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Outage Probability Analysis of Cooperative Cognitive Radio Networks Over $\kappa - \mu$ Shadowed Fading Channels

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ABSTRACT

Over time, wireless technology advancements in the field of communications have been attracting every individual to turn into a wireless user. To accommodate the increasing number of users and to avoid the problem of spectrum scarcity, the concept of Cognitive Radio Network (CRN) has been developed. Cognitive Radio (CR) is an intelligent radio which efficiently detects and allocates the spectrums of primary licensed users (PUs) to the secondary unlicensed users (SUs). The SUs can utilize these spectrums as long as they do not cause harmful interference to the PUs. Interference may occur because of the following reasons: misdetection of spectrum availability and the high transmission power of SU when both SU and PU are present in the same channel at the same time. In order to avoid interference, the radio has to have a very accurate spectrum sensing method, transmit power at SU should be constrained by the peak interference power of PU and the CR should continuously sense the presence of PUs. To increase the wireless coverage area and reliability of CRN, a new technology called Cooperative Cognitive Radio Network (CCRN), which is a combination of CRN and cooperative communications was developed. A CCRN not only increases the reliability and wireless coverage area of CR but also improves the overall performance of the system.

In this context, the main objective of this research work is to evaluate the outage performance of a CCRN in an environment where fading and shadowing also come into the picture and to study the importance of relay networks in CRN.

To fulfill the objectives of this research work, a two-hop decode-and-forward CCRN is considered. The recently introduced $\kappa - \mu$ shadowed fading channel is employed over the CCRN to generate a realistic environment. In order to implement such system as a whole, a deep literature study is performed beforehand.

Analytical expressions for the Probability Density Function (PDF) and Cumulative Distribution Function (CDF) of the Signal-to-Noise Ratio (SNR) are obtained. The analytical expressions and simulation results for Outage Probability (OP) are obtained and compared under different fading parameters. The importance of a multiple-relay system in CRN is presented.

From the results obtained in this research work, we can conclude that the OP decreases with increase in allowable peak interference power at the PU. The transmit power at SU should always be constrained by the peak interference power at the PU to avoid interference. The overall system performance increases with increasing number of relays.

Keywords: Cognitive Radio Networks, Cooperative Communications, Decode-and-Forward Relays, Multiple-relay, Outage Probability

ABBREVIATIONS

CCRN	Cooperative Cognitive Radio Network
CDF	Cumulative Distribution Function
CR	Cognitive Radio
CRN	Cognitive Radio Network
DF	Decode-and-Forward
PDF	Probability Density Function
PU	Primary User
SC	Selection Combining
SNR	Signal-to-Noise Ratio
SU	Secondary User
SU-R	Secondary User-Relay

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CONTENTS

1 INTRODUCTION

1.1 Motivation

Wireless communications have a substantial impact on the present day modern world. There are numerous wireless services available today like mobile telephony, satellite television, radio, video streaming and others. These technologies are not only improving our daily lifestyles but also making our lives much simpler. The need for these wireless technologies along with the requirements of higher data rates and ease of access is growing day by day. But, the radio spectrum available for us is not sufficient to fulfill these requirements. Additionally, most of the available radio spectrums are licensed by government agencies like Federal Communications Commission (FCC). This makes the radio spectrum a limited resource. This limited resource and increasing demand for wireless technologies have led to the problem of spectrum scarcity [1].

To overcome this problem, a new technology called Cognitive Radio (CR), was proposed. CR is an intelligent radio which detects and utilizes the channels of the licensed spectrum. The users in Cognitive Radio Networks (CRNs) are categorized into two types, Primary User (PU) or licensed user and Secondary User (SU) or unlicensed user. PUs are the licensed users with higher priorities to utilize the frequencies. SUs have lower priority to utilize the frequencies compared to PUs.

CR technology allocates the licensed spectrums to secondary unlicensed users effectively without causing harmful interference to the PUs. It detects whether the channel is available or not using different sensing techniques and utilizes the available channels opportunistically [2]. The SUs, while using the channels of licensed users may cause interference to the PUs due to various reasons like transmitting higher power signals, misdetection of the channel occupancy, using a complete channel when it is needed by a PU. To avoid these problems, the CR should continuously sense the presence of PUs which is very challenging.

There is another technology called cooperative communications in which every single mobile antenna acts both as a transmitter and cooperative agent. This method of communication helps CRNs to improve their wireless coverage area and reliability. This technique, when combined with cognitive radio, termed as Cooperative Cognitive Radio Network (CCRN), also increases the wireless coverage

[3] and overcomes the problems caused by the deeply faded channels [4] between transmitter and receiver.

Many literature works have been done on evaluating the performance of CCRNs over Nakagami-*m*, Rayleigh and Rician fading channels [5], [6]. But there is a need to study CCRNs in a more realistic environment to have a better understanding of the performance [4], when shadowing also comes into the picture.

1.2 Related Work

1.2.1 Single relay CRN

Recently, a model was proposed on CCRN assuming a $\kappa - \mu$ shadowed fading channel is present between Secondary User Transmitter (SU-Tx) and Secondary User Receiver (SU-Rx) [4] in a Decode-and-Forward (DF) relay network. The results produced in this paper show that the $\kappa - \mu$ shadowed fading distribution represents an environment similar to the one present in urban areas where the traffic is very high. This is very useful in studying the performance of CCRNs in a realistic environment. However, in [4], the system is concerned with a three node network: a source node communicating with a destination node with the help of a single relay. In this research work, a multiple relay system is considered which helps in increasing the wireless coverage area and improving the overall system performance.

1.2.2 Rayleigh fading distribution

The Rayleigh fading distribution represents a communication channel in which there are obstacles, scattering, attenuation between source and destination but no line-of-sight. The Probability Density Function (PDF) of the signal X with channel coefficient h is given by [5]

$$f_X(x) = \begin{cases} \frac{2x}{\Omega}\exp(-\frac{x^2}{\Omega}), & x \leq 0 \\ 0, & x > 0 \end{cases} \quad (1)$$

where, $\Omega = E\{|h^2|\}$ is the channel mean power and $E\{.\}$ denotes the expectation operator. The PDF and the Cumulative Distribution Function (CDF) of $Y=X^2$ are given by [5] as

$$f_Y(y) = \begin{cases} \frac{1}{\Omega} \exp(-\frac{y}{\Omega}), & y \leq 0 \\ 0, & y > 0 \end{cases} \tag{2}$$

$$F_Y(y) = \begin{cases} 1 - \exp(-\frac{y}{\Omega}), & y \leq 0 \\ 0, & y > 0 \end{cases} \tag{3}$$

In [2], the use of cooperative communications in a cognitive network was presented. The effect of having multiple relays in the network instead of a single relay on outage probability was also studied. However, the obtained results are not exact and do not apply in an environment where shadowing exists. There is a need for this system model to be tested under a more realistic environment instead of Rayleigh fading channel.

1.2.3 Nakagami-*m* fading distribution

Nakagami-*m* fading replicates the communication channel where the wavelength of the carrier is proportional to the size of clusters of scatters [1]. The PDF of $X = h$ is given by [6]

$$f_X(x) = \begin{cases} \frac{2m^m x^{2m-1}}{\Omega^m \Gamma(m)} \exp(-\frac{mx^2}{\Omega}), & x \leq 0 \\ 0, & x > 0 \end{cases} \tag{4}$$

where, $\Gamma(.)$ is the gamma function and m is a fading severity parameter in the range of 0.5 to ∞. The PDF and CDF of the channel power gain $Y=h^2$ are given by

$$f_Y(y) = \begin{cases} \frac{m^m y^{m-1}}{\Omega^m \Gamma(m)} \exp(-\frac{my}{\Omega}), & y \leq 0 \\ 0, & y > 0 \end{cases} \tag{5}$$

$$F_Y(y) = \begin{cases} 1 - \frac{\Gamma(m, my/\Omega)}{\Gamma(m)}, & y \leq 0 \\ 0, & y > 0 \end{cases} \tag{6}$$

where $\Gamma(.,.)$ denotes the incomplete gamma function [1].

The Nakagami-*m* fading distribution can also be used to replicate a communication channel, but it does not consider shadowing effect present in the channel. The detailed description of Nakagami-*m* fading is given in [6].

1.2.4 Amplify-and-forward relay protocol

In Amplify-and-Forward (AF) relaying, the signal is transmitted to the relay in the first hop. The relay amplifies the received signal and transmits it to the destination in the second hop without decoding. The AF relay has the benefit of simple architecture at the relay as it does not perform any decoding. It amplifies the signal at the relay and forwards it to the destination. The choice of amplifying gain depends on the knowledge of the Channel State Information (CSI) of the first hop from source to destination. If the relay is aware of the CSI, the gain can be varied and it is known variable-gain AF relaying [7]. If the relay knows only the statistical behavior of the channel from source to destination, the gain is fixed and it is known as fixed-gain AF relaying. However, as the signal is amplified at the relay, the noise present in the signal also gets amplified which is not desired. Hence the DF relay protocol is considered in this research work as described in Section 2.1.

1.3 Aims and Objectives

The main aim of this thesis is to evaluate the performance of a CCRN, which consists of an SU-Tx, SU-Rx and multiple DF relays over $\kappa - \mu$ shadowed fading channels under Selection Combining (SC) techniques. The analysis includes obtaining the outage probability over a wide range of signal-to-noise ratio (SNR) regimes. Some of the objectives are as follows:

- Calculating the PDF and CDF of the SNR.
- Obtaining an analytical expression for outage probability.
- Analyzing outage probabilities for different fading parameters.
- Designing and simulating a system model with multiple relays.
- Producing a $\kappa - \mu$ shadowed fading over this system model.
- Obtaining simulated results for outage probability.

1.4 Research Questions

The research questions of this thesis are

- Do analytical expressions exist for the PDF and CDF of the SNR for CCRNs over $\kappa - \mu$ shadowed fading?
- What is the effect of a $\kappa - \mu$ shadowed fading channel on the outage performance of the CCRN?

- What is the impact of multiple DF relays network on the outage performance of the CCRN?
- What is the impact of selection combining technique on the outage performance of the CCRN?

1.5 Contributions

The main contribution of this thesis is the evaluation of the outage performance of a CCRN, which consists of SU-Tx, SU-Rx and multiple DF relay network over a more realistic $\kappa - \mu$ shadowed fading channel under SC. The analysis includes obtaining outage probability over a wide range of SNR regimes. Some of the contributions are

- PDF and CDF of the SNR of the system have been calculated.
- An expression for outage probability has been obtained analytically.
- A system model with multiple relays has been designed.
- A $\kappa - \mu$ shadowed fading over the proposed system model has been produced.
- Simulated results for outage probability are obtained.
- Outage probabilities over different fading parameters are analyzed.

1.6 Outline of the thesis

This thesis is structured as follows. Chapter 2 describes mainly about the fundamental concepts related to the thesis. It gives a brief description of cognitive radio networks and cooperative communications. It also gives a basic idea of the background concepts which are a mainstay for this thesis. Chapter 3 presents the system model and the detailed description of the system model. The PDF and CDF expressions of the SNR for the considered system model are derived using an approximation. The OP is straight-forwardly derived from the CDF of the SNR of the signal by considering a gamma threshold value. In Chapter 4, the numerical and simulated results are presented along with a detailed discussion. The conclusions are drawn and future works are suggested in Chapter 5.

2 FUNDAMENTALS

2.1 Decode-and-Forward Protocol

In cooperative communications, the signal is transmitted from the source to the destination in two time slots. In the first time slot, the signal is transmitted directly to the destination through a direct link and to the relays simultaneously. In the second time slot, the relays process and transmit the signal to the destination. At each relay, a relaying protocol is employed to enhance the signal. There are different relaying protocols such as AF relaying protocol, DF relaying protocol and Estimation-and-Forward (EF) relaying protocol. In the AF relaying protocol, the signal at the relay is amplified and forwarded to the destination. The DF relaying protocol decodes the signal at the relay and then forwards the re-encoded signal [1]. In EF relaying protocol, a transformation is applied at the relay which is an estimate of the source signal and then forwards it to the destination. In this research work, the DF relaying protocol is considered.

The DF protocol is classified into fixed DF scheme and adaptive DF [8]. In the fixed DF scheme, the source transmits the signal to the relay and destination simultaneously. The relay decodes the signal and then transmits the re-encoded signal. The maximum mutual interference of the fixed DF scheme between source and destination is given as [1]

$$I_{DF} = \frac{1}{2}\min(\log(1+\rho|h_1|^2), \log(1+\rho|h_0|^2+\rho|h_2|^2)) \tag{7}$$

where ρ is the ratio of the transmit power of the source to the noise power at each terminal and h_0, h_1 and h_2 are the channel coefficients of the links from source to the destination, from source to the relay and from relay to the destination, respectively.

Since the relay should fully decode and re-encode the signal received from the source, the performance of the fixed DF solely depends on the performance of the transmission from the source to the relay. This becomes a problem when there is a loss of the signal at the relay due to attenuation. To overcome this problem, the adaptive DF scheme has been proposed. In this scheme, the relay does not process the signal if it is below a predefined threshold. If the received signal is above the threshold value, the relay decodes and re-encodes before transmitting the signal to the destination.

2.2 Cooperative Communications

The point-to-point communication is not practical in case of long-range communications or when there is severe fading and shadowing present in the channel. In order to overcome this problem, the long-range direct link is assisted with a number of relay links, where each intermediate node acts as a repeater to enhance the quality of the signal [9]. The signal travels in a multipath environment where every single antenna acts both as transmitter and relay. This type of network is called as a cooperative network and the communication done is known as cooperative communications.

