rapid use of high data rate wireless communication equipment's such as wireless metropolitan area network (WMAN), wireless local area network (WLAN), wireless personal area network (WPAN) systems. The national regulation bodies, e.g., Federal Communications Commission (FCC) [1] control and allocate these precious and limited resource of RF spectrums. However, the recent FCC investigations have shown that the utilization of spectrum is not optimal [2-5]. The report has shown that approximately 85% of spectrum is unused or unutilized in various geographic locations and times. We have witnessed from that report that some allocated frequency spectrums are extensively used, for example, cellular network bands. Although, a lot of other frequency spectrums are inefficiently optimized, such as, frequencies for paging and amateur radio. There are two types of users, licensed users or primary users (PUs) and unlicensed users or secondary users (SUs). The SUs are also called cognitive users (CUs). By granting SUs to access the spectrums in the licensed band, spectrum utilization can be improved whenever it would not cause any interference to PUs. Spectrum scarcity created by underutilized licensed spectrum bands thus needed alternative techniques to manage the spectrum band which should be employed to mitigate the problem of inefficient spectrum use and bandwidth limitation, such as Dynamic Spectrum Access (DSA) [2]. The result is in the need of **Cognitive Radios (CRs)**. CR is an intelligent radio that can detect and adapt to its RF spectrum environment on the fly, frame by frame for the best communication performance time to time to pick a channel for a device (i.e., handsets) [6-7].

The CR concept is a well-known solution, firstly coined by J. Mitola [4] for enhancing spectrum optimization while accounting the continuation of licensed spectrum users. The main idea with this new era of radio communication technology is that licensed users are protected against harmful interference while CR exploring and exploiting several spectrum resources.

CR schemes are classified into different types based on interference. Those are interweave, overlay and underlay CR networks based on the type of side information of the network. Interweave is also called as Opportunistic Spectrum Access (OSA). In interweave spectrum technique, SUs try to sense the spectrum holes (which is known as white space) to find if there is any frequency hole available by scanning the spectrum bands [5]. They will use those white spaces to transmit their own transmission, and adapt their broadcasting parameters so that transmissions could be transmitted on them. Those selected white spaces are monitored continuously because they must be vacated if needed by PUs. In that case, an SU can transmit only when the PU is idle or in inactive mode. In contrast, in overlay approach, both the PU and SU engage the spectrum at the same time and use, e.g., dirty paper coding to mitigate the interference [8]. Here, PUs and SUs share the spectrum but PUs have priority over the SUs. In the underlay scheme, both the PU and SU share the same spectrum simultaneously provided that the SUs do not cause any harmful interference on the PUs [9]. Therefore, this underlay spectrum scheme is also known as spectrum sharing [10]. Transmission power is measured by interference temperature. The transmission power of an SU should be lower than a predefined interference threshold to avoid collision with the PU transmission. On the other hand, in the underlay scheme, channel gain information between the SUs and PUs need to be known. By doing so, an SU can adjust its transmission parameters to fulfill the requirements of PUs or the tolerable interference [5, 7]. The underlay approach is considered for this thesis work.

Guarantying Quality of Service (QoS) is a crucial task for future generation wireless networks such as the 4th generation and the 5th generation for several services such as voice, data, and multimedia over packet-switched based networks [11]. Based on data rates, delay bounds, and probabilities of delay bound violation, distinct applications may have diverse QoS demands and traffic characterization. Future generation wireless networks need to be configured in a reliable and powerful manner while maintaining effective use of resources for giving high data rate wireless communications [12]. The efficiency of such networks depends upon how efficiently the traffic can flow by the wireless networks with guaranteed QoS. Service satisfaction of different wireless communication devices mainly depends on their varied tolerable level of delay. Non-real time services, like paging and interactive web surfing need maximum throughput while satisfying loose delay constraint. But, real time services such as multimedia video conference, and live broadcasting need to assure stringent delay bounds compared to high achievable data rate. For these cases, the delay should be minimal for communicating information. QoS guarantees are defined into two types [13]. One is called deterministic or hard guarantees and another is statistical or soft guarantees. In the case of deterministic, it should be guaranteed that no packet or data is lost or delayed during transmission for all the time. In wireless networks, deterministic QoS which requires zero QoS violation probability is hard to perform because of the randomness capacity of a wireless channel over time due to mobility and environment changes. Consequently, statistical QoS guarantees are appropriate for wireless communications because it can tolerate a certain probability of delay violation. So, we will consider statistical QoS in this thesis.

Effective capacity (EC) is a novel technique and an influential mechanism to examine the efficiency of a wireless channel transmission under QoS constraint

[14]. EC is designed to provide a maximum constant arrival rate that a statistical wireless system can support while fulfilling statistical QoS requirements. Recently, in wireless communication, different scopes of application and analysis of EC have attracted large interest [15-20]. QoS provisioning methodologies are needed for guaranteed QoS support. For doing this wireless channel modeling, a queuing investigation of the system is desired. Channel measurement, channel modeling, deriving QoS measures, and relating the control parameters of QoS provisioning techniques to the derived QoS measures are the four steps of a common approach of configuring QoS provisioning techniques at a network node [14]. However, the mechanism in designing QoS provisioning is very complicated to apply the four steps in distinguishing the connection between the control parameters and the computed QoS measures, underlying ubiquitous channel models, *i.e.*, physical-layer channel models. Because, physical-layer channel models are not very easy to understand and cannot be possible to interpret it to complicate link-layer requirements, such as data rate, delay bound and delay-bound violation probability. For supporting QoS by using the existing physical-layer channel models, we have to maintain two complex issues. First, we need to calculate the parameters for the channel model, such as admission control and resource reservation, and later take out the link-layer QoS metrics (queuing analysis) from the physical layer models. But, these two step methods are complex, and may provide inaccurate results because of estimations in obtaining QoS metrics from the physical-layer models. Therefore, it is complicated to use physical-layer models in the case of QoS support. For those reasons, the channel model needs to extend up to the protocol stack from the existing physical-layer channel model to the link-layer channel model. The resulting link-layer model is called "*effective capacity*" in [13]. This EC link model can easily deal with link-level characteristics, such as queuing analysis of a connection and the probability of delay bound violation.

The demand for multimedia services is increasing rapidly, which requires higher data rates and secure transmission over erroneous wireless radio channels while maintaining acceptable QoS provision. Wireless communications have to face a lot of obstacles like, multipath fading, severe path loss and shadowing effects. As a consequence, the cooperative communication (CC) concept has been proposed to mitigate the channel effects in wireless systems [21, 22]. CC can exploit the diversity gain by employing a relay node with the cooperation between the nodes to assist the direct communication link [23], [24], [25]. Mobile wireless devices have only one antenna because of the tiny size and the complexity of it. However, to acquire the transmission between the transmitter and the receiver, a transmitting node demands more than one transmitting antenna which is very unusual in tiny wireless mobile devices. However, the transmission can be possible in a multi-user environment by creating an artificial multi-antenna array, so that, the transmit-diversity can be achieved. This environment can be established by sharing antennas with the help of other single-antenna nodes. Therefore, without implementing several antennas on nodes, secure transmission and the radio coverage can be increased [26]. The relay node processes the transmitter message and forwards the information to the receiver.

The transmission procedure between the transmitter and receiver nodes is structured into two main phases, broadcasting phase and multiple access phase [27, 28]. The transmitter sends its information to both relay as well as destination in the broadcasting phase. On the other hand, the relay processes its received signals from the transmitter before sending it to the receiver. There are several benefits of CC which can perform notable power savings for stretching network life-time [26]. Moreover, the communication range can be expanded and it may retain the execution complexity low. There are mainly three terminals included in a CC relay model, i.e., a source, a relay and a destination [29]. Based on the relaying protocols, the relaying operation is mainly classified into two categories. Those are decode-and-forward (DF) and amplify-and-forward (AF). Both of them have their own merits and demerits. In DF, two tasks have to be done. First of all, the relay needs to decode the received signal from the source signal, and then re-encodes that signal before sending it to the destination. On the other hand, in AF, the relay transmits a scaled version of its received signal by doing simple amplification to the destination. In that scheme, it does not require any signal regeneration. Therefore, the destination may have noise accumulated signal information.

1.2 Thesis Aims and Objectives

The primary aim of this thesis is to exploit the direct communication link for enhancing the effective capacity gain of cognitive radio relay network (CRRN). For achieving this, the following work is done:

- I will present the background knowledge about CRRN and a link layer channel model termed as EC. Consequently, I depicted a system model where spectrum sharing approach is considered.
- Therefore, closed-form expressions for the EC and an analytical expression for the QoS exponent will be derived.
- Moreover, I will evaluate and compare the performance of EC versus QoS exponent for various interference limit values with respect to peak interference power constraints for both direct link and non-direct link channel for the considered system model.
- Finally, I will examine the simulation results which are carried out from the numerical data.
- The theoretical results of this thesis will be obtained by Matlab simulations and verified with numerical results by Monte-Carlo simulations.

1.3 Thesis Contributions and Motivations

In this thesis, the performance of effective capacity with respect to direct link communication model of a CRRN under peak interference power constraints is expected to be enhanced in comparison to non-direct link communication model in Rayleigh fading channel. Multiple relays are used for both direct and non-direct link communication in the analyses. The performance of the capacity gains in this CRRN is improved significantly from previous approaches of non-direct link communication model. Rayleigh fading as statistical time varying channel is regarded for both all theoretical simulations and numerical analyses.

With the increase of new high data rate wireless applications, the demand for the spectrum is increasing quickly. To maintain the effective use of resources for high data rate wireless applications, it requires reliable and powerful transmission configurations. Therefore, the motivation for doing this thesis for me is to follow the analysis in the area of wireless communications. Moreover, it also motivated me to find out the analysis when effective capacity is constrained by peak interference power constraints in CRRN. Also, I want to see the improvement when a direct link channel has been implemented in a spectrum sharing system with respect to effective capacity versus QoS exponent. In other words, to analyze the cross-layer design for cognitive radio relay network is the motivation for this thesis. For doing this, several literatures give me the idea to find the capacity of relay channels in a spectrum sharing environment.

