Master Thesis in Electrical Engineering With Emphasis On Telecommunication Systems
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Decode and Forward Relay Assisting Active Jamming in NOMA System

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The authors declare that they are the sole authors of this thesis and that they have not used any sources other than those listed in the bibliography and identified as references. They further declare that they have not submitted this thesis to any other institution to obtain a degree.

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Abstract

Non-orthogonal multiple access (NOMA), with its exceptional spectrum efficiency, was thought to be a promising technology for upcoming wireless communications. Physical layer security has also been investigated to improve the security performance of the system. Power-domain NOMA has been considered for this paper, where multiple users can share the same spectrum which bases this sharing on distinct power values. Power allocation is used to allocate different power to the users based on their channel condition. Data signals of different users are superimposed on the transmitter's side, and the receiver uses successive interference cancellation (SIC) to remove the unwanted signals before decoding its own signal. There exist an eavesdropper whose motive is to eavesdrop on the confidential information that is being shared with the users. The network model developed in this way consists of two links, one of which considers the relay transmission path from the source to Near User to Far User and the other of which takes into account the direct transmission path from the source to the destination, both of which experience Nakagami-m fading. To degrade the eavesdropper's channel, the jamming technique is used against the eavesdropper where users are assumed to be in a full-duplex mode which aims to improve the security of the physical layer. Secrecy performance metrics such as secrecy outage probability, secrecy capacity, etc. are evaluated and analyzed for the considered system. Mathematical analysis and simulation using MATLAB are done to assess, analyze and visualize the system's performance in the presence of an eavesdropper when the jamming technique is applied. According to simulation results, the active jamming approach enhances the secrecy performance of the entire system and leads to a positive improvement in the secrecy rate.

Keywords: Physical Layer Security, Power-domain NOMA, Decode and Forward Relay, Jamming in NOMA, Nakagami-m Fading, Relay Transmission, Secrecy Performance.

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Contents

List of Figures

List of Abbreviations

1G-5G	First Generation - Fifth Generation
3GPP	Third Generation Partnership Project
AN	Artificial Noise
AWGN	Additive White Gaussian Noise
B5G	Beyond 5G
CD-NOMA	Code Domain Non-Orthogonal Multiple Access
CDF	Cumulative Distributive Function
DF	Decode and Forward
E	Eavesdropper
FD	Full-Duplex
FDMA	Frequency Division Multiple Access
FU	Far User
HD	Half-Duplex
HetNet	Heterogeneous Networks
LTE-A	Long-Term Evolution Advanced
MIMO	Multiple Input Multiple Output
mm-wave	millimeter wave
NOMA	Non-Orthogonal Multiple Access
NU	Near User
OP	Outage Probability
PD-NOMA	Power Domain Non-Orthogonal Multiple Access
PDF	Probability Distributive Function
PLS	Physical Layer Security

S	Source
SC	Secrecy Capacity
SIC	Successive Interference Cancellation
SINR	Signal to Interference plus Noise Ratio
SNR	Signal to Noise Ratio
TDMA	Time Division Multiple Access
UE	User Equipment
UE_1	User Equipment 1
UE_2	User Equipment 2

Chapter 1

Introduction

1.1 Wireless Communication

The most dynamic and rapidly expanding technology sector in the communication industry is wireless communication. We live in a society where communication is omnipresent, and wireless communication in particular has ingrained itself into our daily lives. Data traffic has significantly increased in recent years as a result of the need for extensive multimedia content, a rise in the diversity of devices, etc. We can see that developments in wireless technology have given us a wide range of new services and applications. New security issues have also been introduced by these advancements in the wireless environment [33].