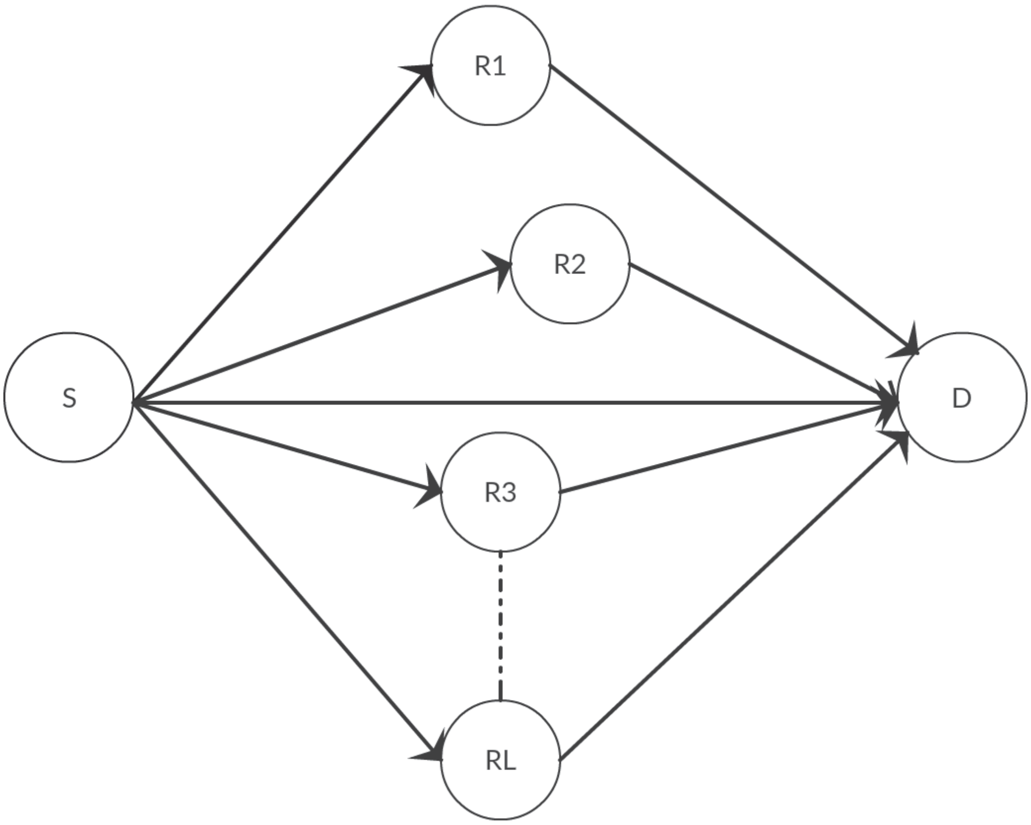

Fig. 1. Topology of a relaying network facilitating cooperative communications.

Cooperative communication is used for creating spatial diversity in a wireless network. It is used to increase the wireless coverage area and reliability. To understand the mechanism of cooperative communications, let us consider that source S should send a message to the destination D. The amount of information received at the destination mainly depends on the communication range. If the distance between S and D is less, then most of the signal gets transmitted to D. This scenario is called short-range communications. But in most of the cases, it is desired to send the information in the long range called long range communications. The point-to-point communication is not preferred in this scenario as the signal may undergo fading, attenuation etc. Hence, to overcome the loss of the signal in long range communications, a cooperative network should be considered.

To fully understand the mechanism of cooperative communications, let us consider Fig. 1. In this figure, a two-hop relay network is shown, where S and D represent source and destination respectively, and R1, R2,..., RL are the relays. We can see that the transmitted signal travels through multi-paths before reaching the destination. In the first hop, the signal is broadcasted to the destination directly through point-to-point communication and to the relays simultaneously. In the second hop, relays process the received signal by adding its overhead to the original signal and then transmit it to the destination. Thus, the relay antenna is used both as a transmitter and cooperative agent. One can also consider a multi-hop relay network in which the transmitter signal passes through two or more number of relays through a single path. The signal from each branch uses two or more hops in a communication network, to transmit information between source and destination [10].

If we consider a system with L number of relays then, there exist $L+1$ number of channels (one for the direct link, L for relays), for the signal to travel from the source to the destination. Finally, a single signal is produced as an output signal at the destination by employing different combining techniques. This type of communication requires high transmission power and many number of channels. To overcome this difficulty, opportunistic relaying is used. Opportunistic relaying is a technique which is employed at the source before the signal gets transmitted. The relay with the strongest source-to-destination path is selected among other paths based on its instantaneous channel measurements to transmit the signal [11]. This type of relaying can transmit a signal without requiring the knowledge of the Channel State Information (CSI) at each relay [12] .

2.3 Cognitive Radio Network

The problem of spectrum scarcity has been the main reason for the development of an innovative technology called Cognitive Radio (CR). CR is an intelligent radio which senses the underlying spectrums and utilizes them effectively by allocating it to the wireless users for communication purposes. This technique was proposed in 1999 by Joseph Mitola [13].

The available spectrum is overly populated because of the growing demand for wireless systems and services. Most of the spectrums are licensed by government agencies. These licensed spectrums are underutilized. Cognitive radio has been developed to utilize these underutilized spectrums by allocating them to the unlicensed users. The users whose spectrums are licensed are called PUs. SUs are those who mostly use unlicensed spectrums and occasionally use the PU channels effectively [14].

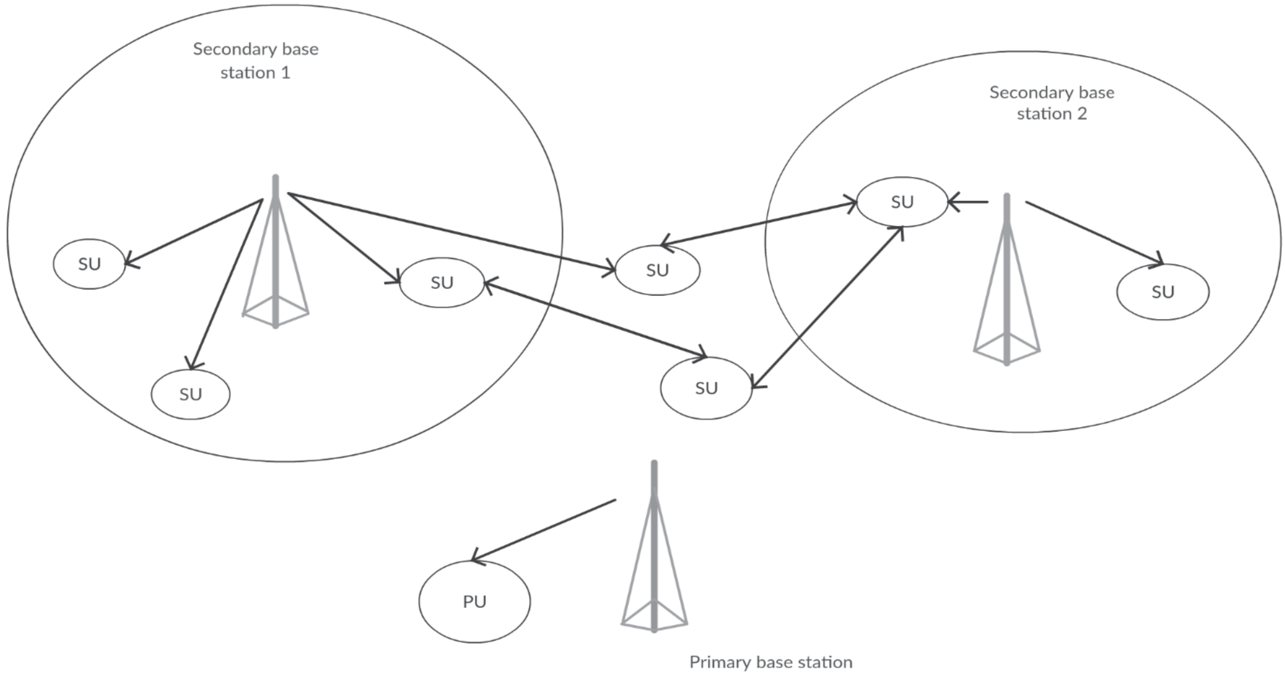

Fig. 2. An example of a topology with co-existing primary and secondary networks.

An example of a topology with co-existing primary and secondary networks is shown in Fig. 2. CRs use different sharing techniques to utilize the licensed spectrum. The licensed spectrum is shared with CR users mainly in three sharing paradigms: Underlay, Overlay and Interweave [15].

In underlay paradigm, the PU and SU transmit the signals simultaneously as long as the peak interference power is maintained. The allowable power to be transmitted by the SU should not exceed the interference level at the PU. In order to achieve this, the CR should have the knowledge of the tolerable interference power at PU. In overlay paradigm, the PUs share knowledge of their messages with SU. The interference constraint is not maintained by the SU but the interference power can be put offset by assisting the PU as relays [16]. In interweave paradigm, the SU can utilize the channel only when it is idle. The CR detects and allocates the vacant channels to the SUs and the interference may occur only when the CR fails to detect the presence of the PU. If the PU comes to occupy the channel, the SU has to vacate the channel immediately. So, the CR have to continuously sense the presence of the PU, which is very hard to achieve. CRs use different sensing techniques to sense the idle spectrum. The different sensing methods are: energy detection, matched filter detection, cyclostationary based detection etc. The vacant channel is detected using any of the above spectrum sensing methods and if idle, they are utilized by the SU for the transmission of data [16].

In this research work, an underlay sharing paradigm is adopted because the SU can utilize any channel readily as long as the interference constraint is maintained. There is no need for the SU to act as a relay or to wait for the PU to vacate the channel unlike overlay or interweave paradigms.

The CR technology is combined with another technology called cooperative communications, which has been described in Section 2.2. These two technologies when combined not only helps to achieve a wide cognitive radio coverage but also increases the reliability and the overall system performance.

2.4 Fading

2.4.1 $\kappa - \mu$ fading distribution

The signal propagating through a wireless channel undergoes distortion, attenuation, scattering and so on. As a result, the signal reaches the destination through different paths which are characterized by fading. There are many distributions which describe the statistical behavior of such signals. However, there exist situations when no distribution yields a perfect fit to the experimental data.

The $\kappa - \mu$ fading distribution describes the statistical behavior of a fading signal in a line-of-sight (LOS) condition [17]. It is controlled by two scaling factors κ and μ. It comprises the one-sided Gaussian, Rician, Rayleigh and Nakagami-*m* distributions. These distributions occur as special cases of the $\kappa - \mu$ fading distribution. However, the $\kappa - \mu$ distribution yields a better fit to experimental data compared to the aforementioned distributions.

2.4.2 $\kappa - \mu$ shadowed fading distribution

In order to get a fundamental insight on how a CCRN performs in a real environment, there is a need for the implementation of such a system. On the other hand, the spectrum allocated to the PUs is licensed and cannot be used for experimental purposes. Hence, the $\kappa - \mu$ shadowed fading model is utilized in this research work, which replicates the behavior of a realistic wireless environment. The statistical behavior of $\kappa - \mu$ shadowed fading is given in [18]. There are two basic types of shadowed fading models, multiplicative shadow and fading models and LOS shadow and fading models. Rician shadowed fading model is an example of an LOS shadowed fading model. It assumes the Rician distribution for multipath fading and Nakagami-*m* for shadowing. Rician shadowed fading occurs as a special case of $\kappa - \mu$ shadowed fading [18]. The $\kappa - \mu$ shadowed fading is a distribution with fading parameters $S_{\kappa\mu} \sim (\kappa, \mu, \xi, \bar{z})$, where $S_{\kappa\mu}$ denotes the $\kappa - \mu$ fading channel with shadowing effect, ξ is a scaling factor and κ and μ are the fading parameters. It unifies the $\kappa - \mu$ distribution and Rician shadow fading and fading along with one-sided Gaussian, Rayleigh, Rician, and Nakagami-*m* distributions. The analytical expressions like CDF, PDF are obtained as a closed form expression in $\kappa - \mu$ shadowed fading models.

The PDF of the instantaneous channel power gain of $\kappa - \mu$ shadowed fading is given by [1]

$$f_z(z) = \frac{\phi_1^{m-\mu} z^{\mu-1}}{\phi_2{}^m \Gamma(\mu)} e^{-\frac{z}{\phi_1}} {}_1F_1\left(m; \mu; \frac{(\phi_2 - \phi_1)z}{\phi_1 \phi_2}\right) \tag{8}$$

where $\phi_1 = \frac{\bar{z}}{\mu(1+k)}$, $\phi_2 = \frac{(\mu k + \xi)\bar{z}}{\mu(1+k)\xi}$, and ${}_1F_1(.;.;.)$ is the Kummer confluent hypergeometric function. $\bar{z}$ is the average power of channel fading.

The CDF of the channel power gain under $\kappa - \mu$ shadowed fading is given by

$$F_z(z) = \frac{(z\alpha)^m}{\Gamma(m+1)} {}_1F_1(m; m+1; -z\alpha) \tag{9}$$

where

$$m = \frac{\xi\mu(1+k)^2}{\xi + \mu k^2 + 2\xi k} \tag{10}$$

and

$$\alpha = \frac{m}{\bar{z}} \tag{11}$$

2.5 Combining Techniques

In a diversity communication technique, the source communicates with the destination directly through a direct link and indirectly through relays. However, we need to produce one output at the destination which can be obtained by various combining techniques. The different types of combining techniques are SC, Maximal Ratio Combining (MRC), and Equal Gain Combining (EGC).

In the SC technique, the selection of the required output signal is done based on its SNR. The signals obtained from different paths are processed at the destination and the branch with the highest SNR is selected [19]. This technique is easy to implement and the analytical expressions for CDF and PDF of the SNR are relatively easy to obtain.

3 OUTAGE ANALYSIS

In the sequel, a two-hop CCRN with the structure shown in Fig. 3 is considered. Initially, in this system model, opportunistic relaying technique is employed at the SU-Tx and the best path is selected through the relays. A one-way communication is considered with the assumption that the signal from the selected branch reaches the destination. At the SU-Rx, two received signals (one through the direct link and the other through the selected relay) are queued and the selection combining technique is employed to select the final output. Analytical expressions for the CDF and PDF of the SNR are derived.