1.4 Thesis Outlines

The remaining parts of this thesis are organized as follows:

Chapter 2: This chapter presents the background knowledge as well as some basic introduction of effective bandwidth (EB) and EC. It also provides brief information about the link layer model of the theory of EB and EC.

Chapter 3: This chapter presents the system model. In addition, it provides the idea about peak interference power constraints of the considered system model.

Chapter 4: In this chapter, a brief mathematical analysis of EC for CRRN under peak interference power constraints is presented. Moreover, a comparison between direct and non-direct link communication with respect to the performance of EC for the considered CRRN is provided. Simulation and analysis results are also presented in this chapter.

Chapter 5: This chapter concludes the thesis work and suggests recommendations for future research work.

Chapter 2: Background and Literature Review

In this chapter, a broad description of EB and EC is discussed over the existing physical layer channel model (PLCM). However, PLCM has some limitations in QoS support. So, this PLCM has been extended to link layer channel model to meet the QoS metrics, such as delay-bound violation probability which we call the resulting model an EC link model. In the following subsection, the theory of EB, EC and the channel model of EC which has link layer objectives are described. EC based framework for statistical QoS guarantees are presented in [13, 14]. A detailed elaboration can also be found in [30].

2.1 Effective Bandwidth and Effective Capacity

In this sub-section, the EC channel model is presented with the help of EC theory. The advantages of this channel model with the existing PLCM are also illustrated here.

An asymptotically close relation between source characteristics, system resources and QoS are provided by the theory of EB [30]. System resources are server capacity and buffer size. This EB theory has originally been applied in wired Asynchronous Transfer Mode (ATM) networks and therefore, a huge amount of works have been provided to the progress of that theory [31]. The EB theory concentrates about the time-varying bursty sources traffic behavior, in an individual function which is the EB function. This EB function can be utilized to indicate the minimum bandwidth which is required to satisfy each traffic to maintain the buffer overflow probability connected to QoS constraint. This EB theory was primarily established for queuing supported systems which have constant service capacity from server.

The EC function can be applied to evaluate the maximum arrival rate which can be prepared from the appropriate server while maintaining a buffer overflow probability related limitation. Even though, this theory was studied for a few years [32-34] without obtaining much attraction by the considerably growing importance of wireless communication systems up to now [14, 35]. This is because of the random nature of the service rate of those systems and therefore the conception of EC seems to be ideal for the modeling of those systems. Most of the previous works have focused on the modeling of the rate changes at the physical layer in the case of EC application to wireless systems [14, 35]. In this thesis, we engage the EC theory for link layer channel models.

A simple and powerful channel model over wireless channel requires efficient allocation of bandwidth and QoS provisioning [13, 14]. Therefore, a link layer communication model is used instead of existing PLCM. Particularly, the wireless link is modeled by two EC functions. Those are the probability of nonempty buffer $\gamma(\mu)$ and QoS exponent $\theta(\mu)$ where μ is the constant source traffic rate. The inverse function of EC is called QoS exponent. Therefore, in wired networks, the EC channel model is called the dual of the EB source traffic model. Moreover, a simple and effective algorithm is generated to approximate the EC function $\{\gamma(\mu),\ \theta(\mu)\}$. This EC channel model covers both the theoretical viewpoint and the experimental viewpoint, *i.e.*, Markov property of fading channels and delay-violation probability [14]. Therefore, the EC channel model follows the following features. Simplicity of implementation, accuracy, efficiency in admission control and resource reservation, and flexibility for bandwidth allocation and connection delay.

2.2 Theory of Effective Bandwidth and Effective Capacity Link Model

The theory of EB can be concluded to take the server's burstiness by a function which is defined as EC function, when the capacity of the server differs randomly with time from the source input [30]. The concept of EC comes from EB theory which is of stochastic nature of a source traffic process that can be designed asymptotically [14]. Therefore, EC is defined as the dual concept of EB [13]. In this Section, we will recollect this EC concept and later try to obtain the maximum achievable effective capacity of a Rayleigh fading channel for a CRRN. Assume that, $\{A(t),\ t \geq 0\}$ defines an arrival process where $A(t)$ stands for the source data amount in bits between the time interval $[0,\ t)$ where t is the window size. Then, the logarithm of the moment generating function determined as asymptotic log-moment generator of $A(t)$ can be defined as in [14] as follows

$$\Lambda(\mu) = \lim_{t \to \infty} \frac{1}{t} \log \mathbb{E}\left[e^{\mu A(t)}\right] \tag{1}$$

where μ denotes the constant source traffic rate. Now, the effective bandwidth function of $A(t)$ is expressed in [14] as

$$\alpha(\mu) = \frac{\Lambda(\mu)}{\mu}, \qquad \forall\, \mu \geq 0. \tag{2}$$

Then, it can be revealed that the probability of queue length $Q(t)$ passing a threshold B by using the large deviations theory in [13, 14 and 32] as

$$\Pr\{Q(t) \geq B\} \sim e^{-\theta_B(r)B} \qquad \text{as} \quad B \to \infty, \tag{3}$$

where r is the channel capacity and B is the buffer size of a queue.

However, (3) can be rewritten for smaller values of B, by following the estimation in [36] as follows:

$$\Pr\{Q(t) \geq B\} \approx \gamma(r) e^{-\theta_B(r)B} \qquad \text{as} \quad B \to \infty, \tag{4}$$

where both $\gamma(r)$ and $\theta_B(r)$ are functions of r. $\gamma(r) = \Pr\{Q(t) \geq 0\}$, represents that the buffer is non-empty for statistically selected time t, while θ_B is the QoS exponent [14]. Therefore, $\{\gamma(r),\ \theta_B(r)\}$ represents a pair of functions which model the source.

If $D(t)$ is the quantity of interest that experiences a delay by a source packet occurring at time t, then the possibility of $D(t)$ passing a delay bound D_{max} is as follows [14]:

$$\Pr\{D(t) \geq D_{max}\} \approx \gamma(r) e^{-\theta(r) D_{max}}. \quad (5)$$

It is evident from (5), that a source with strict QoS demand, i.e., small D_{max} or small ε, requires a larger QoS exponent θ. Here, ε is the probability of maximum tolerable delay bound violation.

Assume that $r(t)$ is the instantaneous channel capacity at time t, then the service provided by the channel can be defined as in [14] by

$$\tilde{S}(t) = \int_0^t r(\tau) d\tau. \quad (6)$$

The channel service $\tilde{S}(t)$ is only depended on the instantaneous channel capacity and therefore it is independent of the arrival process $A(t)$.

Here, it is assume that there exists a log-moment generating function of a channel service $\tilde{S}(t)$, i.e.,

$$\Lambda^{(c)}(-\mu) = \lim_{t \to \infty} \frac{1}{t} \log \mathbb{E}\left[e^{-\mu \tilde{S}(t)}\right], \qquad \forall \mu \geq 0 \quad (7)$$

Here, c is used to indicate the asymptotic log-moment generating function of a stochastic service process provided by the channel service $\tilde{S}(t)$.

Now, the effective capacity function for a stationary Markov fading process $r(t)$ is determined in [14] as

$$\alpha^{(c)}(\mu) = \frac{-\Lambda^{(c)}(-\mu)}{\mu}, \qquad \forall \mu \geq 0. \quad (8)$$

Substituting (7) in (8) gives

$$\alpha^{(c)}(\mu) = -\lim_{t \to \infty} \frac{1}{\mu t} \log \mathbb{E}\left[e^{-\mu \int_0^t r(\tau) d\tau}\right], \qquad \forall \mu \geq 0. \quad (9)$$

Further, $\alpha^{(c)}(\mu)$ can be represented in discrete form as

$$\alpha^{(c)}(\mu) = -\lim_{N\to\infty}\frac{1}{N\mu}\log\mathbb{E}\left[e^{-\mu\sum_{n=1}^{N}R[n]}\right]. \tag{10}$$

Here, the sequence $R[n]$, $n = 1, 2, \ldots,$ is the statistical service process and it is expected to be stationary and ergodic. Moreover, the probability of $D(t)$ exceeding a delay bound D_{max} is given in [14] as follows:

$$\Pr\{D(t) \geq D_{max}\} \approx \gamma^{(c)}(\mu)e^{-\theta^{(c)}(\mu)D_{max}}. \tag{11}$$

where $\{\gamma^{(c)}(\mu),\ \theta^{(c)}(\mu)\}$ representing functions of the source traffic rate μ. The estimation in (11) is perfectly accurate for both large values as well as small values of D_{max} [14]. Therefore, the EC channel model is characterized by the functions pair $\{\gamma^{(c)}(\mu),\ \theta^{(c)}(\mu)\}$.

Now, (11) can be written according to [14] as

$$\varepsilon \approx \gamma^{(c)}(\mu)e^{-\theta^{(c)}(\mu)D_{max}}. \tag{12}$$

where ε is the probability of delay bound violation. So, the presented EC link model can be defined by the function pairs $\{\gamma^{(c)}(\mu),\ \theta^{(c)}(\mu)\}$ as in [14]. Therefore, it can be said that the EC model is a link layer model by the description of these functions. The reason is that the functions instantly distinguish the queuing activity at the link layer.

Chapter 3: System Model of Cognitive Radio Relay Networks

3.1 System and Channel Model

In this thesis, the scenario of an underlay spectrum access based CRRN system is considered where both the primary and secondary link coexists with in same spectrum. We consider two networks in the system model. One is the primary network (PN) which contains one PU transmitter and one PU receiver. The other network is the secondary network (SN). It contains one SU transmitter, one SU receiver, one direct link and multiple relay links. The transmission between the SU transmitter and the receiver is established through the direct link (DL). The communication can also be possible through an intermediate relay node if the channel capacity of DL is poor due to some obstacle existing between the source and the destination node.