Mobile wireless technologies have advanced through roughly five generations of technology over the past few decades. Therefore, there has been an improvement in call quality, higher data rates, greater bandwidth, faster speeds, etc. across the generations. While 5G can allow highly dynamic multimedia applications with a data rate of a gigabit per second (Gbps), 1G can only handle voice communication with a data rate of kilo-bit per second (Kbps). Wireless networks in the fourth generation provide data speeds of up to 1Gbps for low mobility and up to 100 Mbps for high mobility [3]. Comparing the fourth generation to the other generations, there have been several improvements. However, there is still a significant rise in the number of consumers worldwide who want faster connections and continuous, instant communication. The theoretical data rate threshold for fourth-generation (4G) networks has almost been achieved; as a result, there is not enough capacity to support the user base. Due to this, there is a lot of research and development being done on the 5G network. The primary technology for identifying various wireless networks has been the multiple access technique from the first generation (1G) through the 4G. Frequency division multiple access (FDMA) is used in the first generation (1G). In 2G, Time Division Multiple Access (TDMA) is used. In 3G and 4G, respectively, there is orthogonal frequency division multiple access (OFDMA). Orthogonal multiple access (OMA) methods, which are the majority of multiple access techniques now in use from 1G to 4G cellular networks, are believed to be unable to handle the future's extremely high needs for network traffic and user density [8] [14].

In order to prevent or reduce inter-user interference, distinct users are assigned to orthogonal resources in the time, frequency, or code domain. As was previously said, data traffic has skyrocketed recently and will continue to do so in the next years.

In order to manage this exploding data traffic for fifth-generation (5G) and beyond 5G (B5G) wireless networks, spectral efficiency has emerged as a key factor. A few proposals for effective wireless transmission technologies, including mm-wave communication, massive multiple input multiple output (MIMO), Non-orthogonal multiple access (NOMA), heterogeneous networks (HetNet), etc., have been put forth for the 5G era [8] [7].

1.2 Non-Orthogonal Multiple Access

Non-Orthogonal Multiple Access (NOMA), which is predicted to enhance system throughput and provide huge inter-connectivity, has recently drawn a lot of interest from researchers. By using power domain or code domain multiplexing, NOMA enables various users to share time and frequency resources within the same spatial layer. The fundamental concept behind NOMA is that it permits manageable interferences by non-orthogonal resource allocation with an acceptable increase in receiver complexity. Because NOMA uses non-orthogonal resource allocation, the number of supported users or devices is not absolutely constrained by the number of accessible resources and the scheduling granularity of those resources. Therefore, by employing non-orthogonal resource allocation, NOMA can support substantially more users than OMA. The two primary categories of NOMA techniques are power-domain multiplexing and code-domain multiplexing [8] [2].

In this study, we concentrate on power-domain NOMA. Multiple users can share the same spectrum using power-domain NOMA (PD-NOMA), which bases this sharing on distinct power values. In order to ensure high system performance, various users are allotted different power coefficients based on their channel circumstances [5]. To find the users, it employs successive interference cancellation (SIC) at the receiver and superposition coding at the transmitter [19] [16]. It is generally known that the power multiplexing NOMA scheme, which utilizes SIC to fully cancel the multi-user interference, consistently produces a higher cumulative throughput than the OMA methods in a down-link cellular network [23]. Each user in code-domain NOMA is multiplexed across the same time-frequency resources and given a unique code. A message passing algorithm was used to retrieve the desired signal at the receiver's end. Code-domain multiplexing has the potential to increase spectral efficiency, but it demands a large amount of transmission bandwidth and is difficult to integrate into the systems in use today. On the other hand, power-domain multiplexing is easy to deploy since it doesn't involve major changes to the current networks and doesn't need more bandwidth to increase spectral efficiency [4] [30].

According to their proximity to the Source, users may be divided into two categories: near-end users and far-end users [41]. The performance of the system is enhanced in PD-NOMA by distributing varying power levels to diverse users. Different users' data signals are superimposed on the transmitter's side, and the receiver uses SIC to cancel out the undesirable signals before decoding the signal.

Numerous NOMA with relaying contributions have been studied recently, which can increase the spectrum efficiency and transmit reliability of wireless networks. This study examines a NOMA system in which a source uses a decode and forward (DF) relay to connect with two distant users [24]. However, in the relay transmission, the system becomes more open to eavesdropping by sending an additional copy of the distant user's private information over the relay. Therefore, it is essential to figure out how to protect the legitimate distant user from wiretapping. This highlights the requirement for strengthening the system's physical layer security [31].