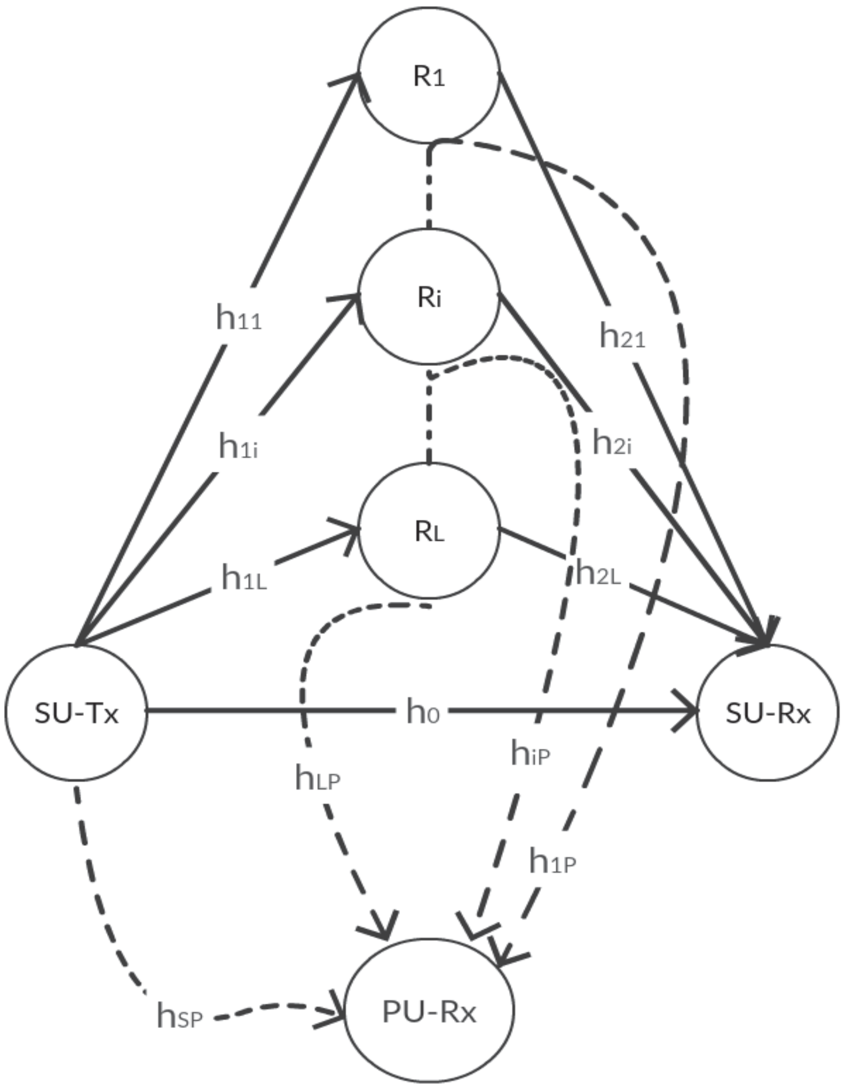

Fig. 3. Topology of the considered CCRN.

The OP is straight-forwardly derived from the CDF of the SNR of the output signal by considering the SNR of the signal is limited by a threshold value.

$$P_{out} = F(\Upsilon = \Upsilon_{th}) \tag{12}$$

where P_{out} is a outage probabilty of the system and Υ and Υ_{th} are the SNR and the threshold SNR of the signal, respectively. The OP is derived in Section 3.1.

3.1 System model

In the first time slot, the signal is transmitted from SU-Tx to SU-Ri. In the second time slot, it is transmitted from SU-Ri to SU-Rx. The transmit power at SU-Tx is constrained by the maximum transmit power P_1 of SU-Tx and the peak interference power *I* at PU-Rx.

Let the signal *x* be sent by SU-Tx. The received signal at SU-Rx in the first time slot through the direct link SU-Tx→ SU-Rx is

$$y_0 = h_0 x + n_0 \tag{13}$$

where h_0 is the channel fading coefficient of the link SU-Tx→ SU-Rx and n_0 is the Additive White Gaussian Noise (AWGN) at SU-Tx.

Let P_1 be the maximum transmit power then the transmit power at the SU-Tx P_s, is constrained by

$$P_s = min\left(P_1, \frac{I}{|h_{sp}|^2}\right) \tag{14}$$

The SNR at SU-Tx through the direct link SU-Tx→ SU-Rx link, denoted by Υ_0, is given by

$$\Upsilon_0 = \frac{P_s\,|h_0|^2}{N_0} \tag{15}$$

where N_0 is the AWGN power at the destination.

Substituting (14) in (15), we get the SNR at SU-Tx through the direct link as

$$\begin{aligned} \Upsilon_0 &= min\left(\frac{P_1|h_0|^2}{N_0}, \frac{I|h_0|^2}{|h_{sp}|^2 N_0}\right) \\ &= min\left(\frac{P_1 X_0}{N_0}, \frac{I X_0}{N_0 X_{sp}}\right) \end{aligned} \tag{16}$$

where $X_0 = |h_0|^2$ and $X_{sp} = |h_{sp}|^2$.

Let us now consider the relaying link SU-Tx→SU-R1→SU-Rx. The received signal at relay R_1 in the first time slot is

$$y_{R_1} = h_{11}x + n_{11} \tag{17}$$

where h_{11} is the channel fading coefficient of the link between SU-Tx and SU-R1 and n_{11} is the AWGN at SU-Rx. Here, the relay acts as a DF relay; it processes the received signal y_{R1} by decoding an estimate $\hat{x}$ of the source transmitted signal x and then forward the decoded signal $\hat{x}$ to the destination. The equation of the received signal at SU-Rx in the second time slot from SU-Ri is given by

$$y_{SR_1D} = h_{21}\hat{x} + n_1 \tag{18}$$

where n_1 is the AWGN at SU-R1 and h_{21} is the channel fading coefficient of the link between SU-R1 and SU-Rx. Similarly, the received signal at SU-Rx through relays $R_2, R_3, \ldots R_L$ are

$$y_{SR_2D} = h_{22}\hat{x} + n_2 \tag{19}$$

$$y_{SR_3D} = h_{23}\hat{x} + n_3 \tag{20}$$

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$$y_{SR_LD} = h_{2L}\hat{x} + n_L \tag{21}$$

Now, let us derive the SNR at SU-Rx of the SU-Tx→SU-Rx link through the i^{th} relay. Assume that opportunistic relaying is deployed and all relays have the same transmit power P_R. The interference from the selected relay at the PU-Rx is constrained by

$$P_R |h_{ip}|^2 \leq I \tag{22}$$

where I is the interference power threshold at PU-Rx. Then, the transmit power at the relay is selected as

$$P_\mathrm{R} = min\left(P_2, \frac{I}{|h_{ip}|^2}\right) \tag{23}$$

where P_2 is the maximum transmit power at SU-Ri. Let the SNR at SU-Ri through the SU-Tx→SU-Ri link be Υ_{1i} and that at the SU-Rx of the link SU-Ri→SU-Rx be Υ_{2i}. Then, we can write

$$\Upsilon_{1i} = \frac{P_s|h_{1i}|^2}{N_0}$$

$$= min\left(\frac{P_1\,|h_{1i}|^2}{N_0}, \frac{\mathrm{I}\,|h_{1i}|^2}{N_0|h_{sp}|^2}\right)$$

$$= min\left(\frac{P_1\,X_{1i}}{N_0}, \frac{IX_{1i}}{X_{sp}N_0}\right) \tag{24}$$

and

$$\Upsilon_{2i} = \frac{P_{\mathrm{R}}\,|h_{2i}|^2}{N_0}$$

$$= min\left(\frac{P_2\,|h_{2i}|^2}{N_0}, \frac{\mathrm{I}\,|h_{2i}|^2}{N_0|h_{ip}|^2}\right)$$

$$= min\left(\frac{P_2\,X_{2i}}{N_0}, \frac{IX_{2i}}{X_{ip}N_0}\right) \tag{25}$$

where $X_{1i}=|h_{1i}|^2$, $X_{2i}=|h_{2i}|^2$ *and* $X_{ip}=|h_{ip}|^2$.

The SNR at SU-Rx of the link SU-Tx→SU-Rx through relay R_i is given by

$$\Upsilon_{SR_iD} = min\left(\frac{P_s\,|h_{1i}|^2}{N_0}, \frac{P_{\mathrm{R}}\,|h_{2i}|^2}{N_0}\right)$$

$$= min(\Upsilon_{1i}, \Upsilon_{2i}) \tag{26}$$

The system utilizes the opportunistic relaying, in which the best path to transmit the signal through the relay is selected at the SU-Tx. The received SNR at SU-Rx through the relaying link is obtained by

$$\Upsilon_t = max(\Upsilon_{SR_1D}, \dots, \Upsilon_{SR_iD}, \dots, \Upsilon_{SR_LD}) \tag{27}$$

The SC technique is employed for combining the signals at SU-Rx. A signal with the highest SNR will be selected among the direct link and relaying links. Thus, the total SNR of the system can be given by

$$\Upsilon_{tot} = max(\Upsilon_0, \Upsilon_t) \tag{28}$$

3.2 PDF and CDF Expressions of the Instantaneous Channel Coefficients of κ − μ Shadowed Fading

Let us recall that the PDF of the instantaneous channel coefficients (h_0, h_{1i}, h_{2i}, h_{sp}, h_{ip}), of κ − μ shadowed fading has the distribution in the form as [4]

$$f_z(z) = \frac{\phi_1^{m-\mu} z^{\mu-1}}{\phi_2{}^m \Gamma(\mu)} e^{-\frac{z}{\phi_1}} {}_1F_1\left(m; \mu; \frac{(\phi_2 - \phi_1)z}{\phi_1 \phi_2}\right) \tag{29}$$

where $\phi_1 = \frac{\bar{z}}{\mu(1+k)}$, $\phi_2 = \frac{(\mu k+m)\bar{z}}{\mu(1+k)m}$ and ${}_1F_1(.;.;.)$ is the Kummer confluent hypergeometric function and $\bar{z}$ is the average power gain of the channel fading.

In the sequel, we also use the fact that the κ − μ shadowed fading can be approximated by gamma random variable $\mathcal{G}(m, \frac{1}{\alpha})$, where

$$m = \frac{\xi\mu(1+k)^2}{\xi+\mu k^2+2\xi k} \tag{30}$$

and

$$\alpha = \frac{m}{\bar{z}} \tag{31}$$

The CDF of the approximated channel power gain under κ − μ shadowed fading is given by [4]

$$F_z(z) = \frac{(z\alpha)^m}{\Gamma(m+1)} {}_1F_1(m; m+1; -z\alpha) \tag{32}$$

3.3 PDF and CDF of Instantaneous Channel Coefficients of Nakagami-*m* Fading Distribution

When using the PDF and CDF of instantaneous channel coefficients obtained in (29) and (32), over κ − μ shadowed fading distribution, the integral of the hypergeometric confluent function cannot be simplified further as shown in the Appendix. Hence, in the following section, the PDF and CDF of κ − μ shadowed fading is approximated to Nakagami-*m* for integer value of *m* in (30) to facilitate further calculation. As a result, the CDF and PDF of the approximated channel power gain as gamma distribution can be derived for integer value of *m* as [6]

$$f_z(z) = \frac{\alpha_i{}^{m_i} z^{m_i-1}}{\Gamma(m_i)} \exp(-\alpha_i z) \tag{33}$$

$$F_z(z) = 1 - \sum_{l=0}^{m_i-1} \frac{\alpha_i^l}{l!} z^l \exp(-\alpha_i z) \tag{34}$$

where m and α can be calculated from the parameters $(\kappa,\mu,\xi,\bar{z})$ of $\kappa - \mu$ shadowed fading channel as

$$m = \frac{m' \mu (1+k)^2}{m' + \mu k^2 + 2m'k} \tag{35}$$

$$\alpha = \frac{m}{\bar{z}} \tag{36}$$

3.4 CDF derivation of the SNR of the Received Signal

The CDF $F_{\gamma_{tot}}(\gamma)$ of the total SNR given in (28) can be calculated as

$$F_{Y_{tot}}(\gamma) = \int_0^\infty F_{Y_{tot}}(\gamma | X_{sp} = x_{sp}) f_{X_{sp}}(x_{sp}) dx_{sp} \tag{37}$$

The conditional CDF $F_{Y_{tot}}(\gamma | X_{sp} = x_{sp})$ in (37) can be given as

$$\begin{aligned} F_{Y_{tot}}(\gamma | X_{sp} = x_{sp}) &= \Pr(\gamma_{tot} | X_{sp} = x_{sp} \le \gamma) \\ &= \Pr(\gamma_0 | X_{sp} = x_{sp}, \gamma_t | X_{sp} = x_{sp} \le \gamma) \\ &= \Pr(\gamma_0 | X_{sp} = x_{sp}, \gamma_{SR_1D} | X_{sp} = x_{sp}, \dots, \gamma_{SR_LD} | X_{sp} = x_{sp} \le \gamma) \\ &= \Pr(\gamma_0 | X_{sp} = x_{sp} \le \gamma) \Pr(\gamma_{SR_1D} | X_{sp} = x_{sp} \le \gamma) \dots \\ &\qquad \Pr(\gamma_{SR_LD} | X_{sp} = x_{sp} \le \gamma) \\ &= F_{Y_0}(\gamma | X_{sp} = x_{sp}) \prod_{i=1}^{L} F_{Y_{SR_iD}}(\gamma | X_{sp} = x_{sp}) \end{aligned} \tag{38}$$

3.4.1 CDF of the SNR at the destination through the direct link

The CDF $F_{Y_0}(\gamma | X_{sp} = x_{sp})$ of the SNR through the direct link can be obtained from (16) as

$$F_{Y_0}(\gamma | X_{sp} = x_{sp}) = \begin{cases} F_{X_0}\left(\frac{\gamma N_0}{P_1}\right), & x_{sp} < \frac{I}{P_1} \\ F_{X_0}\left(\frac{\gamma N_0 x_{sp}}{I}\right), & x_{sp} \ge \frac{I}{P_1} \end{cases} \tag{39}$$

Substituting the CDF given in (32) into (39), we obtain the exact expression for $F_{Y_0}\left(\gamma|X_{sp}=x_{sp}\right)$ as

$$F_{Y_0}\left(\gamma|X_{sp}=x_{sp}\right)=\begin{cases}\left(\frac{\gamma N_0}{P_1\alpha_0}\right)^{m_0}\frac{1}{\Gamma(\alpha_0+1)}{}_1F_1\left(m_0;m_0+1;-\left(\frac{\gamma N_0}{P_1\alpha_0}\right)\right), & x_{sp}<\frac{I}{P_1}\\ \left(\frac{\gamma N_0 x_{sp}}{I\alpha_0}\right)^{m_0}\frac{1}{\Gamma(m_0+1)}{}_1F_1\left(m_0;m_0+1;-\left(\frac{\gamma N_0 x_{sp}}{I\alpha_0}\right)\right), & x_{sp}\geq\frac{I}{P_1}\end{cases} \tag{40}$$

Using the approximated CDF given in (34), the CDF of (40) can be approximated using the Nakagami-*m* approximation as

$$F_{Y_0}\left(\gamma|X_{sp}=x_{sp}\right)=\begin{cases}1-\sum_{k=0}^{m_0-1}\frac{\alpha_0^k}{k!}\left(\frac{\gamma N_0}{P_1}\right)^k\exp\left(-\frac{\alpha_0\gamma N_0}{P_1}\right), & x_{sp}<\frac{I}{P_1}\\ 1-\sum_{k=0}^{m_0-1}\frac{\alpha_0^k}{k!}\left(\frac{\gamma N_0}{I}\right)^k {x_{sp}}^k\exp\left(-\frac{\alpha_0\gamma N_0}{I}x_{sp}\right), & x_{sp}\geq\frac{I}{P_1}\end{cases} \tag{41}$$

where m_0 is an integer which is calculated from the parameter set (κ_0,μ_0,ξ_0,z_0) of $\kappa-\mu$ shadowing channel of the direct link as in (35).