The primary transmitter sends data to the primary receiver in the primary network. In the secondary network, the SU upper layer packets are arranged into frames at the data link layer having equal time duration, T_f. After that, these frames are equally separated into bit streams and preserved in the transmit buffer. These bit streams are transmitted from the SU source to the SU receiver through the relay node over the same spectrum band which is engaged by the primary network. There shall be multiple intermediate relay nodes available nearly in the middle between the secondary source and destination in the system. The best-relay node with the highest achievable rate among the other multiple relay nodes will be selected for the transmission.

Dual hop half duplex DF relaying is used in this thesis. Therefore, it needs two time slots for receiving the signal from transmitter, decode and encode the information and forward it to the destination node. Thus, in the first time slot, the selected relay node by choosing the best relay node in every time slot from those multiple relay nodes in the system listens to the transmitted signal from the SU source. On the other hand, in the second time slot, the relay node decodes the received signal message, re-encodes it and after that forwards it to the secondary network destination. The system model is depicted in Fig. 1.

Given a gamma distribution with unit variance, it is assumed that channel gains are independent and identically distributed (i.i.d.) [12]. Here, the total received signal bandwidth is represented by B and the noise power spectral density by N_0. It is assumed that the channel gains are stationary, ergodic random and block fading processes [12].

Typically, there is no committed feedback channel between the PN and the SN. Therefore, a significant attribute of the underlay cognitive radio (CR) technique is that the knowledge of interference caused to the PUs by SUs are expected to be known [30]. It is assumed that the SN transmitter and receiver have full channel state information (CSI) [30]. Each of the relay nodes in the SN requires the accurate knowledge about the channel gain. So, the channel gain between SU source and the i-th relay h_{SR_i}, and the channel gain from i-th relay to SU destination h_{R_iD} is known by each relay node. The best relay node can be selected for the next time slot by examining the CSI from the SU transmitter. Moreover, h_{SP} and h_{R_iP} are the channel gains between the SU transmitter and PU receiver and from the i-th relay node to the PU receiver, respectively. h_{SD} is the channel gain between the SU transmitter and the SU receiver for direct communication. In [31] and [32], the information has been given how the PU and SU can co-operate with each other and interchange CSI by allowing several techniques. This can be done by sharing the information about the interference channel gains directly from the PU receiver to the SN. In this thesis, only the knowledge of the interference channel power gains is required. For this reason, the primary receiver needs to know about the transmit signal power gain which is sufficient to calculate the interference channel power gains, i.e., h_{SP} and h_{R_iP}. The information about the interference channel power gains that intervenes between the PUs and the SUs can be carried out by a band manager [33]. It is assumed that all nodes are subject to discrete time based Rayleigh fading channels at the secondary network.

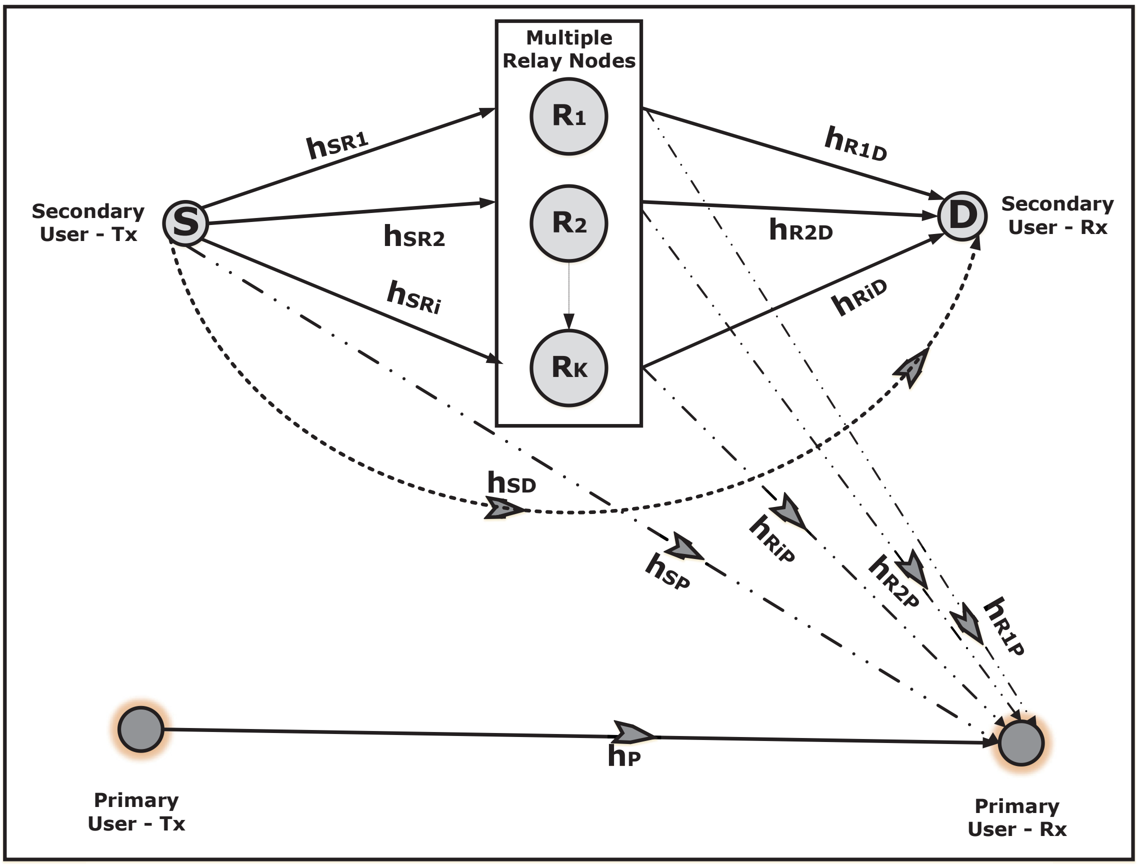

Fig. 1: System Model of a CRRN.

The contender relay nodes are placed approximately in the middle point between the SU transmitter and the SU receiver in the CRRN. This type of scenario is helpful because of the end-to-end efficiency of the relay network is restricted through the lowest capacity of the SU source to relay and the relay to SU destination links. As a result, the average channel gains are almost equal between the forward and the backward relay channels. So, the channel gain can be expected to be the same. Though, the channel gains will not be the same for every frame. So, every time the best relay node needs to be chosen to communicate between secondary transmitter and receiver from the candidate relays. It is also assumed that the distance between the primary network receiver and the secondary network is located comparatively far from each other. Therefore, the average channel gains between the secondary transmitter and the primary receiver and the one between the i-th relay node and the primary receiver are relatively the same.

In wireless communication systems, deterministic delay QoS guarantee produces the result of highly conservative guarantee where the guaranteed lower boundary is a capacity of zero which is clearly useless [14]. Therefore, it is completely worthless to have conservative guarantee because it implies the delay QoS guarantee to infinity. For that reason, we must employ the statistical form to satisfy the delay QoS constraint of the secondary network transmission procedure. In [35] and [36], effective capacity has been used to statistically support the delay QoS of the system, which is a dual theory of effective bandwidth. In the theory of effective bandwidth, the distribution of the queue length process $Q(n)$ can engage in sharing a statistical random variable $Q(\infty)$, which can be written [39] as

$$\theta = -\lim_{y\to\infty} \frac{\ln(\Pr\{Q(\infty) > y\})}{y} \tag{13}$$

where θ is the delay QoS exponent and y is the queue length threshold of the transmit buffer. It is shown that the probability for the queue length of the transmit buffer exceeds a certain threshold, y , declines exponentially as a function of y. $Q(n)$ determines the length of the transmit buffer at time n. $\Pr\{a > b\}$ indicates the probability that the inequality $a > b$ stands true. It is observed from (13) that the QoS exponent θ performs a crucial role for statistical delay QoS guarantee. It should be verified that smaller θ corresponds to looser QoS guarantee, and bigger θ signifies more stringent QoS guarantee. Therefore, it can be said that when $\theta \to 0$, there is no delay constraint which means that the system can suffer randomly extended delay. Then again, $\theta \to \infty$ stands for strict delay constraint. So, in that case the system does not suffer any delay constraint.

Denoting θ as the delay QoS exponent in that system, the highest achievable arrival rate of the SU can be carried out such that a specified QoS constraint is fulfilled.

3.2 Peak Interference Power Constraint

The transmission power of the SU transmitters and the SU relay node transmitters are restricted so that the interference power imposed on the primary receiver is set below a predetermined interference threshold, which is the maximum tolerable interference power level denoted by I_{th} . In this thesis, the peak interference power constraint is considered which can be configured by using [39] as

$$P(\theta, h_{SR_i}, h_{SP})h_{SP} \le I_{th} \tag{14}$$

$$P(\theta, h_{R_iD}, h_{R_iP})h_{R_iP} \le I_{th}; \quad for \ \ i = 1, 2, \dots, K \tag{15}$$

where $P(\theta, h_{SR_i}, h_{SP})h_{SP} \le I_{th}$ denotes the transmit power of the SU transmitter as a function of θ, h_{SR_i} and h_{SP} , and $P(\theta, h_{R_iD}, h_{R_iP})h_{R_iP} \le I_{th}$ represents the transmit power of the i-th relay node transmitter as a function of θ, h_{R_iD} and h_{R_iP} . I_{th} represents the interference threshold limit.

Chapter 4: Comparison of Effective Capacity under Peak Interference Power Constraint

In this chapter, EC which is a dual concept of effective bandwidth [14] has been described for CRRN under peak interference power constraint. Two scenarios have been taken to perform the comparison of EC performance. One is for the scenario when the system does not consider direct link (DL) communication between SU transmitter and SU receiver. The other one is for the situation when it has a direct communication link with the cooperation of multiple intermediate relay nodes for communicating secondary network communication more effectively. Maximize the performance of EC by implementing multiple relay DAF-OFDM (Decode and forward - Orthogonal frequency division multiplexing) with DL supported cognitive radio system without interfering primary network communication is studied in [41].