1.3 Physical Layer Security

In the near future, a large quantity of sensitive and private information will be carried across wireless channels due to the pervasiveness and need for 5G connections. Therefore, one of the key goals in the design and deployment of the 5G network is to offer an unrivaled security service. One of the main issues that every designer of a 5G network may encounter is the security of wireless data transmission. Physical layer security, which differs from conventional cryptographic methods in that it secures wireless signals by smartly utilizing the communications system's flaws, is seen as a promising approach. Physical layer security will safeguard the network's communication phase with careful planning and execution, and cryptography will safeguard the processed data after the communication phase. As a result, they will combine to provide a solid security solution that effectively protects private and sensitive data in the 5G future [39].

By blocking eavesdroppers' access to the channels, the physical layer security helps in increasing secrecy. Eavesdroppers are unauthorized users who attempt to steal the private and sensitive information of legal users by using the same bandwidth as them. A user who can access, alter, delete, or inject the data as an authorized user is considered an active eavesdropper. A user who can just decode data and examine it is considered a passive eavesdropper.

When compared to cryptography, physical layer security has two key benefits, which makes it especially appropriate for 5G networks. First off, physical layer security measures don't rely on computing complexity, so even if illegal smart devices in the 5G network have tremendous computational capabilities, the degree of security will not be harmed. Furthermore, physical layer security methods are highly scalable. Devices in the 5G network are constantly coupled to nodes at various architectural levels, each of which has a range of processing power and power. Additionally, because the network is decentralized, devices always join or leave it at unpredictable times. Distribution and administration of cryptographic keys thus become quite difficult. To address this, the 5G network's physical layer security can either enable direct secure data connection or make it easier for users to share cryptographic keys [13] [10].

Physical layer security is seen to be one of the key solutions for protecting sensitive data from eavesdroppers. It was suggested to use physical layer security to get around many of the drawbacks of traditional methods. The source and the authorized user frequently attempt to interact and enhance their ability for secrecy from eavesdroppers while the source transfers secret information to a destination. The most widely used metrics to assess the secrecy performance of wireless networks are Secrecy capacity and Outage probability. The probability that the instantaneous secrecy capacity will fall below the desired secrecy rate is known as the secrecy outage probability [28]. The capacity between the primary user channel and the unauthorized eavesdropper channel can be regarded as the secrecy rate. Under the condition that the channels are unknown to unauthorized users or that the unauthorized users' channel is louder than that of the authorized users, perfect secrecy can be achieved using physical layer approaches. While the upper-layer operation is a major component of standard encryption strategies, it is intriguing to learn whether the physical layer can have some built-in security to support upper-layer security designs [36]. Numerous solutions, including artificial-noise (AN)-aided transmission, full-duplex techniques, and cooperative relay transmission, have been suggested in the context of physical layer security to improve the secrecy performance of wireless communications [12]. In this research [12], the authors looked at secure transmission in full-duplex networks with artificial noise assistance. Cooperative beamforming (CB) and cooperative jamming (CJ) are two secure transmission techniques that have been studied extensively by researchers .

In wireless networks, there are many widely used techniques to increase security at the physical layer, including beam-forming, artificial noise, power allocation, jamming, etc. Using beamforming, the signal strength in OMA is increased at the receivers while being reduced in other connections. Many experiments have been done on using artificial noise in the presence of an eavesdropper to diminish its performance, even if this approach doesn't meet the NOMA standards [25] [11]. To increase the security of the NOMA system, artificial noise is supplied to the eavesdropper while the communication is taking place. A far user is enlisted to adaptively produce a jamming signal to confuse the untrusted relay in the jamming technique. The untrusted relay's potential to eavesdrop on communications is successfully suppressed by the right design of the jamming transmission rate, which ensures that the jamming signal can only be decoded at the nearby user and not at the untrusted relay [35] [41]. Physical layer security provides simple and effective security measures, while NOMA ensures great spectral efficiency, low latency, and large availability.

1.4 Motivation

Given the limited availability of bandwidth, NOMA is essential for delivering 5G wireless networks with high system throughput, high reliability, expanded coverage, low latency, and widespread connection. Because of this, NOMA is now acknowledged as a key enabling technology for 5G wireless communication networks. NOMA has recently been incorporated into 3GPP Long-Term Evolution Advanced (LTE-A) due to the benefit of spectral efficiency, which further supports the significance of NOMA in future wireless networks. Thus, one of the major tasks in the development of 5G wireless networks is to provide NOMA technology with an unmatched degree of security. When the material is confidential, secure data transfer against hackers and eavesdroppers is essential. The essential security need for wireless networks is to stop eavesdroppers from eavesdropping on any sensitive information since they are prone to assaults. According to Shannon's physical layer security study, [34], the level of security depends on the amount of information that eavesdroppers are aware of. In the instance of an active eavesdropper, the attacker controls the whole conversation and establishes separate connections between the source and receiver as well as transmits messages between them to give the impression that they are speaking directly to one another. Additionally, passive eavesdroppers just decode the information that was transmitted, not disturbing or interrupting the conversation.