3.4.2 CDF of the SNR at the destination through the i^{th} relay

The conditional CDF $F_{Y_{SR_iD}}\left(\gamma|X_{sp}=x_{sp}\right)$ of the SNR at SU-Rx through the i^{th} relay R_i is given by

$$\begin{aligned}F_{Y_{SR_iD}}\left(\gamma|X_{sp}=x_{sp}\right)&=\Pr(\gamma_{SR_iD}|X_{sp}=x_{sp}\leq\gamma)\\&=\Pr\left(\min(\gamma_{1i},\gamma_{2i})|X_{sp}=x_{sp}\leq\gamma\right)\\&=1-\Pr\left(\min(\gamma_{1i},\gamma_{2i})\,|X_{sp}=x_{sp}\geq\gamma\right)\\&=1-\Pr(\gamma_{1i}|X_{sp}=x_{sp}\geq\gamma)\Pr(\gamma_{2i}|X_{sp}=x_{sp}\geq\gamma)\\&=1-\left[1-\Pr(\gamma_{1i}|X_{sp}=x_{sp}\leq\gamma)\right]\left[1-\Pr(\gamma_{2i}|X_{sp}=x_{sp}\leq\gamma)\right]\\&=1-\left[1-F_{Y_{1i}}\left(\gamma|X_{sp}=x_{sp}\right)\right]\left[1-F_{Y_{2i}}\left(\gamma|X_{sp}=x_{sp}\right)\right]\end{aligned} \tag{42}$$

From (24), the CDF $F_{Y_{1i}}\left(\gamma|_{X_{sp}=x_{sp}}\right)$ is split into the following two cases:

$$F_{Y_{1i}}\left(\gamma|_{X_{sp}=x_{sp}}\right)=\begin{cases}F_{X_{1i}}\left(\frac{\gamma N_0}{P_1}\right), & x_{sp}<\frac{I}{P_1}\\ F_{X_{1i}}\left(\frac{\gamma N_0 x_{sp}}{I}\right), & x_{sp}\geq\frac{I}{P_1}\end{cases} \tag{43}$$

Substituting (32) into (43) gives the exact expression for $F_{Y_{1i}}(\gamma|X_{sp}=x_{sp})$ as

$$F_{Y_{1i}}(\gamma|X_{sp}=x_{sp})=\begin{cases}\left(\frac{\gamma N_0}{P_1\alpha_{1i}}\right)^{m_{1i}}\frac{1}{\Gamma(m_{1i}+1)}\,{}_1F_1\left(m_{1i};m_{1i}+1;-\left(\frac{\gamma N_0}{P_1\alpha_{1i}}\right)\right), & x_{sp}<\frac{I}{P_1}\\ \left(\frac{\gamma N_0 x_{sp}}{I\alpha_{1i}}\right)^{m_{1i}}\frac{1}{\Gamma(m_{1i}+1)}\,{}_1F_1\left(m_{1i};m_{1i}+1;-\left(\frac{\gamma N_0 x_{sp}}{I\alpha_{1i}}\right)\right), & x_{sp}\geq\frac{I}{P_1}\end{cases} \quad (44)$$

Using the Nakagami-*m* approximated CDF, $F_{Y_{1i}}(\gamma|X_{sp}=x_{sp})$ is given by

$$F_{Y_{1i}}(\gamma|X_{sp}=x_{sp})=\begin{cases}1-\sum_{l=0}^{m_{1i}-1}\frac{\alpha_{1i}^l}{l!}\left(\frac{\gamma N_0}{P_1}\right)^l\exp\left(-\frac{\alpha_{1i}\gamma N_0}{P_1}\right), & x_{sp}<\frac{I}{P_1}\\ 1-\sum_{l=0}^{m_{1i}-1}\frac{\alpha_{1i}^l}{l!}\left(\frac{\gamma N_0}{I}\right)^l x_{sp}{}^l\exp\left(-\frac{\alpha_{1i}\gamma N_0}{I}x_{sp}\right), & x_{sp}\geq\frac{I}{P_1}\end{cases} \quad (45)$$

The CDF $F_{Y_{2i}}(\gamma|X_{sp}=x_{sp})$ in (42) can be obtained from (25) as

$$F_{Y_{2i}}(\gamma|X_{sp}=x_{sp})=F_{Y_{2i}}(\gamma) \quad (46)$$

where $F_{Y_{2i}}(\gamma)=\int_0^\infty F_{Y_{2i}}(\gamma|X_{ip}=x_{ip})f_{X_{ip}}(x_{ip})dx_{ip}$.

From (25), the CDF $F_{Y_{2i}}(\gamma|X_{ip}=x_{ip})$ is

$$F_{Y_{2i}}(\gamma|X_{ip}=x_{ip})=\begin{cases}F_{X_{2i}}\left(\frac{\gamma N_0}{P_2}\right), & x_{ip}<\frac{I}{P_2}\\ F_{X_{2i}}\left(\frac{\gamma N_0 x_{ip}}{I}\right), & x_{ip}\geq\frac{I}{P_2}\end{cases} \quad (47)$$

Using expression of the CDF in (32), $F_{Y_{2i}}(\gamma|X_{sp}=x_{sp})$ is expressed as

$$F_{Y_{2i}}(\gamma|X_{ip}=x_{ip})=\begin{cases}\left(\frac{\gamma N_0}{P_2\alpha_{2i}}\right)^{m_{2i}}\frac{1}{\Gamma(m_{2i}+1)}\,{}_1F_1\left(m_{2i};m_{2i}+1;-\left(\frac{\gamma N_0}{P_2\alpha_{2i}}\right)\right), & x_{ip}<\frac{I}{P_2}\\ \left(\frac{\gamma N_0 x_{ip}}{I\alpha_{2i}}\right)^{m_{2i}}\frac{1}{\Gamma(m_{2i}+1)}\,{}_1F_1\left(m_{2i};m_{2i}+1;-\left(\frac{\gamma N_0 x_{Rp}}{I\alpha_{2i}}\right)\right), & x_{ip}\geq\frac{I}{P_2}\end{cases} \quad (48)$$

The CDF of Y_{2i} can be calculated from (48) as

$$F_{Y_{2i}}(\gamma)=\int_0^{I/P_2}F_{X_{2i}}\left(\frac{\gamma N_0}{P_2}\right)f_{X_{ip}}(x_{ip})dx_{ip}+\int_{I/P_2}^{\infty}F_{X_{2i}}\left(\frac{\gamma N_0 x_{ip}}{I}\right)f_{X_{ip}}(x_{ip})dx_{ip} \quad (49)$$

Here, X_{ip} is approximated by a Nakagami-*m* distribution. The PDF $f_{X_{ip}}(x_{ip})$ of the SNR is given by

$$f_{X_{ip}}(x_{ip}) = \frac{\alpha_{ip}{}^{m_{ip}}}{\Gamma(m_{ip})} x_{ip}^{m_{ip}-1} \exp(-\alpha_{ip} x_{ip}) \tag{50}$$

where m_{ip} is an integer.

Using the approximated CDF for $F_{X_{2i}}\left(\frac{\gamma N_0}{P_2}\right)$, we have

$$F_{X_{2i}}\left(\frac{\gamma N_0}{P_2}\right) = 1 - \sum_{p=0}^{m_{2i}-1} \frac{\alpha_{2i}^p}{p!}\left(\frac{\gamma N_0}{P_2}\right)^p \exp\left(-\frac{\alpha_{2i}\gamma N_0}{P_2}\right) \tag{51}$$

Similarly, the approximated CDF expression for $F_{X_{2i}}\left(\frac{\gamma N_0 x_{ip}}{I}\right)$ is given as

$$F_{X_{2i}}\left(\frac{\gamma N_0 x_{ip}}{I}\right) = 1 - \sum_{p=0}^{m_{2i}-1} \frac{\alpha_{2i}^p}{p!}\left(\frac{\gamma N_0 x_{ip}}{I}\right)^p \exp\left(-\frac{\alpha_{2i}\gamma N_0 x_{ip}}{I}\right) \tag{52}$$

Substituting (50), (51) and (52) into (49), we get

$$\begin{aligned} F_{\Upsilon_{2i}}(\gamma) &= \int_0^{I/P_2}\left[1 - \sum_{p=0}^{m_{2i}-1} \frac{\alpha_{2i}^p}{p!}\left(\frac{\gamma N_0}{P_2}\right)^p \exp\left(-\frac{\alpha_{2i}\gamma N_0}{P_2}\right)\right] f_{X_{ip}}(x_{ip}) dx_{ip} \\ &\quad + \int_0^{I/P_2}\left[1 - \sum_{p=0}^{m_{2i}-1} \frac{\alpha_{2i}^p}{p!}\left(\frac{\gamma N_0 x_{ip}}{I}\right)^p \exp\left(-\frac{\alpha_{2i}\gamma N_0 x_{ip}}{I}\right)\right] f_{X_{ip}}(x_{ip}) dx_{ip} \end{aligned} \tag{53}$$

$$\begin{aligned} F_{\Upsilon_{2i}}(\gamma) &= \int_0^{\frac{I}{P_2}} f_{X_{ip}}(x_{ip}) dx_{ip} \\ &\quad - \sum_{p=0}^{m_{2i}-1} \frac{\alpha_{2i}^p}{p!}\left(\frac{\gamma N_0}{P_2}\right)^p \exp\left(-\frac{\alpha_{2i}\gamma N_0}{P_2}\right) \int_0^{\frac{I}{P_2}} f_{X_{ip}}(x_{ip}) dx_{ip} + \int_{\frac{I}{P_2}}^{\infty} f_{X_{ip}}(x_{ip}) dx_{ip} \\ &\quad - \int_{I/P_2}^{\infty} \sum_{p=0}^{m_{2i}-1} \frac{\alpha_{2i}^p}{p!}\left(\frac{\gamma N_0 x_{ip}}{I}\right)^p \exp\left(-\frac{\alpha_{2i}\gamma N_0 x_{ip}}{I}\right) f_{X_{ip}}(x_{ip})\, dx_{ip} \end{aligned} \tag{54}$$

$$\begin{aligned} F_{\Upsilon_{2i}}(\gamma) &= F_{\Upsilon_{2i}}\left(\gamma|_{X_{sp}=x_{sp}}\right) = 1 - \sum_{p=0}^{m_{2i}-1} \frac{\alpha_{2i}^p}{p!}\left(\frac{\gamma N_0}{P_2}\right)^p \\ &\quad \times \exp\left(-\frac{\alpha_{2i}\gamma N_0}{P_2}\right) \frac{\alpha_{ip}{}^{m_{ip}}}{\Gamma(m_{ip})} F_{X_{ip}}\left(\frac{I}{P2}\right) - \sum_{p=0}^{m_{2i}-1} \frac{\alpha_{2i}^p}{p!}\left(\frac{\gamma N_0}{P_2}\right)^p \\ &\quad \times \frac{\alpha_{ip}{}^{m_{ip}}}{\Gamma(m_{ip})} \int_{I/P_2}^{\infty} \exp\left(-\frac{\alpha_{2i}\gamma N_0 + \alpha_{ip} I}{I} x_{ip}\right) x_{ip}^{p+m_{ip}-1} dx_{ip} \end{aligned} \tag{55}$$

Using (3.352.1) of [20] to solve the integral, (55) is re-written as

$$F_{Y_{2i}}(\gamma) = 1 - \sum_{p=0}^{m_{2i}-1} \frac{\alpha_{2i}^{p}}{p!}\left(\frac{\gamma N_0}{P_2}\right)^{p} \exp\left(-\frac{\alpha_{2i}\gamma N_0}{P_2}\right) F_{X_{ip}}\left(\frac{I}{P_2}\right) - \sum_{p=0}^{m_{2i}-1} \frac{\alpha_{2i}^{p}}{p!}\left(\frac{\gamma N_0}{I}\right)^{p} \times \frac{{\alpha_{ip}}^{m_{ip}}}{\Gamma(m_{ip})}\left(\frac{I}{\alpha_{2i}\gamma N_0 + \alpha_{ip} I}\right)^{p+m_{ip}} \Gamma\left(p+m_{ip}, \frac{I\alpha_{ip} + \alpha_{2i}\gamma N_0}{P_2}\right) \quad (56)$$