4.1 Effective capacity analysis

In this section, we recall the idea of EC and acquire the maximum EC of the secondary user link while collaborating multiple relay links in the environment of cognitive radio relay network under the peak interference power constraint. After that, an analytical expression of EC is obtained of a Rayleigh fading relay channel in spectrum sharing networks (14) and (15).

Assume that $\{R[n],\ n = 1,\ 2, \ldots,\}$ is the stochastic service process which is discrete time stationary and ergodic. Therefore, the capacity function is given by

$$\Lambda\,(-\theta)\ =\ \lim_{N\to\infty}\frac{1}{N}\ln\left(\varepsilon\left\{e^{-\theta\sum_{n=1}^{N}R[n]}\right\}\right) \tag{16}$$

So, the EC of the service process denoted by $E_c(\theta)$ can be written as follows [14]:

$$\mathrm{E_c}(\theta)\ = -\frac{\Lambda\,(-\theta)}{\theta} \tag{17}$$

$$\mathrm{E_c}(\theta) = -\lim_{N\to\infty}\frac{1}{N\theta}\ln\left(\varepsilon\left\{e^{-\theta\sum_{n=1}^{N}R[n]}\right\}\right) \tag{18}$$

where $\theta > 0$. The EC given in (18) is the maximum constant arrival rate provided by the channel to guarantee a QoS exponent specified by θ, represented as the delay constraint. Moreover, we are considering block Rayleigh fading channels, where the sequence $\{R[n],\ n = 1,\ 2, \ldots,\}$ is uncorrelated, the EC can be simplified as [14]

$$E_c(\theta) = -\lim_{N\to\infty}\frac{1}{N\theta}\ln\left(\varepsilon\left\{e^{-\theta N R[n]}\right\}\right)$$

$$= -\frac{1}{\theta}\ln\left(\varepsilon\left\{e^{-\theta R[n]}\right\}\right) \quad (19)$$

In the subsequent sections, analytical expressions are derived for the EC of CRRN's by the help of (19). In this chapter, an analytical expression of EC is obtained where multiple relay nodes are available without direct link communication channel. Also, we derive an analytical expression of EC where the transmission can be done through direct link channel coexisting with multiple relay nodes.

4.2 Effective capacity without direct link in CRRN

In this section, the performance of EC without direct link communication is considered. This means that the transmission is done via multiple relay links for the secondary network by choosing the best relay node among other candidate relay nodes. Here, we follow the same analytical steps for finding the performance of EC for non-direct link channel with multiple K relay nodes as in [40] and [42]. Based on [40] and [42], we exploit the direct communication link and compare it with the non-direct communication link channel.

4.2.1 Effective capacity analysis for multiple relay nodes without direct link

The transmission is done in two time slots for the secondary network transmission. The SU transmitter utilizes the spectrum band which is allocated for the primary network to broadcast its signal to the relay nodes in the first time slot. It is assumed that the transmission power of the secondary and relay transmitters are limited to satisfy the interference threshold, I_{th} in (14). In addition, in the second time slot, a single relay node, R_i, among other multiple relay nodes is ready to relay the signal to the SU destination. Its power is also limited to meet the interference threshold requirement for not interfering with the PU transmission in (15).

Now, the data rates of the SU transmitter link and SU relay link can be expressed by using [39] as

$$R_{S_i} = \frac{T_f B}{2}\ln\left(1 + \frac{h_{SR_i}P(\theta, h_{SR_i}, h_{SP})}{N_o B}\right) \quad (20)$$

$$R_{R_i} = \frac{T_f B}{2}\ln\left(1 + \frac{h_{R_iD}P(\theta, h_{R_iD}, h_{R_iP})}{N_o B}\right) \quad (21)$$

where R_{S_i} and R_{R_i} represent the data rates of the SU transmission link and SU relay link in terms of peak interference power, respectively. $P(\theta, h_{SR_i}, h_{SP})$ and $P(\theta, h_{R_iD}, h_{R_iP})$ denote the transmit power of the SU transmitter and the i-th relay node as a function of $\theta, h_{SR_i}, h_{SP}, h_{R_iD},$ and $h_{R_iP},$ respectively. Here, T_f is time duration, B is signal bandwidth, N_o is noise power spectral density and it is assumed that the receiver noise is additive white Gaussian noise with zero mean.

Furthermore,

h_{SR_i} is the channel gain between the SU transmitter and the i-th relay node,

h_{R_iD} is the channel gain between the i-th relay node and the SU receiver,

h_{SP} is the channel gain between the secondary user transmitter and the primary user receiver,

h_{R_iP} is the channel gain between the i-th relay node and the primary user receiver, and

h_{SD} is the channel gain between the SU transmitter and the SU receiver for direct communication.

So, the data rate of the secondary link can be found by using (20) and (21) as

$$R_i = \min\left(R_{S_i},\, R_{R_i}\right)$$

Then, the data rate of the relay channel in terms of peak interference power constraint is

$$R_i = \frac{T_f B}{2} \min\left\{\ln\left(1 + \frac{h_{SR_i}}{h_{SP}} \frac{I_{th}}{N_o B}\right), \ln\left(1 + \frac{h_{R_iD}}{h_{R_iP}} \frac{I_{th}}{N_o B}\right)\right\} \qquad (22)$$

An analytical expression of the effective capacity of the CRRN channel in Rayleigh flat fading environment can be achieved. A new random variable is defined as $Z = \min\left(\frac{h_{SR_i}}{h_{SP}}, \frac{h_{R_iD}}{h_{R_iP}}\right)$. Now, we will derive the cumulative distribution function (CDF), and then the probability density function (PDF) using this new random variable Z. Specifically, the CDF of Z can be written by using [40] as follows:

$$F_{Z_i}(z \mid h_{SP}) = \Pr\left(\min\left\{\frac{h_{SR_i}}{h_{SP}}, \frac{h_{R_iD}}{h_{R_iP}}\right\} \le z \mid h_{SP}\right)$$

$$or\ \ F_{Z_i}(z \mid h_{SP}) = 1 - \Pr\left(\min\left\{\frac{h_{SR_i}}{h_{SP}}, \frac{h_{R_iD}}{h_{R_iP}}\right\} > z \mid h_{SP}\right)$$

$$or\ \ F_{Z_i}(z \mid h_{SP}) = F_{\frac{h_{SR_i}}{h_{SP}}}(z \mid h_{SP}) + F_{\frac{h_{R_iD}}{h_{R_iP}}}(z \mid h_{SP}) - F_{\frac{h_{SR_i}}{h_{SP}}}(z \mid h_{SP}) \times F_{\frac{h_{R_iD}}{h_{R_iP}}}(z \mid h_{SP}) \qquad (23)$$

The channel gain between the SU transmitter and the SU relays, h_{SR_i} is fully dependent on the channel gain from the SU transmitter to the PU receiver, h_{SP}. Therefore, the ratio of the channel gains $\frac{h_{SR_i}}{h_{SP}}$ is dependent on h_{SP}.

The CDF of $F_{Z_i}(z \mid h_{SP})$ is applicable for the i-th channel path. Suppose, $X = h_{SP}$ and $Y_i = \frac{h_{R_iD}}{h_{R_iP}}$. Putting X and Y_i in (23) gives

$$F_{Z_i}(z \mid h_{SP}) = F_{\frac{h_{SR_i}}{X}}(z \mid h_{SP}) + F_{Y_i}(z \mid h_{SP}) - F_{\frac{h_{SR_i}}{X}}(z \mid h_{SP}) \times F_{Y_i}(z \mid h_{SP}) \tag{24}$$

Now, $F_{\frac{h_{SR_i}}{X}}(z \mid h_{SP})$ and $F_{Y_i}(z \mid h_{SP})$ will be derived separately, and later put in (24) as follows:

$$F_{\frac{h_{SR_i}}{X}}(z \mid h_{SP}) = \Pr\left(\frac{h_{SR_i}}{X} \leq z \mid h_{SP}\right) = 1 - e^{-zX} \tag{25}$$

Here, Y_i is an independent random variable. Therefore, the CDF of Y_i can be formed with the help of conditional distribution as follows:

$$F_{Y_i}(z \mid h_{SP}) = 1 - \frac{1}{1+z} \tag{26}$$

Now, replacing (25) and (26) in (24) and after making some simplifications, the CDF for single relay node can be written as

$$F_{Z_i}(z \mid h_{SP}) = 1 - e^{-zX} + 1 - \frac{1}{1\ +\ z} - (1 - e^{-zX}) \times \left(1 - \frac{1}{1\ +\ z}\right)$$

$$or \quad F_{Z_i}(z \mid h_{SP}) = 1 - e^{-zX} + 1 - \frac{1}{1\ +\ z} - 1 + \frac{1}{1\ +\ z} + e^{-zX} - \frac{e^{-zX}}{1\ +\ z}$$

$$\therefore \quad F_{Z_i}(z \mid h_{SP}) = 1 - \frac{e^{-zX}}{1\ +\ z} \tag{27}$$

In the multiple relay node case, there are multiple intermediate nodes present in the system to relay the data from SU source to SU destination. Therefore, the relay node with highest achievable rate is selected to access the radio spectrum band for the following time-slot. As a result, the whole channel data rate of the system can be considered as the highest separated path rates indicated by

$$R_1 = \max\{R_i\}, \qquad i = 1, \ldots, K \tag{28}$$

where R_i can be initiated from (22). Now, in the subsequent arrangement, an analytical expression for the EC under CRRN of the secondary relay channel will be obtained.