It was noted that traditional methods and key schemes have shortcomings in protecting sensitive information from eavesdroppers. One of the physical layer security techniques, jamming reduces the eavesdropper's performance to increase the system's performance. Therefore, users who are aware that an eavesdropper is present in a full duplex utilize jamming to reduce the eavesdropper's ability to intercept data. While physical layer security provides simple and reliable security solutions, raising the system's sum secrecy rate and enhancing performance, NOMA systems ensure high spectrum efficiency and low latency.

1.5 Aim and Objectives

1.5.1 Aim

The major goal of this thesis work is to establish a DF relay network between the users in order to implement physical layer security for the power-domain NOMA system where the channels experience the Nakagami-m fading. In order to make the eavesdropper's channel noisier, we also plan to use the jamming technique and observe the improvement in the secrecy performance of the system. We conduct a mathematical analysis, derive the equations, and run simulations for the considered system's secrecy outage probability and secrecy capacity in order to quantify the acquired secrecy performance.

1.5.2 Objectives

To enhance the performance of the system, a distinct user in the NOMA system employs an active jamming technique against eavesdroppers to degrade its performance. The analytic framework for performance metrics is developed, and simulation in MATLAB is used to study parameters like outage probability and secrecy capacity. The thesis's primary objectives are as follows:

- Deployment of active jamming technique against the eavesdropper.
- Obtaining necessary equations to analyze the performance metrics.
- Analyzing the secrecy of physical layer in the power-domain NOMA system.

- Simulating the desired NOMA system in Matlab software.
- Observing the performance of the system in the Nakagami-m fading environment.

1.6 Research Questions

- **RQ1:** What is the response of outage probability of the users in the NOMA system?
- **RQ2:** How does the implementation of the active jamming technique improve the secrecy performance of the power domain NOMA system?
- **RQ3:** What is the response of secrecy capacity of the full-duplex relay PD-NOMA system with active jamming by varying fading severity and path loss exponent parameters?

1.7 Research Methodology

1.7.1 Literature Review

To gain initial background knowledge about the physical layer, physical layer security, NOMA systems, 5G technologies, etc, we performed a brief study. We considered several journal articles, and conference papers based on NOMA, physical layer security, active jamming, security metrics in NOMA, Nakagami-m fading, and eavesdroppers in wireless communications. ACM digital library, Scopus, IEEE Xplore, and Google Scholar are a few of the digital libraries where these publications are searched. Then, using the active jamming approach with decode-and-forward relaying, we established an analytical framework to examine the system performance of the intended NOMA model.

Inclusion criteria:

- Articles should be in English.
- Articles can be conference papers, journal articles or books.
- Articles that are related to the current research are considered.

1.7.2 Mathematical Analysis

We used mathematical analysis for the desired system. In particular, we derived the expressions for transmitted and received signals for the system. We model the distribution of the fading channel. That helped us to attain the SINR and SNR at the receiver and eavesdropper. We then worked towards deriving the required security metrics to answer the research questions.

1.7.3 Simulation

We used MATLAB software to generate the transmitted signals and simulate the fading environment for the power-domain NOMA in the physical layer. After that, we observed the received signal of the considered system over the simulated channel and formulate the obtained performance metrics in the simulation process. We also compared the simulation results with and without active jamming against the eavesdropper. To illustrate how the considered system performed in relation to the security metrics, many graphs are shown.