By substituting (43) and (46) into (42), the CDF expression for $F_{Y_{SR_iD}}(\gamma|X_{sp} = x_{sp})$ can be given as

$$F_{Y_{SR_iD}}(\gamma|X_{sp} = x_{sp}) = \begin{cases} 1 - \left[1 - F_{X_{1i}}\left(\frac{\gamma N_0}{P_1}\right)\right]\left[1 - F_{Y_{2i}}(\gamma)\right], & x_{sp} < \frac{I}{P_1} \\ 1 - \left[1 - F_{X_{1i}}\left(\frac{\gamma N_0 x_{sp}}{I}\right)\right]\left[1 - F_{Y_{2i}}(\gamma)\right], & x_{sp} \geq \frac{I}{P_1} \end{cases} \quad (57)$$

If $x_{sp} < \frac{I}{P_1}$, then

$$F_{Y_{SR_iD}}(\gamma|X_{sp} = x_{sp}) = 1 - \sum_{l=0}^{m_{1i}-1} \frac{\alpha_{1i}^{l}}{l!}\left(\frac{\gamma N_0}{P_1}\right)^{l} \exp\left(-\frac{\alpha_{1i}\gamma N_0}{P_1}\right) \times\left\{\sum_{p=0}^{m_{2i}-1} \frac{\alpha_{2i}^{p}}{p!}\left(\frac{\gamma N_0}{P_2}\right)^{p} \exp\left(-\frac{\alpha_{2i}\gamma N_0}{P_2}\right) F_{X_{ip}}\left(\frac{I}{P_2}\right) + \sum_{p=0}^{m_{2i}-1} \frac{\alpha_{2i}^{p}}{p!}\left(\frac{\gamma N_0}{I}\right)^{p} \frac{{\alpha_{ip}}^{m_{ip}}}{\Gamma(m_{ip})}\left(\frac{I}{\alpha_{2i}\gamma N_0 + \alpha_{ip} I}\right)^{p+m_{ip}} \Gamma\left(p+m_{ip}, \frac{I\alpha_{ip} + \alpha_{2i}\gamma N_0}{P_2}\right)\right\} \quad (58)$$

If $x_{sp} \geq \frac{I}{P_1}$, then

$$F_{Y_{SR_iD}}(\gamma|X_{sp} = x_{sp}) = 1 - \sum_{l=0}^{m_{1i}-1} \frac{\alpha_{1i}^{l}}{l!}\left(\frac{\gamma N_0 x_{ip}}{I}\right)^{l} \exp\left(-\frac{\alpha_{2i}\gamma N_0 x_{ip}}{I}\right) \times\left\{\sum_{p=0}^{m_{2i}-1} \frac{\alpha_{2i}^{p}}{p!}\left(\frac{\gamma N_0}{P_2}\right)^{p} \exp\left(-\frac{\alpha_{2i}\gamma N_0}{P_2}\right) F_{X_{ip}}\left(\frac{I}{P_2}\right) + \sum_{p=0}^{m_{2i}-1} \frac{\alpha_{2i}^{p}}{p!}\left(\frac{\gamma N_0}{I}\right)^{p} \times \frac{{\alpha_{ip}}^{m_{ip}}}{\Gamma(m_{ip})}\left(\frac{I}{\alpha_{2i}\gamma N_0 + \alpha_{ip} I}\right)^{p+m_{ip}} \Gamma\left(p+m_{ip}, \frac{I\alpha_{ip} + \alpha_{2i}\gamma N_0}{P_2}\right)\right\} \quad (59)$$

3.4.3 Final CDF of the total SNR of the received signal at the destination

The total CDF $F_{Y_{tot}}(\gamma|X_{sp} = x_{sp})$ can be obtained by substituting (39) and (57) into (38) as

$$F_{Y_{tot}}(\gamma|X_{sp} = x_{sp}) = \begin{cases} F_{X_0}\left(\frac{\gamma N_0}{P_1}\right)\left(F_{Y_{SR_iD}}(\gamma|X_{sp} = x_{sp})\right)^{L}, & x_{sp} < \frac{I}{P_1} \\ F_{X_0}\left(\frac{\gamma N_0 x_{sp}}{I}\right)\left(F_{Y_{SR_iD}}(\gamma|X_{sp} = x_{sp})\right)^{L}, & x_{sp} \geq \frac{I}{P_1} \end{cases} \quad (60)$$

By substituting (41), (58) and (59) into (60), we get the following two cases:

If $x_{sp} < \frac{I}{P_1}$, then

$$F_{\Upsilon_{tot}}(\gamma|X_{sp}=x_{sp}) = \left[1-\sum_{k=0}^{m_0-1}\frac{\alpha_0^k}{k!}\left(\frac{\gamma N_0}{P_1}\right)^k \exp\left(-\frac{\alpha_0\gamma N_0}{P_1}\right)\right]\Bigg\{1 - \sum_{l=0}^{m_{1i}-1}\frac{\alpha_{1i}^l}{l!}\left(\frac{\gamma N_0}{P_1}\right)^l \exp\left(-\frac{\alpha_{1i}\gamma N_0}{P_1}\right)\left[\sum_{p=0}^{m_{2i}-1}\frac{\alpha_{2i}^p}{p!}\left(\frac{\gamma N_0}{P_2}\right)^p \exp\left(-\frac{\alpha_{2i}\gamma N_0}{P_2}\right)F_{X_{ip}}\left(\frac{I}{P_2}\right) + \sum_{p=0}^{m_{2i}-1}\frac{\alpha_{2i}^p}{p!}\left(\frac{\gamma N_0}{I}\right)^p \frac{{\alpha_{ip}}^{m_{ip}}}{\Gamma(m_{ip})}\left(\frac{I}{\alpha_{2i}\gamma N_0+\alpha_{ip}I}\right)^{p+m_{ip}} \Gamma\left(p+m_{ip},\frac{I\alpha_{ip}+\alpha_{2i}\gamma N_0}{P_2}\right)\right]\Bigg\}^L \quad (61)$$

If $x_{sp} \geq \frac{I}{P_1}$, then

$$F_{\Upsilon_{tot}}(\gamma|X_{sp}=x_{sp}) = \left[1-\sum_{k=0}^{m_0-1}\frac{\alpha_0^k}{k!}\left(\frac{\gamma N_0}{I}\right)^k {x_{sp}}^k \exp\left(-\frac{\alpha_0\gamma N_0}{I}x_{sp}\right)\right]\Bigg\{1 - \sum_{l=0}^{m_{1i}-1}\frac{\alpha_{1i}^l}{l!}\left(\frac{\gamma N_0}{I}\right)^l {x_{sp}}^l \exp\left(-\frac{\alpha_{1i}\gamma N_0}{I}x_{sp}\right)\left[\sum_{p=0}^{m_{2i}-1}\frac{\alpha_{2i}^p}{p!}\left(\frac{\gamma N_0}{P_2}\right)^p \exp\left(-\frac{\alpha_{2i}\gamma N_0}{P_2}\right)F_{X_{ip}}\left(\frac{I}{P_2}\right) + \sum_{p=0}^{m_{2i}-1}\frac{\alpha_{2i}^p}{p!}\left(\frac{\gamma N_0}{I}\right)^p \frac{{\alpha_{ip}}^{m_{ip}}}{\Gamma(m_{ip})}\left(\frac{I}{\alpha_{2i}\gamma N_0+\alpha_{ip}I}\right)^{p+m_{ip}} \Gamma\left(p+m_{ip},\frac{I\alpha_{ip}+\alpha_{2i}\gamma N_0}{P_2}\right)\right]\Bigg\}^L \quad (62)$$

Now, we are ready to calculate the CDF of the total SNR Υ_{tot} from (60) as

$$F_{\Upsilon_{tot}}(\gamma) = \int_0^\infty F_{\Upsilon_{tot}}(\gamma|X_{sp}=x_{sp}) f_{X_{sp}}(x_{sp})\,dx_{sp} \quad (63)$$

where $f_{X_{sp}}(x_{sp})$ can be approximated from (33) as

$$f_{X_{sp}}(x_{sp}) = \frac{{\alpha_{sp}}^{m_{sp}}}{\Gamma(m_{sp})} x_{sp}^{m_{sp}-1} \exp(-\alpha_{sp}x_{sp}) \quad (64)$$

Substituting (61), (62) and (64) into (63) we get

$$
\begin{aligned}
F_{\Upsilon_{tot}}(\gamma) = &\Bigg[1 \\
&- \sum_{k=0}^{m_0-1} \frac{\alpha_0^k}{k!}\left(\frac{\gamma N_0}{P_1}\right)^k \exp\left(-\frac{\alpha_0\gamma N_0}{P_1}\right)\Bigg]\Bigg\{1 \\
&- \sum_{l=0}^{m_{1i}-1} \frac{\alpha_{1i}^l}{l!}\left(\frac{\gamma N_0}{P_1}\right)^l \exp\left(-\frac{\alpha_{1i}\gamma N_0}{P_1}\right)\Bigg[\sum_{p=0}^{m_{2i}-1} \frac{\alpha_{2i}^p}{p!}\left(\frac{\gamma N_0}{P_2}\right)^p \exp\left(-\frac{\alpha_{2i}\gamma N_0}{P_2}\right) F_{X_{ip}}\left(\frac{I}{P_2}\right) \\
&+ \sum_{p=0}^{m_{2i}-1} \frac{\alpha_{2i}^p}{p!}\left(\frac{\gamma N_0}{I}\right)^p \frac{{\alpha_{ip}}^{m_{ip}}}{\Gamma(m_{ip})}\left(\frac{I}{\alpha_{2i}\gamma N_0 + \alpha_{ip} I}\right)^{p+m_{ip}} \Gamma\left(p+m_{ip}, \frac{I\alpha_{ip} + \alpha_{2i}\gamma N_0}{P_2}\right)\Bigg]\Bigg\}^L \\
&\times F_{X_{sp}}\left(\frac{I}{P_1}\right) \\
&+ \int_{\frac{I}{P_1}}^{\infty} \Bigg[f_{X_{sp}}(x_{sp}) \\
&- \sum_{k=0}^{m_0-1} \frac{\alpha_0^k}{k!}\left(\frac{\gamma N_0}{I}\right)^k {x_{sp}}^k \exp\left(-\frac{\alpha_0\gamma N_0}{I} x_{sp}\right) f_{X_{sp}}(x_{sp})\Bigg]\Bigg\{1 \\
&- \sum_{l=0}^{m_{1i}-1} \frac{\alpha_{1i}^l}{l!}\left(\frac{\gamma N_0}{I}\right)^l {x_{sp}}^l \exp\left(-\frac{\alpha_{1i}\gamma N_0}{I} x_{sp}\right)\Bigg[\sum_{p=0}^{m_{2i}-1} \frac{\alpha_{2i}^p}{p!}\left(\frac{\gamma N_0}{P_2}\right)^p \exp\left(-\frac{\alpha_{2i}\gamma N_0}{P_2}\right) F_{X_{ip}}\left(\frac{I}{P_2}\right) \\
&+ \sum_{p=0}^{m_{2i}-1} \frac{\alpha_{2i}^p}{p!}\left(\frac{\gamma N_0}{I}\right)^p \frac{{\alpha_{ip}}^{m_{ip}}}{\Gamma(m_{ip})}\left(\frac{I}{\alpha_{2i}\gamma N_0 + \alpha_{ip} I}\right)^{p+m_{ip}} \Gamma\left(p+m_{ip}, \frac{I\alpha_{ip} + \alpha_{2i}\gamma N_0}{P_2}\right)\Bigg]\Bigg\}^L
\end{aligned}
\tag{65}
$$

We can further simplify (65) by using binomial expansion and then applying (3.352.1) and (3.351.2) from [20] to solve the resulting integrals. After some algebraic modification, we can obtain the CDF of the total SNR Υ_{tot} as