If there are K multiple relays available in the system in i.i.d. Rayleigh fading channel, then the total CDF is the product of all individual path CDF's of the system. Therefore, the total CDF of the system for K relays can be written by using [40] as follows:

$$F_Z(z \mid h_{SP}) = \Pr\left(\max\{Z_1, Z_2, \ . \ . \ . \ , \ Z_K\} \le z \mid h_{SP}\right)$$
$$= \prod_{i=1}^{K} \Pr(Z_i \le z \mid h_{SP}) = \left(1 - \frac{e^{-zX}}{1 + z}\right)^K \tag{29}$$

By taking binomial expansion, (29) can be written as

$$F_Z(z \mid h_{SP}) = \left(1 - \frac{e^{-zX}}{1 + z}\right)^K = \sum_{l=0}^{K} \binom{K}{l} (-1)^l \left(\frac{e^{-zX}}{1 + z}\right)^l \tag{30}$$

Here $F_Z(z \mid h_{SP})$ can be simplified by using conditional distribution as

$$F_Z(z) = \int_0^{\infty} F_Z(z \mid h_{SP}) \, . \, f_{h_{SP}}(x) dx$$

$$= \sum_{l=0}^{K} \binom{K}{l} \frac{(-1)^l}{(1+z)^l} \frac{1}{(zl+1)}$$

$$\therefore \qquad F_Z(z) = \sum_{l=0}^{K} \binom{K}{l} \frac{(-1)^l}{(1+z)^l} \frac{1}{(zl+1)} \tag{31}$$

Then, the PDF of the random variable Z can be obtained by differentiating (31) as follows:

$$f_Z(z) = \sum_{l=1}^{K} \binom{K}{l} (-1)^{l+1} l \left(\frac{1}{(1+z)^l (zl+1)^2} + \frac{1}{(1+z)^{(l+1)} (zl+1)}\right) \tag{32}$$

Therefore, the EC can be obtained from (19) as

$$E_c(\theta) = \ -\frac{1}{\theta} \ln\left(\varepsilon\left\{e^{-R_1[n]\theta}\right\}\right) = -\frac{1}{\theta} \ln\left(\int_0^{\infty} e^{-R_1[n]\theta} f_Z(z)\right)$$

The above form of EC can be expanded in integral form according to [40] as

$$\therefore E_c(\theta) = -\frac{1}{\theta}\ln\left[\int_0^\infty \left(1+\frac{zI_{th}}{N_0B}\right)^{-\alpha} \sum_{l=1}^{K}\binom{K}{l}(-1)^{l+1} l \left(\frac{1}{(1+z)^l (zl+1)^2} + \frac{1}{(1+z)^{(l+1)}(zl+1)}\right) dz\right] \tag{33}$$

Doing some simplifications and calculations in (33) and using [40, eq. (3.25)], gives

$$E_c(\theta) = -\frac{1}{\theta}\ln\left(\left[\int_0^\infty \left(1+\frac{zI_{th}}{N_0B}\right)^{-\alpha} \sum_{l=1}^{K}(-1)^{l+1}\binom{K}{l} l \left(\sum_{n=1}^{l}\frac{(-l)^{n-1}n}{(1-l)^{n+1}(1+z)^{l-n+1}} + (-1)^l \sum_{m=0}^{1}\frac{l^{l+m}}{(1-l)^{l+m}(1+zl)^{2-m}} + \sum_{n=1}^{l+1}\frac{(-l)^{n-1}}{(1-l)^n(1+z)^{l-n+2}} + \frac{(-l)^{l+1}}{(1-l)^{l+1}(1+zl)}\right) dz\right]\right) \tag{34}$$

Equation (34) can be more simplified by using [40, eq.(3.26)] which can guide us to a closed form expression for the EC of the secondary user relay link system subject to the peak interference power constraint for Rayleigh fading environment as

$$E_c(\theta) = -\frac{1}{\theta}\ln\left[\sum_{l=2}^{K}\binom{K}{l}\sum_{n=1}^{l}(-1)^{n+l}\frac{nl^n}{(1-l)^{n+1}(\alpha+l-n)}\,{}_2F_1\left(\alpha,1;\alpha+l-n;1-\frac{I_{th}}{N_0B}\right) - \sum_{m=0}^{1}\left(\frac{l}{1-l}\right)^{l+m}\frac{1}{(\alpha-m+1)}\,{}_2F_1\left(\alpha,1;\alpha-m+2;1-\frac{I_{th}}{N_0Bl}\right) + \sum_{n=1}^{l+1}(-1)^{n+l}\left(\frac{l}{1-l}\right)^n\frac{1}{(\alpha+l-n+1)}\,{}_2F_1\left(\alpha,1;\alpha+l-n+2;1-\frac{I_{th}}{N_0B}\right) + \sum_{l=2}^{k}\left(\frac{l}{1-l}\right)^{l+1}\frac{1}{\alpha}\,{}_2F_1\left(\alpha,1;\alpha+1;1-\frac{I_{th}}{N_0Bl}\right) + \frac{2K}{(\alpha+2)^2}\,{}_2F_1\left(\alpha,1;\alpha+3;1-\frac{I_{th}}{N_0B}\right)\right] \tag{35}$$

where ${}_2F_1(a, b; c; z)$ denotes the Gauss hypergeometric function [38]. Eq. (15.1.1) in [38] is used to solve the Gauss hypergeometric function.

4.3 Effective capacity with direct link in CRRN

In this section, direct link communication channel co-existing with multiple K relay nodes of a CRRN is considered for optimizing EC performance. Here, the secondary source can transmit data to the secondary destination through a direct link. Therefore, it can increase the performance of the secondary system by saving time and system energy because of the direct communication [41]. If the direct link communication is stopped due to a blockage existing in some frequencies or if the direct link channel quality is very poor for the secondary transmission, the communication can be done via multiple K relay nodes from secondary source to destination.

4.3.1 Effective capacity analysis for direct link co-exists with multiple relay nodes

In this subsection, the performance of the EC of the secondary user relay link under peak interference power constraint when the SU transmitter communicates with SU receiver through direct link channel is studied. There are K relay nodes available along with the direct communication link to support the secondary user's communication. Therefore, the data rate can be written for SU transmitter to SU destination for direct link channel as

$$R_{SD} = \frac{T_f B}{2} \ln\left(1 + \frac{h_{SD}}{h_{SP}} \frac{I_{th}}{N_o B}\right) \quad (36)$$

from (22) it is already defined that the data rate of the relay channel is

$$R_i = \frac{T_f B}{2} \min \left\{\ln\left(1 + \frac{h_{SR_i}}{h_{SP}} \frac{I_{th}}{N_o B}\right), \ln\left(1 + \frac{h_{R_iD}}{h_{R_iP}} \frac{I_{th}}{N_o B}\right)\right\}$$

and from (28) the total channel data rate of a secondary relay channel without direct link is

$$R_1 = \max\{R_i\}, \qquad \text{where } i = 1, \dots, K$$

Therefore, the total data rate with direct link channel of a system can be defined by using (28) and (36) as follows:

$$R = \max\ \{R_1, R_{SD}\}, \quad (37)$$

It can be seen from (37) that the total data rate R is the product of the highest achievable individual data rate of a relay channel and the data rate of the direct channel.

Let us define an another random variable as $\Upsilon_{TOT} = \max\left\{R_1, \frac{h_{SD}}{h_{SP}}\right\}$ or $\Upsilon_{TOT} = \max\left\{\max\{Z_1, Z_2, \ . \ . \ . \ , \ Z_K\}, \ \frac{h_{SD}}{h_{SP}}\right\}$

Therefore, we can find the CDF of the system in terms of Υ_{TOT} and name it $F_{\Upsilon_{TOT}}(z \mid h_{SP})$ as

$$F_{\Upsilon_{TOT}}(z \mid h_{SP}) = \Pr\left(\max\left\{\max\{Z_1, Z_2, \ . \ . \ . \ , \ Z_K\}, \frac{h_{SD}}{h_{SP}}\right\} \le z \mid h_{SP}\right) \tag{38}$$

$$= [\Pr\{\max(Z_1, Z_2, \ . \ . \ . \ , \ Z_K \le z \mid h_{SP})\}] \times \left[\Pr\left\{\frac{h_{SD}}{h_{SP}} \le z \mid h_{SP}\right\}\right]$$

$$= \left[\prod_{i=1, \ \dots \ ,K} Pr\{Z_i \le z \mid h_{SP}\}\right] \times \left[\Pr\left\{\frac{h_{SD}}{h_{SP}} \le z \mid h_{SP}\right\}\right]$$

$$= \left[\prod_{i=1, \ \dots \ ,K} F_{Z_i}(z \mid h_{SP})\right] \times \left[F_{\frac{h_{SD}}{h_{SP}}}(z \mid h_{SP})\right]$$

$$\therefore \quad F_{\Upsilon_{TOT}}(z \mid h_{SP}) = \left(1 - \frac{e^{-zX}}{1 \ + \ z}\right)^K \times (1 - e^{-zx}) \tag{39}$$

Using binomial expansion in (39), we get

$$F_{\Upsilon_{TOT}}(z \mid h_{SP}) = \left\{\sum_{l=0}^{K} \binom{K}{l} (-1)^l \frac{e^{-zlx}}{(1+z)^l}\right\} - \left\{\sum_{l=0}^{K} \binom{K}{l} (-1)^l \frac{e^{-zlx} e^{-zx}}{(1+z)^l}\right\} \tag{40}$$

Now, using conditional distribution in (40) and after performing some simplifications, we get

$$F_{\Upsilon_{TOT}}(z) = \int_0^\infty F_{\Upsilon_{TOT}}(z \mid h_{SP}) \, f_{h_{SP}}(x) dx$$

$$= \int_0^\infty \left[\left\{\sum_{l=0}^{K} \binom{K}{l} (-1)^l \frac{e^{-zlx}}{(1+z)^l}\right\} - \left\{\sum_{l=0}^{K} \binom{K}{l} (-1)^l \frac{e^{-zlx} e^{-zx}}{(1+z)^l}\right\}\right] e^{-x} dx$$

$$\therefore \ F_{\Upsilon_{TOT}}(z) = \sum_{l=0}^{K} \binom{K}{l} \frac{(-1)^l}{(1+z)^l} \left[\frac{1}{(zl+1)} - \frac{1}{(zl+z+1)}\right] \tag{41}$$