Chapter 2

Related Work

Security is a matter of paramount significance, yet it presents a big problem for wireless communications. Xiao Tang et al. [37] states that traditionally, half-duplex (HD) transmission is used to study the physical layer since it is the pattern currently used in wireless systems. A typical eavesdropper remains silent while wiretapping legitimate transmissions or sending out interference signals to risk legitimate transmissions. Their model utilizes wireless channels that follow Rayleigh fading and are essentially static. The eavesdropper, who is described as passive, is still largely based on the HD assumption. In contrast, full-duplex (FD) based communications, which have the potential to increase spectral efficiency, have most recently sparked an increase in interest in the sector. To improve physical layer security, FD is more frequently used on the side of the legitimate user. Eavesdropping can be successfully hindered using FD technology, which allows simultaneous transmissions and receptions or creates additional interference to jam the eavesdropper. For physical layer security, FD technology has significant drawbacks as well. In particular, when the eavesdropper has FD capability, it transforms into an active eavesdropper that can do jamming and eavesdropping simultaneously. When a legitimate user and an eavesdropper communicate, it is crucial to look into the security problem and security performance of the systems.

A multiple-antenna FD relay was suggested as part of the jamming method by the authors of papers [21] and [22] for the NOMA system. The Rayleigh fading that occurs on the channels is also taken into account by the authors of this research. When using a decode-forward relay, which forwards data and creates artificial jamming to prevent eavesdropping, they evaluated two pairs of users to execute secure transmission. They then created a closed-form expression for the probability of a secrecy outage (SOP).

The NOMA system's secrecy was investigated in this paper [15] using user scheduling and jamming. The author considered that independent, non-identically distributed Rayleigh fading occurs for all channels of NUs. Multi-user NOMA systems leverage user scheduling to counteract external eavesdroppers who just passively listen in on legitimate transmissions. However, the design of secure NOMA transmission is more difficult than the external eavesdropping scenario when an inside node, such as the relay that aids the FU, seeks to gain sensitive information. An FU-based jamming approach is devised to protect the cooperative NOMA transmission in order to avoid potential information leakage at the untrusted relay. Furthermore, they suggested an opportunistic NU scheduling approach to optimize the total secrecy rate while ensuring fair channel access for all NUs in order to lessen the influence of the jamming signal at the planned NU and improve the secrecy performance.

In order to increase an up-link NOMA system's secrecy performance in the presence of an eavesdropper, this research [20] examines the performance of a jamming-aided up-link NOMA system. As anticipated, FD jamming enhances secrecy performance, although it has a little impact that causes the gain to progressively decrease in the high power regime. The channels among the base station were assumed to be mutually independent and to experience quasi-static Rayleigh fading in the system model.

The NOMA-inspired jamming and relaying system proposed in this study [26] aims to improve the physical layer security of untrusted relay networks. They divided it into two parts. The untrusted relay is intended to be confused by the superimposed signal and jamming signal that the source provides in the first phase. This is done by utilizing the beamforming design and varying the source's transmission rate. To increase the secrecy sum rate, the untrusted relay sends its received signals in the second phase while the source concurrently transmits a fresh desired signal that the untrusted relay cannot wiretap. The channels in the network exhibit quasi-static fading, meaning that the channel coefficients vary independently across fading blocks but stay static inside a single fading block.

The author of this paper [32] investigated the physical layer security of the NOMA system using the jamming technique without a relay in between the users. The author analyzed the NOMA system in comparison with the OMA system. Numerical results were presented with also a simulation of the system in MATLAB. The author's proposed system runs in the Rayleigh fading environment.

The outage performance of NOMA over Nakagami-m fading channels with fixed gain amplify and forward (AF) relaying has been studied [40]. With and without the relaying mechanism, the authors observed how users behaved during outages. They have suggested that employing the NOMA approach instead of traditional multiple access methods can assure user fairness.

Numerous studies were conducted on NOMA employing the jammer technique to enhance its secrecy capabilities. In the Nakagami-m fading environment, it is interesting to examine the secrecy performance of a power-domain NOMA system with active jamming and a full-duplex relay network between the users.

Chapter 3

System Model

This NOMA system consists of a source, also called as base station(S), that simultaneously communicates with two users UE_1 and UE_2 in the power domain. However, in this environment, there exists an eavesdropper (E), who tries to tap information from both users UE_1 and UE_2. UE_1 and UE_2 will be working in full-duplex relaying mode. Assume that, the user UE_1 is the near user with a distance of d_{UE_1} from the S, and the user UE_2 is the far user with a distance of d_{UE_2} from the S. The eavesdropper is at a distance of d_E from the S.