$$
\begin{aligned}
F_{\Upsilon_{tot}}(\gamma) &= \Bigg[1 - \sum_{k=0}^{m_0-1} \frac{\alpha_0^k}{k!}\left(\frac{\gamma N_0}{P_1}\right)^k exp\left(-\frac{\alpha_0\gamma N_0}{P_1}\right)\Bigg]\Bigg\{1 \\
&- \sum_{l=0}^{m_{1i}-1} \frac{\alpha_{1i}^l}{l!}\left(\frac{\gamma N_0}{P_1}\right)^l exp\left(-\frac{\alpha_{1i}\gamma N_0}{P_1}\right)\Bigg[\sum_{p=0}^{m_{2i}-1} \frac{\alpha_{2i}^p}{p!}\left(\frac{\gamma N_0}{P_2}\right)^p exp\left(-\frac{\alpha_{2i}\gamma N_0}{P_2}\right)\Bigg[1 \\
&- \sum_{r=0}^{m_{ip}-1} \frac{\alpha_{ip}^r}{r!}\left(\frac{I}{P_2}\right)^r exp\left(-\frac{\alpha_{ip}I}{P_2}\right)\Bigg] \\
&+ \sum_{p=0}^{m_{2i}-1} \frac{\alpha_{2i}^p}{p!}\left(\frac{\gamma N_0}{I}\right)^p \frac{{\alpha_{ip}}^{m_{ip}}}{\Gamma(m_{ip})}\left(\frac{I}{\alpha_{2i}\gamma N_0 + \alpha_{ip}I}\right)^{p+m_{ip}} \Gamma\left(p+m_{ip}, \frac{I\alpha_{ip} + \alpha_{2i}\gamma N_0}{P_2}\right)\Bigg]\Bigg\}^L \Bigg[1 \\
&- \sum_{s=0}^{m_{sp}-1} \frac{\alpha_{sp}^s}{s!}\left(\frac{I}{P_1}\right)^s exp\left(-\frac{\alpha_{sp}I}{P_1}\right)\Bigg] + \frac{1}{\Gamma(m_{sp})}{\alpha_{sp}}^{-1}\Gamma\left(m_{sp}, \frac{I\alpha_{sp}}{P_1}\right) \\
&- \frac{{\alpha_{sp}}^{m_{sp}}}{\Gamma(m_{sp})}\sum_{k=0}^{m_0-1} \frac{\alpha_0^k}{k!}\left(\frac{\gamma N_0}{I}\right)^k \left(\frac{I}{\alpha_{sp}I + \alpha_0\gamma N_0}\right)^{k+m_{sp}} \Gamma\left(m_{sp} + k, \frac{I\alpha_{sp} + \alpha_0\gamma N_0}{P_1}\right) \\
&+ \sum_{n=1}^{L}(-1)^n \binom{L}{n}\Bigg[\sum_{p=0}^{m_{2i}-1} \frac{\alpha_{2i}^p}{p!}\left(\frac{\gamma N_0}{P_2}\right)^p exp\left(-\frac{\alpha_{2i}\gamma N_0}{P_2}\right)\Bigg[1 - \sum_{r=0}^{m_{ip}-1} \frac{\alpha_{ip}^r}{r!}\left(\frac{I}{P_2}\right)^r exp\left(-\frac{\alpha_{ip}I}{P_2}\right)\Bigg] \\
&+ \sum_{p=0}^{m_{2i}-1} \frac{\alpha_{2i}^p}{p!}\left(\frac{\gamma N_0}{I}\right)^p \frac{{\alpha_{ip}}^{m_{ip}}}{\Gamma(m_{ip})}\left(\frac{I}{\alpha_{2i}\gamma N_0 + \alpha_{ip}I}\right)^{p+m_{ip}} \Gamma\left(p+m_{ip}, \frac{I\alpha_{ip} + \alpha_{2i}\gamma N_0}{P_2}\right)\Bigg]^n \frac{{\alpha_{sp}}^{m_{sp}}}{\Gamma(m_{sp})} \\
&\times \sum_{l_1=0}^{m_{1i}-1} .. \sum_{l_n=0}^{m_{1i}-1} \frac{\alpha_{1i}^{\sum_{j=1}^{n} l_j}}{\prod_{j=1}^{n} l_j!}\left(\frac{\gamma N_0}{I}\right)^{\sum_{j=1}^{n} l_j} \left(\frac{I}{n\alpha_{1i}\gamma N_0 + \alpha_{sp}I}\right)^{\sum_{j=1}^{n} l_j + m_{sp}} \Gamma\Bigg(\sum_{j=1}^{n} l_j \\
&+ m_{sp}, \frac{I\alpha_{sp} + n\alpha_{1i}\gamma N_0}{P_1}\Bigg) \\
&- \sum_{n=1}^{L}(-1)^n \binom{L}{n}\Bigg\{\sum_{p=0}^{m_{2i}-1} \frac{\alpha_{2i}^p}{p!}\left(\frac{\gamma N_0}{P_2}\right)^p exp\left(-\frac{\alpha_{2i}\gamma N_0}{P_2}\right)\Bigg[1 - \sum_{r=0}^{m_{ip}-1} \frac{\alpha_{ip}^r}{r!}\left(\frac{I}{P_2}\right)^r exp\left(-\frac{\alpha_{ip}I}{P_2}\right)\Bigg] \\
&+ \sum_{p=0}^{m_{2i}-1} \frac{\alpha_{2i}^p}{p!}\left(\frac{\gamma N_0}{I}\right)^p \frac{{\alpha_{ip}}^{m_{ip}}}{\Gamma(m_{ip})}\left(\frac{I}{\alpha_{2i}\gamma N_0 + \alpha_{ip}I}\right)^{p+m_{ip}} \Gamma\left(p+m_{ip}, \frac{I\alpha_{ip} + \alpha_{2i}\gamma N_0}{P_2}\right)\Bigg\}^n \frac{{\alpha_{sp}}^{m_{sp}}}{\Gamma(m_{sp})} \\
&\times \sum_{k=0}^{m_0-1} \frac{\alpha_0^k}{k!}\left(\frac{\gamma N_0}{I}\right)^k \sum_{l_1=0}^{m_{1i}-1} .. \sum_{l_n=0}^{m_{1i}-1} \frac{\alpha_{1i}^{\sum_{j=1}^{n} l_j}}{\prod_{j=1}^{n} l_j!}\left(\frac{\gamma N_0}{I}\right)^{\sum_{j=1}^{n} l_j} \left(\frac{I}{n\alpha_{1i}\gamma N_0 + \alpha_{sp}I + \alpha_0\gamma N_0}\right)^{\sum_{j=1}^{n} l_j + m_{sp} + k} \\
&\times\Gamma\left(\sum_{j=1}^{n} l_j + m_{sp} + k, \frac{I\alpha_{sp} + n\alpha_{1i}\gamma N_0 + \alpha_0\gamma N_0}{P_1}\right)
\end{aligned} \tag{66}
$$

The OP is obtained from (66) by considering $F_{\Upsilon_{tot}}(\gamma = \gamma_{th})$. Hence the OP is given by

$$P_{out} = F_{\Upsilon_{tot}}(\gamma = \gamma_{th}) \quad (67)$$

Thus, the obtained OP is run for simulation and analysis results to study the outage performance of the system model is done using (66).

4 NUMERICAL RESULTS

In this chapter, the outage performance of the two-hop DF CCRN is analyzed over $\kappa - \mu$ shadowed fading channel. To study the importance of the relay system in CRN, a multiple relay system is considered with the number of relays set to $L=3$. The transmission medium is assumed to be $\kappa - \mu$ shadowed fading with arbitrary fading parameters $S_{\kappa\mu} \sim (\kappa_i, \mu_i, \xi_i, \bar{z}_i)$ where $(\kappa_0, \mu_0, \xi_0) \sim (2,5,2)$, $(\kappa_1, \mu_1, \xi_1) \sim (2,5,2)$, $(\kappa_2, \mu_2, \xi_2) \sim (2,5,2)$, $(\kappa_{sp}, \mu_{sp}, \xi_{sp}) \sim (2,5,2)$ and $(\kappa_{rp}, \mu_{rp}, \xi_{rp}) \sim (2,5,2)$. The average gamma threshold value γ_i is assumed to be 3dB. Further, the AWGN power at the destination denoted by N_0 is assumed to be 1. The number of iterations for each simulation is averaged over 10^6 independent realizations.

The transmit power at source and relay denoted by P_s and P_R, are constrained by their maximum transmit power P_1 and P_2, respectively. The OP is observed at different points of P_1. P_1 and P_2 are fixed at 10dBW. The transmit power at the source and the relay should also be constrained by the maximum acceptable interference power at PU-Tx. This maximum allowable power at PU is called as the peak interference power and is denoted by I. If I is fixed independent to P_1 and P_2, an outage floor will be approached. This shows that the transmiT power at SU should be restricted by both the peak interference power at PU-Tx and their maximum transmit power. The parameters considered are given in Table 1.

Table 1. Parameters settings

Parameters	**Symbol**	**Value**
Number of iterations	N	10^6
Number of relays	L	3
AWGN power	N_0	1
Average gamma threshold	γ_i	3dB
Maximum transmit power at source	P_1	10dBW
Maximum transmit power at relays	P_2	10dBW

Peak interference power at PU	I	6dBW
Scaling parameter	m	2
Fading parameter κ, through direct link and relays	$\kappa_0, \kappa_1, \kappa_2, \kappa_{sp}, \kappa_{ip}$	2, 2, 2, 2, 2
Fading parameter μ, through direct link and relays	$\mu_0, \mu_1, \mu_2, \mu_{sp}, \mu_{ip}$	5, 5, 5, 5, 5
Normalized distances between source and destination through direct path and through relays	$d_0, d_1, d_2, d_{sp}, d_{ip}$	1, 0.9, 0.9, 1.2, 1.2
Path loss component	n	4

4.1 Effect of Peak Interference Power on OP

In this section, the OP is shown over transmit SNR for different values of I/N_0 at PU. The behavior of OP is studied for the cases when I is independent of the maximum transmit power at SU-Tx and SU-R. The following are the cases considered:

Case 1: P_1/N_0=10dBW, P_2/N_0=10dBW and I/N_0=12dBW;
Case 2: P_1/N_0=10dBW, P_2/N_0=10dBW and I/N_0=17dBW;

All the other parameters are fixed as mentioned in Table 1. The transmission power at SU is constrained by the maximum transmit power and the peak interference power. The transmission power at SU should be less than the peak interference power in a cognitive network as given in (19). If I is fixed independent to the transmission power at source P_1 and relay P_2 an outage floor is obtained.

Fig. 4 shows simulation results of OP vs SNR for the above-considered cases. It is observed that, when I/N_0 is fixed at 12dB, 17dB the OP decreases with SNR till a certain point and attains a constant value at the higher *SNR* values. Which means, when the peak interference power *I* at PU is independent of the transmission power P_1 and P_2, an outage floor is approached.

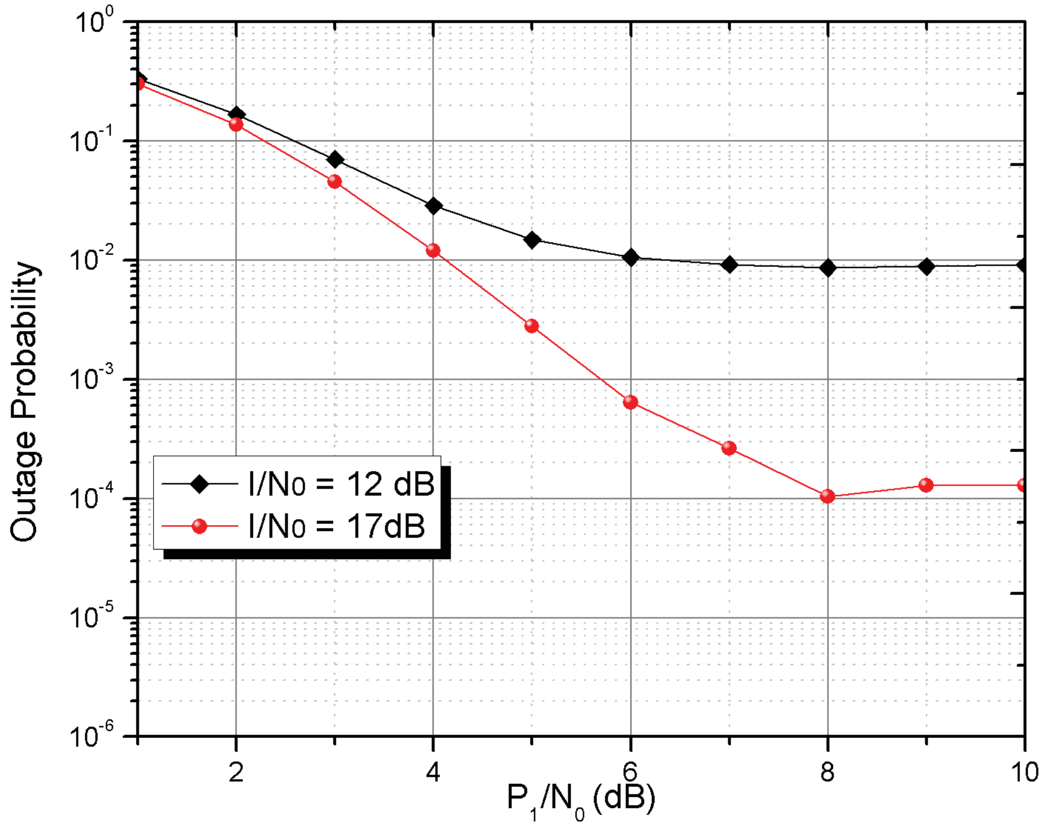

Fig. 4 The effect of peak interference power on outage probability.

4.2 Comparison of Analytical and Simulated Results

In this section, the analytical results and simulated results are compared. All the parameters are fixed at the values given in Table 1. The CDF expression obtained in Section 3 is plotted using the software Mathematica. The source code is implemented in Matlab for simulation results. Both the graphs are plotted using the software called Origin. It is observed from Fig. 5 that the numerical and simulated results exactly match. This shows the correctness of the derivations and that the $\kappa - \mu$ shadowed fading distribution gives the exact experimental fit to data.

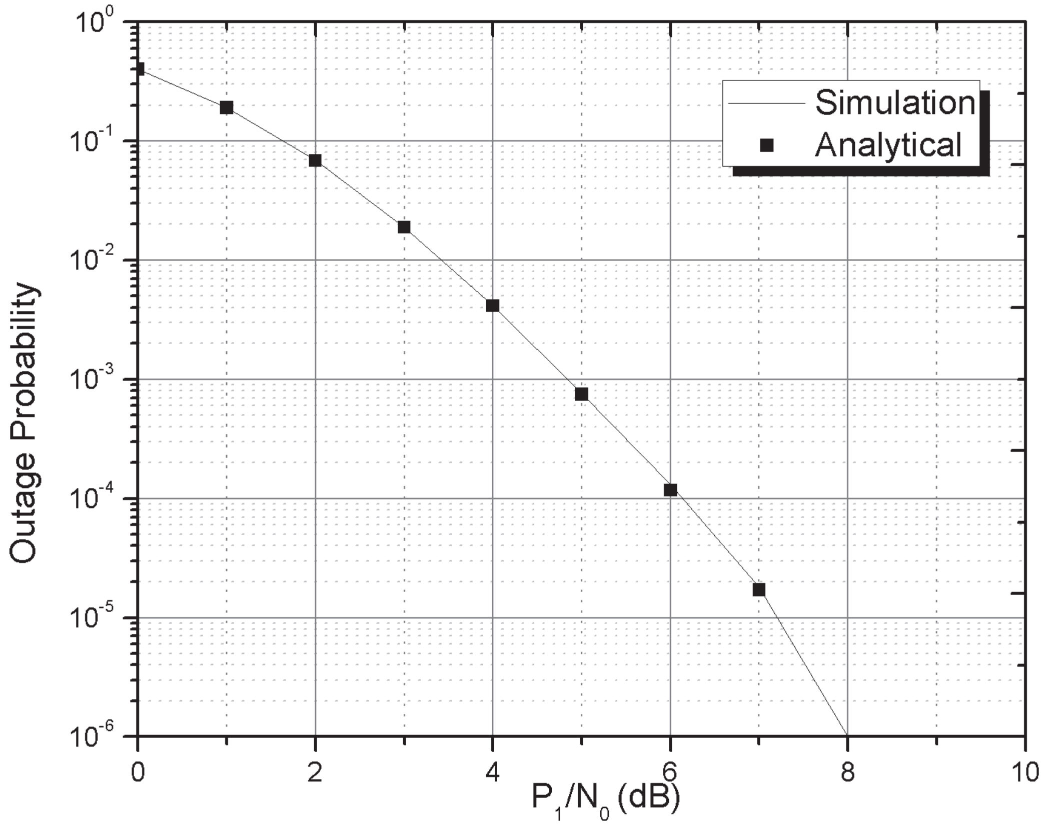

Fig. 5 Simulated and analytical results for OP for CCRN.