From (41), we can further write

$$F_{\Upsilon_{TOT}}(z) = \sum_{l=0}^{K} \binom{K}{l} (-1)^l \left[\frac{1}{(1+z)^l} \frac{1}{(zl+1)} - \frac{1}{(1+z)^l} \frac{1}{(1+z(l+1))}\right] \tag{42}$$

By taking partial fractions of $\left[\frac{1}{(1+z)^l}\frac{1}{(zl+1)} - \frac{1}{(1+z)^l}\frac{1}{(1+z(l+1))}\right]$ from (42) separately as follows:

$$\frac{1}{(1+z)^l}\frac{1}{(zl+1)} = \sum_{n=1}^{l}\frac{(-1)^{n-1}(l)^{n-1}}{(1-l)^n(1+z)^{l-n+1}} + \frac{(-1)^l(l)^l}{(1-l)^l(zl+1)} \tag{43}$$

$$\frac{1}{(1+z)^l}\frac{1}{\big(1+z(l+1)\big)} = \sum_{n=1}^{l}\frac{(-1)^{n-1}(l+1)^{n-1}}{(-l)^n(1+z)^{l-n+1}} + \frac{(-1)^l(l+1)^l}{(-l)^l\big(1+z(l+1)\big)} \tag{44}$$

Eq. (43) and (44) has been generated by using the mathematical induction method.

Now, differentiating (43) and (44) with regards to z gives

$$\frac{d}{dz}\left[\sum_{n=1}^{l}\frac{(-1)^{n-1}(l)^{n-1}}{(1-l)^n(1+z)^{l-n+1}} + \frac{(-1)^l(l)^l}{(1-l)^l(zl+1)}\right] = \sum_{n=1}^{l}\frac{(-1)^n(l)^{n-1}(l-n+1)}{(1-l)^n(1+z)^{l-n+2}} + \frac{(-1)^{l+1}(l)^{l+1}}{(1-l)^l(zl+1)^2} \tag{45}$$

$$\frac{d}{dz}\left[\sum_{n=1}^{l}\frac{(-1)^{n-1}(l+1)^{n-1}}{(-l)^n(1+z)^{l-n+1}} + \frac{(-1)^l(l+1)^l}{(-l)^l\big(1+z(l+1)\big)}\right] = \sum_{n=1}^{l}\frac{(-1)^n(l+1)^{n-1}(l-n+1)}{(-l)^n(1+z)^{l-n+2}} + \frac{(-1)^{l+1}(l+1)^{l+1}}{(-l)^l\big(1+z(l+1)\big)^2} \tag{46}$$

Therefore, we can find the PDF by differentiating (41) as

$$f_{Y_{TOT}}(z) = \frac{d}{dz}\left[F_{Y_{TOT}}(z)\right] \tag{47}$$

Inserting (45) and (46) in (47), we get

$$f_{Y_{TOT}}(z) = \sum_{l=0}^{K}\binom{K}{l}(-1)^l\left\{\sum_{n=1}^{l}\frac{(-1)^n(l)^{n-1}(l-n+1)}{(1-l)^n(1+z)^{l-n+2}} + \frac{(-1)^{l+1}(l)^{l+1}}{(1-l)^l(zl+1)^2} + \sum_{n=1}^{l}\frac{(-1)^n(l+1)^{n-1}(l-n+1)}{(-l)^n(1+z)^{l-n+2}} + \frac{(-1)^{l+1}(l+1)^{l+1}}{(-l)^l\big(1+z(l+1)\big)^2}\right\} \tag{48}$$

The EC in (19) can be used here for direct link communication as

$$E_c(\theta) = -\frac{1}{\theta}\ln\left[\int_0^\infty \left(1+\frac{zI_{th}}{N_0B}\right)^{-\alpha} f_{\Upsilon_{TOT}}(z)\,dz\right] \tag{49}$$

Therefore, by inserting (48) in (49) the integral form of EC for direct link communication is obtained as

$$\therefore E_c(\theta) = -\frac{1}{\theta}\left(\ln\left[\int_0^\infty \left(1+\frac{zI_{th}}{N_0B}\right)^{-\alpha} \sum_{l=0}^{K}\binom{K}{l}(-1)^l \left\{\sum_{n=1}^{l}\frac{(-1)^n(l)^{n-1}(l-n+1)}{(1-l)^n(1+z)^{l-n+2}} + \frac{(-1)^{l+1}(l)^{l+1}}{(1-l)^l(zl+1)^2} + \sum_{n=1}^{l}\frac{(-1)^n(l+1)^{n-1}(l-n+1)}{(-l)^n(1+z)^{l-n+2}} + \frac{(-1)^{l+1}(l+1)^{l+1}}{(-l)^l\big(1+z(l+1)\big)^2}\right\} dz\right]\right) \tag{50}$$

An analytical expression for the integral form in (50) can be obtained using [37, eq. (3.197.5, 3.197.1)] as

$$\begin{aligned} E_c(\theta) = -\frac{1}{\theta}\ln\Bigg[&\sum_{l=2}^{K}\binom{K}{l}\sum_{n=1}^{l}\frac{(-1)^{n+l}l^{n-1}(l-n+1)}{(1-l)^n(\alpha+l-n+1)}\,{}_2F_1\left(\alpha,1;\alpha+l-n+2;1-\frac{I_{th}}{N_0B}\right)\\ &-\sum_{l=2}^{K}\binom{K}{l}\frac{l^l}{(1-l)^l(\alpha+1)}\,{}_2F_1\left(\alpha,1;\alpha+2;1-\frac{I_{th}}{N_0Bl}\right)\\ &-\sum_{l=2}^{K}\binom{K}{l}\sum_{n=1}^{l}\frac{(-1)^l(l+1)^{n-1}(l-n+1)}{l^n(\alpha+l-n+1)}\,{}_2F_1\left(\alpha,1;\alpha+l-n+2;1-\frac{I_{th}}{N_0B}\right)\\ &-\sum_{l=2}^{K}\binom{K}{l}\frac{(-1)^l(l+1)^l}{l^l(\alpha+1)}\,{}_2F_1\left(\alpha,1;\alpha+2;1-\frac{I_{th}}{N_0B(l+1)}\right)\\ &+\frac{2K}{(\alpha+2)}\,{}_2F_1\left(\alpha,1;\alpha+3;1-\frac{I_{th}}{N_0B}\right)+\frac{1}{(\alpha+1)}\,{}_2F_1\left(\alpha,1;\alpha+2;1-\frac{I_{th}}{N_0B}\right)\\ &+\frac{K}{(\alpha+1)}\,{}_2F_1\left(\alpha,1;\alpha+2;1-\frac{I_{th}}{N_0B}\right)\\ &-\frac{2K}{(\alpha+1)}\,{}_2F_1\left(\alpha,1;\alpha+2;1-\frac{I_{th}}{2N_0B}\right)\Bigg] \end{aligned} \tag{51}$$

where (51) is an analytical expression under peak interference power constraint where K multiple relay nodes are available in the system along with a direct communication link.

4.4 Numerical results

In this section, numerical results are provided to demonstrate the EC of the cognitive radio relay network link using decode-and-forward relay in Rayleigh fading environment under peak interference power constraint to validate the derived analytical expressions. All numerical results are carried out by Monte-Carlo simulations and compared with Matlab simulations. Both numerical simulation and theoretical results are matching well. For the ease of implementation in this thesis, we assumed $N_0 B = 1$ and $T_f B = 1$.

In Fig. 2, the normalized EC under peak interference power constraints, (14) and (15), is plotted against delay QoS exponents, θ. The analysis is done for different values of interference-limit, I_{th}. We consider the analysis for multiple relays ($K = 2$). The EC given on the vertical axis in this figure and the unit is shown in Nats/s/Hz. The QoS exponent θ is presented on the horizontal axis. The plots with different markers without any lines depict the simulation results. The solid and dashed lines without any markers show the analytical results. The figure shows that the analytical results and the simulation results match very well.

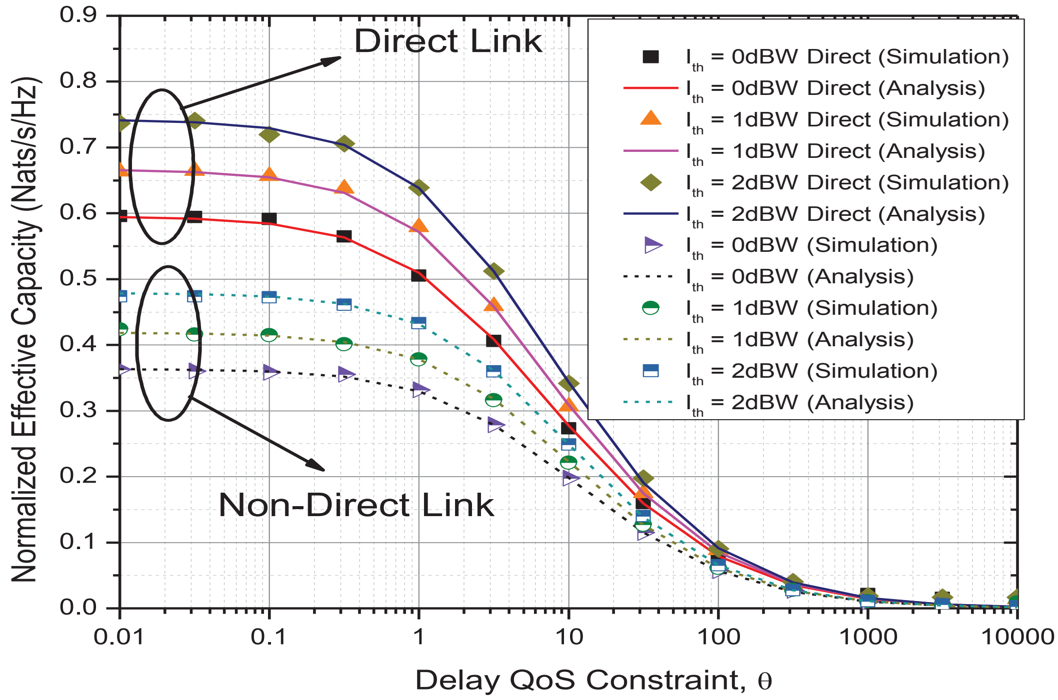

Fig. 2. Comparison of direct and non-direct link performance for normalized effective capacity versus delay constraint under peak interference power constraint for various interference threshold limits, $I_{th} = 0, 1, 2$ dBW.