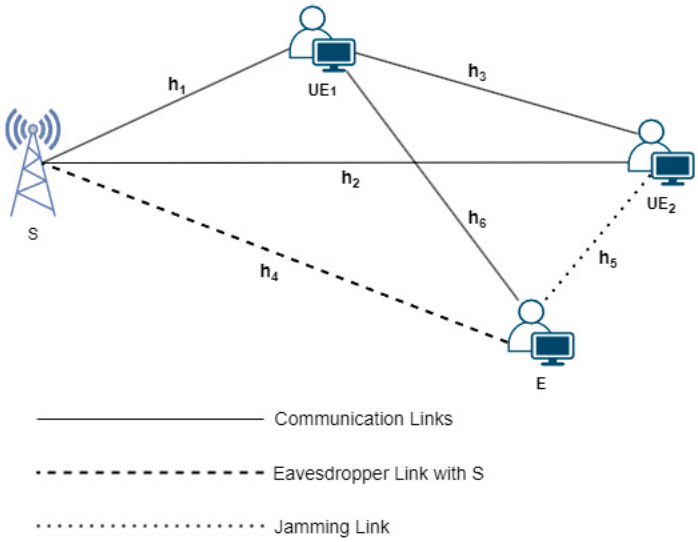

Figure 3.1: System Model

The S transmits a superimposed signal to both users UE_1 and UE_2. Let's denote h_1, h_2, h_3, h_4, h_5 and h_6 as the channel coefficients for the links from S to UE_1, S to UE_2, UE_1 to UE_2, S to eavesdropper, UE_2 to eavesdropper and UE_1 to eavesdropper respectively.

3.1 Signal Expressions

Since we are using a power-domain NOMA system, the S allocates the power to the users based on the user's distance; i.e., more power is allocated to the far user signal and less power is allocated to the near user signal.

Let's assume that $x_1(t)$ and $x_2(t)$ represent data signals of UE_1,UE_2 with unit power respectively. Here, the user UE_1 is assumed to be located nearer to S, and the user UE_2 is farther from S. So according to the power-domain NOMA principle, more power coefficient is allocated to far user UE_2 than the near user UE_1 i.e., $\alpha_1+\alpha_2=1$ where $\alpha_1 < \alpha_2$. Here, both users UE_1 and UE_2 are assumed to be working in full-duplex relaying mode i.e., the communications use two-time slots and both users can send and receive the signals at the same time.

In time instant t the superimposed signal transmitted by S is

$$x_s(t) = \sqrt{\alpha_1 P_s}\, x_1(t) + \sqrt{\alpha_2 P_s}\, x_2(t) \tag{3.1}$$

where $x_1(t)$ and $x_2(t)$ represents the data signals that sends to the users UE_1 and UE_2 at time instant t. P_s represents the transmission power that S allocates to the users. α_1 and α_2 are the power allocation coefficients of UE_1 and UE_2 .

The signal which is received by the user UE_1 is given as

$$y_1(t) = h_1 x_s(t) + n_1(t) \tag{3.2}$$

Equation after substituting $x_s(t)$ in $y_1(t)$, we get

$$\begin{aligned} y_1(t) &= h_1(\sqrt{\alpha_1 P_s}\, x_1(t) + \sqrt{\alpha_2 P_s}\, x_2(t)) + n_1(t) \\ y_1(t) &= h_1\sqrt{\alpha_1 P_s}\, x_1(t) + h_1\sqrt{\alpha_2 P_s}\, x_2(t) + n_1(t) \end{aligned} \tag{3.3}$$

As defined earlier, here h_1 represents the channel coefficient from S to UE_1 and $n_1(t)$ is the Additive White Gaussian Noise (AWGN) with zero mean and N_0 variance.

Due to the support from UE_1, the signal received at the user UE_2 comes from both the S and UE_1.