4.3 OP vs SNR for Different Values of Fading Parameters

In this section, the OP behavior is observed for various fading severity parameters *m*. The OP over SNR is plotted for *m*=1, *m*=2. The scaling parameters through all the branches represented by ξ_0, ξ_1, ξ_{i2}, ξ_{isp}, ξ_{irp}, are considered to be integers.

The following are the cases considered in Fig. 6:

Case 1: *m*=1

The *m*=1 curve in Fig. 6. shows that OP attains higher values which show the degradation of overall system performance.

Case 2: *m*=2

The OP in this case attains lower values when compared to Case 1. This shows that at higher values of *m*, the system performance increases.

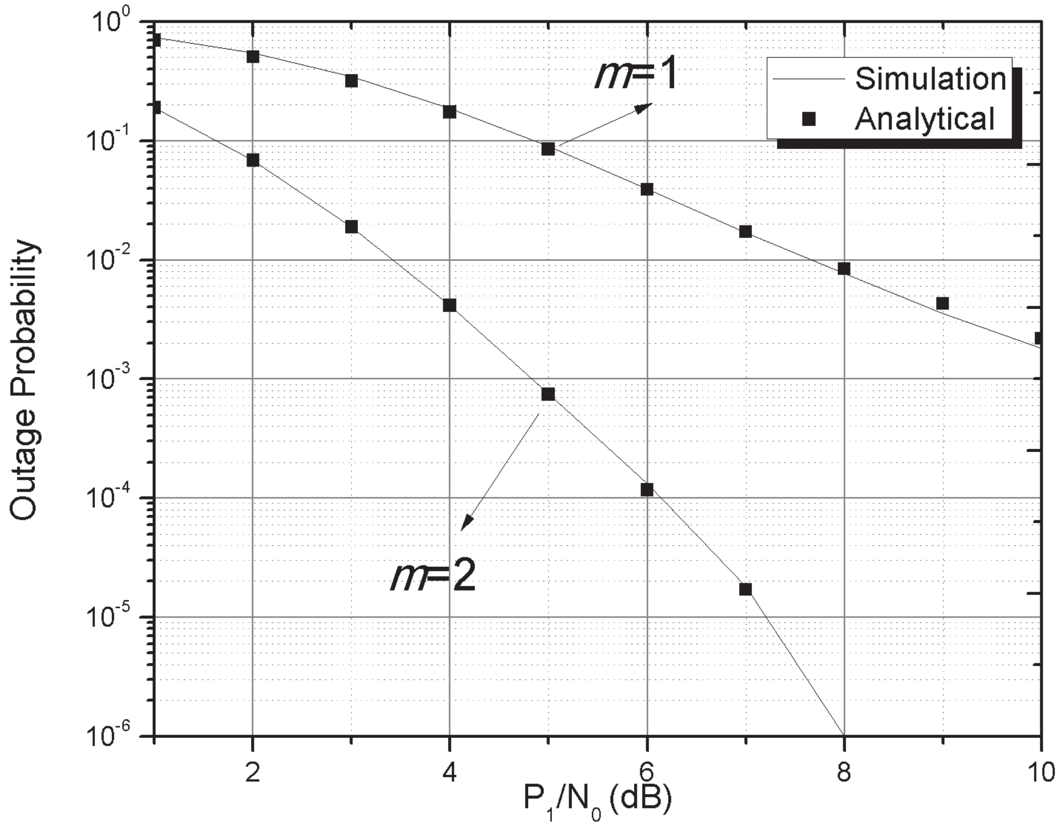

Fig. 6 OP versus SNR for different fading severity parameter *m*.

4.4 Comparison of CRN and CCRN

In this section, the importance of the relay network in CRN is studied. Initially, a simple CRN with a direct link between source and destination is considered. Then, a multiple relay network is considered to assist the CRN with L=3. The OP is plotted over P_1/N_0 for both networks.

Fig. 7 shows the OP behavior for the above two scenarios. It is observed that when there is only a direct link present in the system, the OP attains higher values, which shows the degradation of the system performance of the system. When a multiple relay network is considered along with CRN, the OP decreases comparatively resulting in a much better performance of the system.

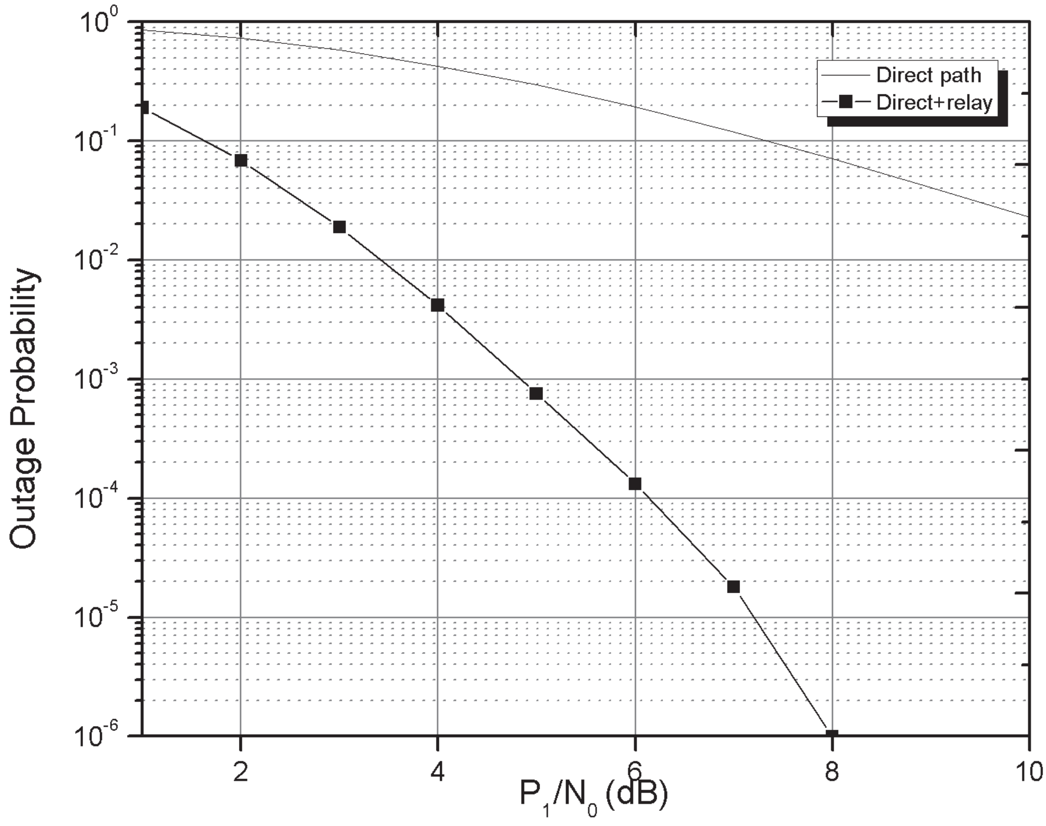

Fig. 7 The performance of CRN and CCRN.

4.5 OP for Different Number of Relays

The importance of the relay network over CRN is studied in Section 4.4. In this section, the impact of the number of relays on the OP of the CCRN is studied. In Fig. 8, the OP is plotted over P_s/N_0 for L=3, 5, 10. The curves show the simulation and analytical results for the parameters fixed at values as given in Table 1 with varying the number of relays. It can be observed that the performance of the CCRN improves with the number of relays.

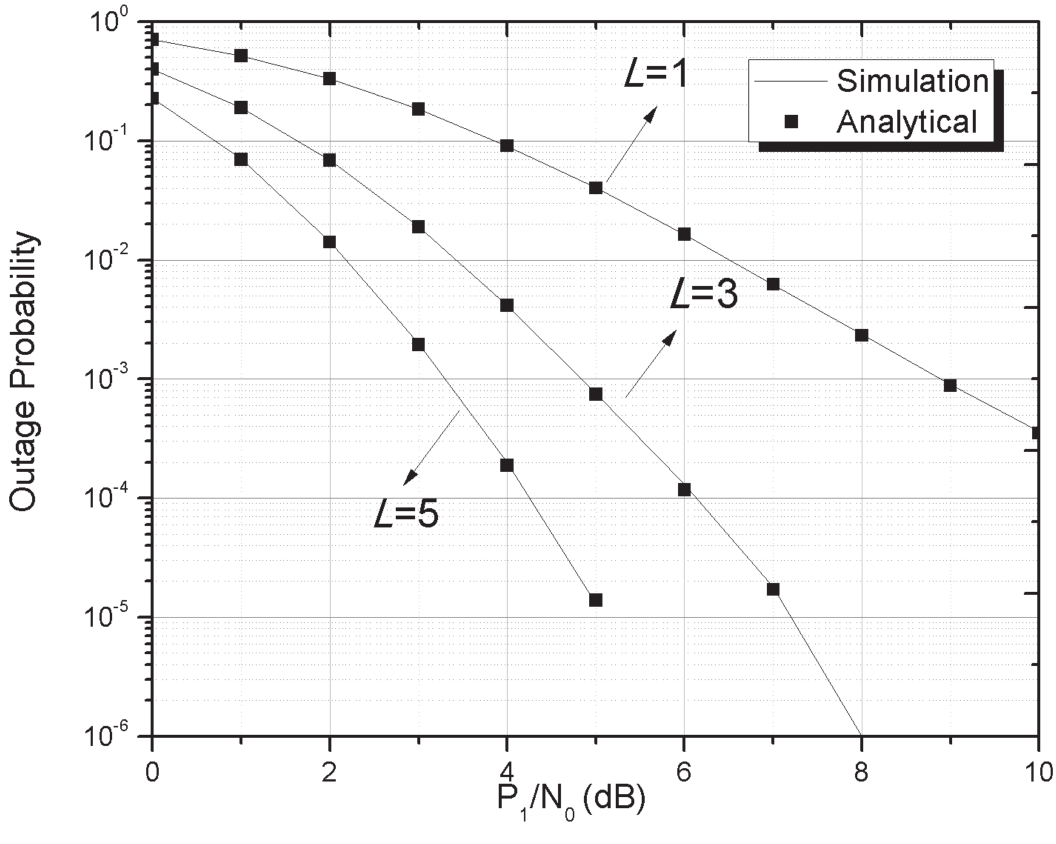

Fig. 8 Multiple relay impact on OP of CCRN over $\kappa - \mu$ shadowed fading channel.

When L=1, the OP curve is larger than in the curves when L= 3, 5. Hence, the OP decreases with increasing number of relays resulting in the better overall system performance.

5 CONCLUSION AND FUTURE WORK

The main purpose of this research work has been to show the importance of deploying a multiple relay network that assists a CRN and to evaluate the performance of such a CCRN in a realistic environment. To achieve this objective, different methods have been considered. CRNs are not fully developed yet and they have less support for modeling. The system model used in this research work is very useful to obtain the performance metrics in a realistic environment. The $\kappa - \mu$ shadowed fading distribution considered, replicates the wireless communication channel.

The CDF and PDF of the SNR have been derived for the proposed system model. The OP expression is derived straightforwardly from the obtained CDF expression. These expressions have been validated by comparing them with simulation results. This system has been implemented in Matlab. The source code is obtained and the results are plotted. The numerical analysis is done using the software Mathematica. The analytical and simulation results are obtained and compared using the software Origin, to show the correctness of the derivations.

The results obtained in Section 4 show that the assumed fading distribution gives exact fit to the numerical data. It is observed that, to obtain a better system performance for CCRN, the transmit power at secondary user should be constrained by the peak interference power at the primary user. The cooperative communications, when combined with CRN, improves its performance. The overall performance of the CCRN increases with increasing the number of relays. The more the number of relays, the better the performance of the overall system.

As a future work, other performance metrics such as capacity and symbol error probability can be analyzed. Different combining techniques can be adapted other than SC at the destination. multiple-input-multiple-output systems can be introduced in this system model to improve the spatial diversity, capacity etc., of the system.

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APPENDIX

In this appendix, the derivation of the OP for the system model presented in Section 3 is obtained over $\kappa - \mu$ shadowed channel.

CDF expression of the SNR of the signal through direct link and relays.

Let us consider the system model presented in Fig. 3. It is a two-hop DF system with opportunistic relaying at the relays. The total SNR of this system can be obtained by employing SC technique at the receiver as given in (21) of Section 3:

$$\Upsilon_{tot} = max(\Upsilon_o, \Upsilon_{SR_1D}, \dots, \Upsilon_{SR_iD}, \dots, \Upsilon_{SR_LD}) \quad \text{(A.1)}$$

where $\Upsilon_o, \Upsilon_{SR_1D}, \dots, \Upsilon_{SR_iD}, \dots, \Upsilon_{SR_lD}$ are the SNR of the direct link, through the first relay, i^{th} relay and L^{th} relay respectively, whose expressions are given in Section 3.

The PDF of the instantaneous channel coefficients through the direct link and the relays of the system $\kappa - \mu$ shadowed fading is given by

$$f_z(z) = \frac{\phi_1^{m-\mu} z^{\mu-1}}{{\phi_2}^m \Gamma(\mu)} e^{-\frac{z}{\phi^1}} {}_1F_1\left(m; \mu; \frac{(\phi_2 - \phi_1)z}{\phi_1 \phi_2}\right) \quad \text{(A.2)}$$

where $\phi_1 = \frac{\bar{z}}{\mu(1+k)}$, $\phi_2 = \frac{(\mu k+m)\bar{z}}{\mu(1+k)m}$ and ${}_1F_1(.;.;.)$ is the Kummer confluent hypergeometric function and $\bar{z}$ is the average power gain of the channel fading.