In Fig. 2, we compare direct and non-direct link channel performance in terms of gain accomplished with multiple relay nodes in the cognitive radio relay network. The figure shows significant improvement of the capacity gain as a result of exploiting direct communication link along with multiple relay nodes compare to no direct link communication system. The rate of the EC gains in the slope decreases with increases of QoS exponent θ, which means that the higher EC gain can be achieved as a result of implementing direct communication link along with multiple relay nodes for smaller values of θ. It can also be seen from this figure, when θ = 0.01 (1/bit), we are getting highest value of EC gain for both cases, i.e., system with direct link or without direct link communication. But, performance of the EC for the system with direct link communication enhanced enormously due to exploit a direct communication link oppose to non-direct communication link system.

Moreover, in Fig. 2, we can observe that the performance of EC for different values of interference threshold, i.e., $I_{th} = 0, 1, 2$ dBW. It shows higher capacity gain by increasing the interference thresholds for a specific range of QoS exponent θ. Therefore, it is observed that the gain of the effective capacity is improved tremendously when there is a direct communication link in the system along with the existing multiple relay nodes.

We also analyze and compare the scenario of changing the performance of

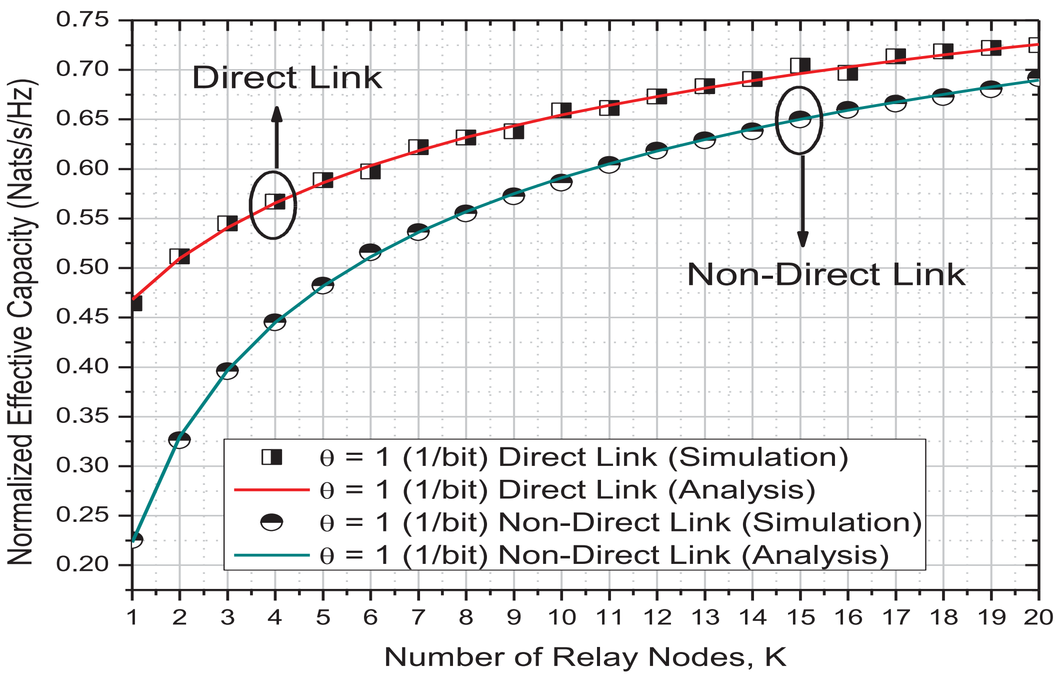

Fig. 3. Comparison of direct and non-direct link system performance for normalized effective capacity versus number of relay nodes K for QoS exponent value $\theta = 1$ (1/bit) and $I_{th} = 1$dBW .

effective capacity by increasing the number of relay nodes K from 1 to 20 in the secondary relay network both the cases for the systems of direct and non-direct link channel for delay QoS constraint θ and $I_{th} = 1$ dBW in Fig. 3. It shows that if the number of relay node increases, the capacity also increases. The marker shows the simulation results and the solid line shows the analytical results for both the cases. It is observed that the simulation results and the analytical results match very well. One can also notice that the system with direct link channel shows significantly higher capacity compare to the system without direct link channel.

Fig. 4 shows the normalized effective capacity versus various interference thresholds I_{th} where the number of relay nodes is $K = 2$ for the system of direct and non-direct link channel for single delay QoS exponent θ. The performance gain increases considerably for direct communication link compare to non-direct link. The marker without line shows the simulation results and the solid line shows the analytical results for both cases. The circle shows the direct and non-direct link channel system from the figure. Here, it is observed that if the interference threshold increases, the effective capacity gain also increases. But, the performance of effective capacity is considerably higher with direct link channel compare to non-direct link channel.

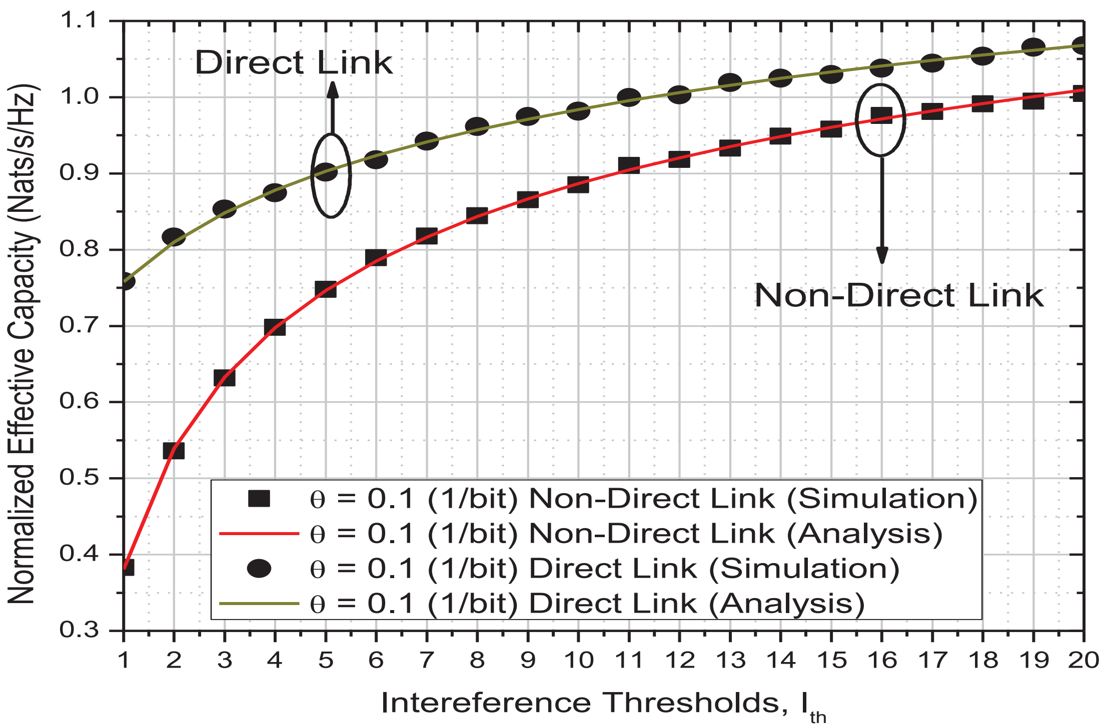

Fig. 4. Comparison of direct and non-direct link system performance for normalized effective capacity versus different interference thresholds I_{th} for QoS exponent value $\theta = 0.1$ (1/bit) and $K = 2$.

Conclusion

This thesis has investigated a spectrum-sharing cognitive radio relay network and has examined the effects of exploiting the direct link (DL) communication on the maximum data rate obtainable of the secondary users channel under statistical delay QoS constraints by considering effective capacity as the channel model. It is expected that the spectrum band allocated for a primary user may be approached and utilized by a secondary user as long as the secondary user corresponds to certain thresholds on the interference limitations set by the primary user. On the primary network side, the primary user transmission is secured from the highest interference power imposed on the primary receiver side by the transmission at the secondary network to be below peak values. Taking into account the limited interference power, the effective capacity is obtained and compared for the secondary relay network when multiple relay nodes are used, with and without DL communication channel. The numerical results show that if the allowable interference threshold increases, then the achievable effective capacity in the network also increases for both scenarios, i.e., with and without DL communication. Moreover, it is also verified that if the number of relay nodes increases, then the performance of the effective capacity also increases for both cases. However, the performance gain of effective capacity is increased considerably by implementing a direct link channel in the system compare to non-direct link channel for all the scenarios. On the other hand, the capacity gain does not benefit if the delay constraint is loosened though an increase in interference threshold or number of relay nodes. Analytical expressions are found for the effective capacity of these systems in Rayleigh fading environments. The numerical results are provided and also demonstrated that the capacity benefits enormously by exploiting the direct communication link compare to non-direct communication link in the system.