Let's call the signal $y_{21}(t)$ which is from the S as

$$y_{21}(t) = h_2\sqrt{\alpha_1 P_s} x_1(t) + h_2\sqrt{\alpha_2 P_s} x_2(t) + n_2(t) \tag{3.4}$$

Let's call the signal $y_{22}(t+1)$ which is from UE_1 as

$$y_{22}(t+1) = h_3\sqrt{\alpha_2 P_s}\, x_2(t) + n_2(t+1) \tag{3.5}$$

Here, we are considering relay from the user UE_1. So, $y_{21}(t)$ and $y_{22}(t)$ represents the signal received by the user UE_2 from UE_1 and from S, respectively. h_2 represents the channel coefficient from the S to UE_2 and $n_2(t)$ is the AWGN at UE_2 with zero mean and N_0 variance.

Let's assume that both users UE_1 and UE_2 know about the presence of the eavesdropper E. so, UE2 operates in full duplex mode, i.e., it simultaneously receives the signal coming from S and UE_1 and generates a jamming signal to interfere the received signal at E and degrade its capacity to eavesdrop the signals at the same time.

The signal which is received by the Eavesdropper is given as

$$y_E(t) = h_4(\sqrt{\alpha_1 P_s} x_1(t) + \sqrt{\alpha_2 P_s}\, x_2(t)) + h_3\sqrt{P_1} x_j(t) + n_E(t)$$

$$y_E(t) = h_4\sqrt{\alpha_1 P_s}\, x_1(t) + h_4\sqrt{\alpha_2 P_s} x_2(t) + h_4\sqrt{P_1} x_j(t) + n_E(t) \tag{3.6}$$

Here $x_j(t)$ is the jamming signal that UE_2 broadcast to confuse the E. Because and the users UE_1 and UE_2 can cancel the jamming signal as they know that there will be an incoming jamming signal $x_j(t)$.

3.2 Signal-to-Interference-plus-Noise Ratio

We assumed that UE_1 is near to S and UE_2 is far from the S. Based on the principle of NOMA in the power domain, the power allocated for UE_2 is more than UE_1 i.e ($\alpha_1 < \alpha_2$). Here, UE_2 can directly decode the signal but UE_1 should first decode UE_2's signal and then eliminate UE_2's signal using successive interference cancellation(SIC). After applying SIC, UE_1 finally retrieves its signal.

Here, UE_1 can not decode its signal directly so, UE_1 decodes UE_2's signal first, UE_1 signal will be considered as interference for UE_2's signal.

Signal-to-interference-plus-noise ratio (SINR) γ_{11} when the user UE_1 decodes the signal of the user UE_2 is expressed as

$$\gamma_{11} = \frac{|h_1\sqrt{\alpha_2 P_s} x_2(t)|^2}{|h_1\sqrt{\alpha_1 P_s} x_1(t) + n_1(t)|^2} \tag{3.7}$$

$$\gamma_{11} = \frac{|h_1|^2\alpha_2 P_s}{|h_1|^2\alpha_1 P_s + N_o} \tag{3.8}$$

Let us consider $X_1 = |h_1|^2$ which is channel power gain from S to UE_1. The average power transmitted at S is given as $\overline{\gamma_s} = \frac{P_s}{N_o}$

$$\gamma_{11} = \frac{\alpha_2\overline{\gamma_s}X_1}{\alpha_1\overline{\gamma_s}X_1 + 1} \tag{3.9}$$

After applying SIC, the leftover signal at UE_1 is expressed as

$$y_1(t) = h_1\sqrt{\alpha_1 P_s} x_1(t) + n_1(t) \tag{3.10}$$

SINR γ_{12} when the UE$_1$ decodes its own signal after applying SIC is expressed as.

$$\gamma_{12} = \frac{|h_1\sqrt{\alpha_1 P_s}x_1(t)|^2}{|n_1(t)|^2} \tag{3.11}$$

Let us consider $X_1 = |h_1|^2$ which is channel power gain from S to UE$_1$.

$$\gamma_{12} = \alpha_1\overline{\gamma_s}X_1 \tag{3.12}$$

In order to correctly decode the signal, the UE$_1$ needs to decode the UE$_2$'s signal and it's own signal correctly. So, the end-to-end SINR at the UE$_1$ is given as

$$\gamma_1 = min(\gamma_{11}, \gamma_{12}) \tag{3.13}$$

Here, UE$_2$ will receive the signal from UE$_1$, which is over the relay link, and another direct signal from S. Signal from UE$_1$ contains only $x_2(t)$ signal and the another signal from S is a superimposed signal.