The CDF of the instantaneous channel coefficients over $\kappa - \mu$ shadowed fading is approximated by gamma RV denoted by $\mathcal{G}(\alpha, \beta)$, where

$$m = \frac{\xi\mu(1+k)^2}{\xi+\mu k^2+2\xi k} \quad \text{(A.4)}$$

and

$$\beta_i = \frac{\bar{\Upsilon}}{\alpha_i} \quad \text{(A.5)}$$

The PDF and CDF of the channel power gain under $\kappa - \mu$ shadowed fading are as given in (8) and (9).

The CDF $F_{\gamma tot}(\gamma)$ of the total SNR given in (28) can be calculated as

$$F_{\Upsilon_{tot}}(\gamma) = \int_{0}^{\infty} F_{\Upsilon_{tot}}(\gamma|X_{sp} = x_{sp}) f_{X_{sp}}(x_{sp}) dx_{sp} \tag{A.6}$$

The conditional CDF $F_{\Upsilon_{tot}}(\gamma|X_{sp} = x_{sp})$ in (37) can be given as

$$\begin{aligned} F_{\Upsilon_{tot}}(\gamma|X_{sp} = x_{sp}) &= \Pr(\gamma_{tot}|X_{sp} = x_{sp} \le \gamma) \\ &= \Pr(\gamma_0|X_{sp} = x_{sp}, \gamma_t|X_{sp} = x_{sp} \le \gamma) \\ &= \Pr(\gamma_0|X_{sp} = x_{sp}, \gamma_{SR_1D}|X_{sp} = x_{sp}, \dots, \gamma_{SR_LD}|X_{sp} = x_{sp} \le \gamma) \\ &= \Pr(\gamma_0|X_{sp} = x_{sp} \le \gamma) \Pr(\gamma_{SR_1D}|X_{sp} = x_{sp} \le \gamma) \dots \\ &\quad \times \Pr(\gamma_{SR_LD}|X_{sp} = x_{sp} \le \gamma) \\ &= F_{\Upsilon_0}(\gamma|X_{sp} = x_{sp}) \prod_{i=1}^{L} F_{\Upsilon_{SR_iD}}(\gamma|X_{sp} = x_{sp}) \end{aligned} \tag{A.7}$$

The CDF $F_{\Upsilon_0}(\gamma|X_{sp} = x_{sp})$ of the SNR through the direct link can be obtained from (16) as

$$F_{\Upsilon_0}(\gamma|X_{sp} = x_{sp}) = \begin{cases} F_{X_0}\left(\frac{\gamma N_0}{P_1}\right), & x_{sp} < \frac{I}{P_1} \\ F_{X_0}\left(\frac{\gamma N_0 x_{sp}}{I}\right), & x_{sp} \ge \frac{I}{P_1} \end{cases} \tag{A.8}$$

Substituting the CDF given in (32) into (A.8), we obtain

$$F_{\Upsilon_0}(\gamma|X_{sp} = x_{sp}) = \begin{cases} \left(\frac{\gamma N_0}{P_1 \alpha_0}\right)^{m_0} \frac{1}{\Gamma(\alpha_0 + 1)} {}_1F_1\left(m_0; m_0 + 1; -\left(\frac{\gamma N_0}{P_1 \alpha_0}\right)\right), & x_{sp} < \frac{I}{P_1} \\ \left(\frac{\gamma N_0 x_{sp}}{I \alpha_0}\right)^{m_0} \frac{1}{\Gamma(m_0 + 1)} {}_1F_1\left(m_0; m_0 + 1; -\left(\frac{\gamma N_0 x_{sp}}{I \alpha_0}\right)\right), & x_{sp} \ge \frac{I}{P_1} \end{cases} \tag{A.9}$$

The conditional CDF $F_{\Upsilon_{SR_iD}}(\gamma|X_{sp} = x_{sp})$ of the SNR at SU-Rx through the i^{th} relay R_i is given by

$$\begin{aligned} F_{\Upsilon_{SR_iD}}(\gamma|X_{sp} = x_{sp}) &= \Pr(\gamma_{SR_iD}|X_{sp} = x_{sp} \le \gamma) \\ &= \Pr(\min(\gamma_{1i}, \gamma_{2i})|X_{sp} = x_{sp} \le \gamma) \\ &= 1 - \Pr(\min(\gamma_{1i}, \gamma_{2i})\,|X_{sp} = x_{sp} \ge \gamma) \\ &= 1 - \Pr(\gamma_{1i}|X_{sp} = x_{sp} \ge \gamma)\Pr(\gamma_{2i}|X_{sp} = x_{sp} \ge \gamma) \\ &= 1 - [1 - \Pr(\gamma_{1i}|X_{sp} = x_{sp} \le \gamma)][1 - \Pr(\gamma_{2i}|X_{sp} = x_{sp} \le \gamma)] \\ &= 1 - [1 - F_{\Upsilon_{1i}}(\gamma|X_{sp} = x_{sp})][1 - F_{\Upsilon_{2i}}(\gamma|X_{sp} = x_{sp})] \end{aligned} \tag{A.10}$$

Then, the CDF $F_{Y_{1i}}\left(\gamma|_{X_{sp}=x_{sp}}\right)$ is split into the following two cases:

$$F_{Y_{1i}}\left(\gamma|_{X_{sp}=x_{sp}}\right)=\begin{cases} F_{X_{1i}}\left(\frac{\gamma N_0}{P_1}\right), & x_{sp}<\frac{I}{P_1} \\ F_{X_{1i}}\left(\frac{\gamma N_0 x_{sp}}{I}\right), & x_{sp}\geq\frac{I}{P_1} \end{cases} \tag{A.11}$$

Substituting (32) into (43) gives

$$F_{Y_{1i}}(\gamma|X_{sp}=x_{sp}) = \begin{cases} \left(\frac{\gamma N_0}{P_1\alpha_{1i}}\right)^{m_{1i}}\frac{1}{\Gamma(m_{1i}+1)}\,{}_1F_1\left(m_{1i};m_{1i}+1;-\left(\frac{\gamma N_0}{P_1\alpha_{1i}}\right)\right), & x_{sp}<\frac{I}{P_1} \\ \left(\frac{\gamma N_0 x_{sp}}{I\alpha_{1i}}\right)^{m_{1i}}\frac{1}{\Gamma(m_{1i}+1)}\,{}_1F_1\left(m_{1i};m_{1i}+1;-\left(\frac{\gamma N_0 x_{sp}}{I\alpha_{1i}}\right)\right), & x_{sp}\geq\frac{I}{P_1} \end{cases} \tag{A.12}$$

The CDF $F_{Y_{2i}}(\gamma|X_{sp}=x_{sp})$ can be obtained from (25) as

$$F_{Y_{2i}}(\gamma|X_{sp}=x_{sp}) = F_{Y_{2i}}(\gamma) \tag{A.13}$$

where $F_{Y_{2i}}(\gamma)=\int_0^\infty F_{Y_{2i}}(\gamma|X_{ip}=x_{ip})f_{X_{ip}}(x_{ip})dx_{ip}$.

Then, the CDF $F_{Y_{2i}}(\gamma|X_{ip}=x_{ip})$ is

$$F_{Y_{2i}}(\gamma|X_{ip}=x_{ip})=\begin{cases} F_{X_{2i}}\left(\frac{\gamma N_0}{P_2}\right), & x_{ip}<\frac{I}{P_2} \\ F_{X_{2i}}\left(\frac{\gamma N_0 x_{ip}}{I}\right), & x_{ip}\geq\frac{I}{P_2} \end{cases} \tag{A.14}$$

Using expression of the CDF in (32), $F_{Y_{2i}}(\gamma|X_{sp}=x_{sp})$ is expressed as

$$F_{Y_{2i}}(\gamma|X_{ip}=x_{ip}) = \begin{cases} \left(\frac{\gamma N_0}{P_2\alpha_{2i}}\right)^{m_{2i}}\frac{1}{\Gamma(m_{2i}+1)}\,{}_1F_1\left(m_{2i};m_{2i}+1;-\left(\frac{\gamma N_0}{P_2\alpha_{2i}}\right)\right), & x_{ip}<\frac{I}{P_2} \\ \left(\frac{\gamma N_0 x_{ip}}{I\alpha_{2i}}\right)^{m_{2i}}\frac{1}{\Gamma(m_{2i}+1)}\,{}_1F_1\left(m_{2i};m_{2i}+1;-\left(\frac{\gamma N_0 x_{Rp}}{I\alpha_{2i}}\right)\right), & x_{ip}\geq\frac{I}{P_2} \end{cases} \tag{A.15}$$

The CDF of Y_{2i} can be calculated from (A.15) as

$$F_{\Upsilon_{2i}}(\gamma) = \int_{0}^{I/P_2} F_{X_{2i}}\left(\frac{\gamma N_0}{P_2}\right) f_{X_{ip}}(x_{ip}) dx_{ip} + \int_{I/P_2}^{\infty} F_{X_{2i}}\left(\frac{\gamma N_0 x_{ip}}{I}\right) f_{X_{ip}}(x_{ip}) dx_{ip} \tag{A.16}$$

Here, X_{ip} is approximated by a Nakagami-*m* distribution. The PDF $f_{X_{ip}}(x_{ip})$ of the SNR is given by

$$f_{X_{ip}}(x_{ip}) = \frac{{\alpha_{ip}}^{m_{ip}}}{\Gamma(m_{ip})} {x_{ip}}^{m_{ip}-1} \exp(-\alpha_{ip} x_{ip}) \tag{A.17}$$

where m_{ip} is an integer.

Using the approximated CDF for $F_{X_{2i}}\left(\frac{\gamma N_0}{P_2}\right)$, we have

$$F_{X_{2i}}\left(\frac{\gamma N_0}{P_2}\right) = 1 - \sum_{p=0}^{m_{2i}-1} \frac{\alpha_{2i}^{p}}{p!}\left(\frac{\gamma N_0}{P_2}\right)^{p} \exp\left(-\frac{\alpha_{2i}\gamma N_0}{P_2}\right) \tag{A.18}$$

Similarly, the approximated CDF expression for $F_{X_{2i}}\left(\frac{\gamma N_0 x_{ip}}{I}\right)$ is given as

$$F_{X_{2i}}\left(\frac{\gamma N_0 x_{ip}}{I}\right) = 1 - \sum_{p=0}^{m_{2i}-1} \frac{\alpha_{2i}^{p}}{p!}\left(\frac{\gamma N_0 x_{ip}}{I}\right)^{p} \exp\left(-\frac{\alpha_{2i}\gamma N_0 x_{ip}}{I}\right) \tag{A.19}$$

By substituting (A.12) and (A.14) into (A.10), the CDF expression for $F_{\Upsilon_{SR_iD}}(\gamma|X_{sp} = x_{sp})$ can be given as

$$F_{\Upsilon_{SR_iD}}(\gamma|X_{sp} = x_{sp}) = \begin{cases} 1 - \left[1 - F_{X_{1i}}\left(\frac{\gamma N_0}{P_1}\right)\right]\left[1 - F_{\Upsilon_{2i}}(\gamma)\right], & x_{sp} < \frac{I}{P_1} \\ 1 - \left[1 - F_{X_{1i}}\left(\frac{\gamma N_0 x_{sp}}{I}\right)\right]\left[1 - F_{\Upsilon_{2i}}(\gamma)\right], & x_{sp} \geq \frac{I}{P_1} \end{cases} \tag{A.20}$$

The total CDF $F_{\Upsilon_{tot}}(\gamma|X_{sp} = x_{sp})$ can be obtained by substituting (A.11) and (A.20) into (A.6) as

$$F_{\Upsilon_{tot}}(\gamma|X_{sp} = x_{sp}) = \begin{cases} F_{X_0}\left(\frac{\gamma N_0}{P_1}\right)\left(F_{\Upsilon_{SR_iD}}(\gamma|X_{sp} = x_{sp})\right)^{L}, & x_{sp} < \frac{I}{P_1} \\ F_{X_0}\left(\frac{\gamma N_0 x_{sp}}{I}\right)\left(F_{\Upsilon_{SR_iD}}(\gamma|X_{sp} = x_{sp})\right)^{L}, & x_{sp} \geq \frac{I}{P_1} \end{cases} \tag{A.21}$$

Now, we are ready to calculate the CDF of the total SNR Υ_{tot} from (A.21) as

$$F_{\Upsilon_{tot}}(\gamma) = \int_{0}^{\infty} F_{\Upsilon_{tot}}(\gamma|X_{sp} = x_{sp}) f_{X_{sp}}(x_{sp}) dx_{sp} \tag{A.22}$$

By substituting (A.2), (A.14) and (A.20) into (A.22), we get the $F_{\Upsilon_{tot}}(\gamma)$ as

$$
\begin{aligned}
F_{\Upsilon_{tot}}(\gamma) &= \int_{0}^{I/P_2} F_{X_0}\left(\frac{\gamma N_0}{P_2}\right)\left\{1-\left[1-F_{X_{2i}}\left(\frac{\gamma N_0}{P_2}\right)\right]\right\}[1 \\
&- F_{\Upsilon_{2i}}(\gamma)]\frac{\phi_1^{m-\mu} {x_{sp}}^{\mu-1}}{{\phi_2}^m \Gamma(\mu)} e^{-\frac{x_{sp}}{\phi^1}} {}_1F_1\left(m;\mu;\frac{(\phi_2-\phi_1)x_{sp}}{\phi_1\phi_2}\right) dx_{sp} \\
&+ \int_{I/P_2}^{\infty} F_{X_0}\left(\frac{\gamma N_0 x_{sp}}{I}\right)\left\{1-\left[1-F_{X_{2i}}\left(\frac{\gamma N_0 x_{sp}}{I}\right)\right]\right\}[1 \\
&- F_{\Upsilon_{2i}}(\gamma)]\frac{\phi_1^{m-\mu} {x_{sp}}^{\mu-1}}{{\phi_2}^m \Gamma(\mu)} e^{-\frac{x_{sp}}{\phi^1}} {}_1F_1\left(m;\mu;\frac{(\phi_2-\phi_1)x_{sp}}{\phi_1\phi_2}\right) dx_{sp}
\end{aligned}
\tag{A.23}
$$

The integral in (A.23) cannot be further solved. Hence, it is approximated using Nakagami-*m* approximation.