Bibliography

[1] Federal Communication Commission (2002, Nov.) “Spectrum Policy Task Force Report,” . [Online]. Available: http://hraunfoss.fcc.gov/edocs public/attachmatch/DOC-228542A1.pdf

[2] B. Wang and K. J. R. Lui, “Advances in Cognitive Radio Networks: A Survey,” *IEEE J. Sel. Topics Signal Process.*, vol. 5, no. 1, pp. 5-23, Feb. 2011.

[3] H. Chen and M. Guizani, “Next Generation Wireless Systems and Networks,” John Wiley and Sons Ltd., Chichester, Apr. 2006.

[4] J. Mitola, "Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio," *Ph.D. Dissertation*, KTH Roy. Inst. Technol., Stockholm, Sweden, May, 2000.

[5] S. Haykin, "Cognitive Radio: Brain-empowered Wireless Communications," *IEEE J. Sel. Areas Communications*, vol. 23, no. 2, pp. 201-220, Feb. 2005.

[6] J. Mitola and J. G. Q. Maguire, “Cognitive Radio: Making Software Radios More Personal,” *IEEE Personal Commun.*, vol. 6, no. 4, pp. 13–18, Aug. 1999.

[7] I. A. Goldsmith, S. A. Jafar, and S. Srinivasa, “Breaking Spectrum Gridlock with Cognitive Radios: An Information Theoretic Perspective,” in *Proc. IEEE*, vol. 97, no. 5, pp. 894–914, May 2009.

[8] P. M. N. Devroye and V. Tarokh, “Achievable Rates in Cognitive Radio Channels,” *IEEE Trans. Inf. Theory*, vol. 52, no. 5, pp. 1813–1827, May 2006.

[9] A. Ghasemi and E. S. Sousa, “Fundamental Limits of Spectrum-sharing in Fading Environments,” *IEEE Trans. on Wireless Commun.*, vol. 6, no. 2, pp. 649–658, Feb. 2007.

[10] M. A. Hagos and M. Mohamed, “Impact of Interference from Primary User on the Performance of Cognitive Radio Networks,”. [Online] available: http://www.bth.se/fou/cuppsats.nsf/all/f8b355c5835dcd3ec1257ab0005bccf8?OpenDocument

[11] J. Tang and X. Zhang, "Quality-of-Service Driven Power and Rate Adaptation over Wireless Links," *IEEE Trans. on Wireless Commun.*, vol. 6, no. 8, pp. 3058-3068, Aug. 2007.

[12] M. C. Gursoy, D. Qiao, and S. Velipasalar, "Analysis of Energy Efficiency in Fading Channels under QoS Constraints," *IEEE Trans. on Wireless Commun.*, vol. 8, no. 8, pp. 4252-4263, Aug. 2009.

[13] D. Wu, "Providing Quality-of-service Guarantees in Wireless Networks," *Ph.D. Dissertation*, Department of Electrical and Computer Engineering, Carnegie Mellon University, Aug. 2003.

[14] D. Wu and R. Negi, "Effective Capacity: A Wireless Link Model for Support of Quality of Service," *IEEE Trans. on Wireless Commun.*, vol. 2, no. 4, pp. 630-643, Jul. 2003.

[15] J. Tang and X. Zhang, "Quality-of-service Driven Power and Rate Adaptation over Wireless Links," *IEEE Trans. on Wireless Commun.*, vol. 6, no. 8, pp. 3058-3068, Aug. 2007.

[16] J. Tang and X. Zhang, "Quality-of-service Driven Power and Rate Adaptation for Multichannel Communications over Wireless Links," *IEEE Trans. on Wireless Commun.*, vol. 6, no. 12, pp. 4349-4360, Dec. 2007.

[17] G. Femenias, J. Ramis, and L. Carrasco, "Using Two-Dimensional Markov Models and the Effective-Capacity Approach for Cross-Layer Design in AMC/ARQ-Based Wireless Networks," *IEEE Trans. on Veh. Techn.*, vol. 58, no. 8, pp. 4193-4203, Oct. 2009.

[18] S. Ren and K. B. Letaief, "Maximizing the Effective Capacity for Wireless Cooperative Relay Networks with QoS Guarantees," *IEEE Trans. on Commun.*, vol. 57, no. 7, pp. 2148-2159, Jul. 2009.

[19] S. Shakkottai, "Effective Capacity and QoS for Wireless Scheduling," *IEEE Trans. on Automatic Control*, vol. 53, no. 3, pp. 749-761, Apr. 2008.

[20] A. Balasubramanian and S. L. Miller, "The Effective Capacity of a Time Division Downlink Scheduling System," *IEEE Trans. on Commun.*, vol. 58, no. 1, pp. 73-78, Jan. 2010.

[21] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative Diversity in Wireless Networks: Efficient Protocols and Outage Behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062-3080, Nov. 2004.

[22] T. M. Cover and A. A. El Gamal, "Capacity Theorems for the Relay Channel," *IEEE Trans. Inf. Theory*, vol. 25, no. 5, pp. 572-584, Jan. 1979.

[23] G. Kramer, M. Gastpar, and P. Gupta, "Cooperative Strategies and Capacity Theorems for Relay Networks," *IEEE Trans. Inf. Theory*, vol. 51, no. 9, pp. 3037-3063, Sep. 2005.

[24] M. O. Hasna and M. S. Alouini, "Optimal Power Allocation for Relayed Transmissions over Rayleigh Fading Channels," *IEEE Trans. Wireless Commun.*, vol. 3, no. 6, pp. 1999-2004, Nov. 2004.

[25] J. Laneman and G. Wornell, "Energy-efficient Antenna Sharing and Relaying for Wireless Networks," in *Proc. IEEE Wireless Commun. and Networking Conf.*, Chicago , USA, vol. 1, pp. 7-12, Sep. 2000.

[26] T. Q. Duong, "On Cooperative Communications and Its Application to Mobile Multimedia," *Lic. Dissertation,* School of Engineering, Blekinge Institute of Technology, Karlskrona, Sweden, 2010.

[27] T. Q. Duong, V. N. Q. Bao, G. C. Alexandropoulos, and H.-J. Zepernick,"Cooperative Spectrum Sharing Networks with AF Relay and Selection Diversity," *Electron. Lett.*, vol. 47, no. 20, pp. 1149-1151, Sep. 2011.

[28] T. Q. Duong, V. N. Q. Bao, and H.-J. Zepernick, "On the Performance of Selection Decode-and-Forward Relay Networks over Nakagami-m Fading Channels," *IEEE Commun. Lett.* , vol. 13, no. 3, pp. 172-174, Mar. 2009.

[29] E. C. van der Meulen, "Three-terminal Communication Channels," *Advances in Applied Probability*, vol. 3, no. 1, pp. 120-154, Mar. 1971.

[30] E. Kafetzakis, K. Kontovasilis, and I. Stavrakakis, "A Novel Effective Capacity Based Framework for Providing Statistical QoS Guarantees in IEEE 802.11 WLANs," *Computer Communications*, vol. 35, no. 2, pp. 249-262, Jan. 2012.

[31] F. Kelly, S. Zachary, and I. Zeidins, "Notes on Effective Bandwidths," in *Proc. Stochastic Networks: Theory and Applications*, vol. 4, Oxford University Press, pp. 141-168, 1996.

[32] C. Chang, "Stability, Queue Length, and Delay of Deterministic and Stochastic Queuing Networks," *IEEE Trans. Automat. Control*, vol. 39, no. 5, pp. 913-931, May 1994.

[33] W. Whitt, "Tail Probabilities with Statistical Multiplexing and Effective Bandwidths in Multi-class Queues," *Telecommun. Syst.*, vol. 2, no. 1, pp. 71-107, Aug. 1993.

[34] C. S. Chang and J. A. Thomas, "Effective Bandwidth in High-speed Digital Networks," *IEEE J. on Selected Areas in Commun.*, vol. 13, no. 6, pp. 1091-1100, Aug. 1995.

[35] X. Zhang, J. Tang, H. Chen, S. Ci, and M. Guizani, "Cross-layer-based Modeling for Quality of Service Guarantees in Mobile Wireless Networks," *IEEE Commun. Magazine*, vol. 44, no. 1, pp. 100-106, Jan. 2006.

[36] G. L. Choudhury, D. M. Lucantoni, and W. Whitt, "Squeezing the Most Out of ATM," *IEEE Trans. on Commun.*, vol. 44, no. 2, pp. 203-217, Feb. 1996.

[37] I. S. Gradshteyn and I. M. Ryzhik, "Table of Integrals, Series, and Products," 6th ed. San Diego, CA: Academic Press, Aug. 2000.

[38] I. A. Stegun and M. Abramowitz, "Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables," New York: Dover, Jun. 1964.

[39] L. Musavian and S. Aissa, "Cross-layer Analysis of Cognitive Radio Relay Networks under Quality of Service Constraints," in *Proc. IEEE Veh. Technol. Conf.*, Barcelona, Spain, pp. 1-5, Apr. 2009.

[40] A. Gopalakrishna, "Capacity Analysis of Cognitive Radio Relay Networks under Transmission and Interference Power Constraints,". [Online] available: http://www.bth.se/fou/cuppsats.nsf/1d345136c12b9a52c1256608004f0519/25bd710780d0da0bc1257ab6002f5839!OpenDocument

[41] M. Shaat and F. Bader, "Joint Resource Optimization in Decode and Forward Multi-relay Cognitive Network with Direct Link" in *Proc. IEEE Wireless Commun. and Networking Conf.,* Shanghai, China, pp. 1398-1403, Apr. 2012.

[42] A. Gopalakrishna and D. B. Ha, "Capacity Analysis of Cognitive Radio Relay Networks with Interference Power Constraints in Fading channels," in *Proc. Computing, Management and Telecommunications International Conference,* Ho Chi Minh City, Vietnam, pp. 111-116, Jan. 2013.