SINR γ_{21} when the UE$_2$ decodes signal from S is obtained as

$$\gamma_{21} = \frac{|h_2\sqrt{\alpha_2 P_s}x_2(t)|^2}{|h_2\sqrt{\alpha_1 P_s}x_1(t) + n_2(t)|^2} \tag{3.14}$$

$$\gamma_{21} = \frac{|h_2|^2\alpha_2 P_s}{|h_2|^2\alpha_1 P_s + N_o} \tag{3.15}$$

Let us consider $X_2 = |h_2|^2$ as channel power gain from S to UE$_1$. Then we can rewrite 3.15 as

$$\gamma_{21} = \frac{\alpha_2\overline{\gamma_s}X_2}{\alpha_1\overline{\gamma_s}X_2 + 1} \tag{3.16}$$

SINR γ_{22} when the UE$_2$ decodes the signal from UE$_1$ is expressed as

$$\gamma_{22} = \frac{|h_3\sqrt{\alpha_2 P_s}x_2(t)|^2}{|n_2(t+1)|^2} \tag{3.17}$$

$$\gamma_{22} = \frac{|h_3|^2\alpha_2 P_s}{N_o} \tag{3.18}$$

Let us consider $X_3 = |h_3|^2$ which is channel power gain from S to UE$_1$.

$$\gamma_{22} = \alpha_2\overline{\gamma_s}X_3 \tag{3.19}$$

The end-to-end SINR at UE$_2$

$$\gamma_2 = max(\gamma_{21}, \gamma_{22}) \tag{3.20}$$

SINR γ_{1E} when E decoding the user UE$_1$'s signal

$$\gamma_{1E} = \frac{|h_4\sqrt{\alpha_2 P_s}x_2(t)|^2}{|h_4\sqrt{\alpha_1 P_s}x_1(t) + h_6\sqrt{\alpha_2 P_s}x_2(t-1) + h_5\sqrt{P_1}x_j(t) + n_E(t)|^2} \tag{3.21}$$

$$\gamma_{1E} = \frac{|h_4|^2\alpha_2 P_s}{|h_4|^2\alpha P_s + |h_6|^2\alpha_2 P_s + |h_5|^2 P_1 + N_o} \tag{3.22}$$

Let us consider $X_4 = |h_4|^2$, $X_5 = |h_5|^2$ which is channel power gain from S to UE$_1$. The average power transmitted at UE$_2$ is $\overline{\gamma}_1 = \frac{P_2}{N_o}$.

$$\gamma_{1E} = \frac{\alpha_2\overline{\gamma}_s X_4}{\alpha_1\overline{\gamma}_s X_4 + \alpha_2\overline{\gamma}_s X_6 + \overline{\gamma}_1 X_5 + 1} \tag{3.23}$$

After decoding signal $x_2(t)$ Eavesdropper will eliminate the $x_2(t)$ signal and then E tries to decode the signal $x_1(t)$ of UE$_1$. The signal after removing x_2(t) from the superimposed signal.

$$y_E(t) = h_4\sqrt{\alpha_1 P_s}x_1(t) + h_5\sqrt{P_1}x_j(t) + h_6\sqrt{\alpha_2 P_s}x_2(t-1) + n_E(t) \tag{3.24}$$

SINR γ_{2E} when E decoding the user UE$_1$'s signal

$$\gamma_{2E} = \frac{|h_4\sqrt{\alpha_1 P_s}x_2(t)|^2}{|h_5\sqrt{P_1}x_j(t) + h_6\sqrt{\alpha_2 P_s}x_2(t-1) + n_E(t)|^2} \tag{3.25}$$

$$\gamma_{2E} = \frac{|h_4|^2\alpha_1 P_s}{|h_5|^2 P_1 + |h_6|^2\alpha_2 P_s + N_o} \tag{3.26}$$

Let us consider $X_4 = |h_4|^2$, $X_5 = |h_5|^2$ which is channel power gain from S to UE$_1$ and average power transmitted at S is $\overline{\gamma}_s = \frac{P_s}{N_o}$. The channel power gain from UE$_2$ to Eavesdropper is $\overline{\gamma}_1 = \frac{P_1}{N_o}$.

$$\gamma_{2E} = \frac{\alpha_1\overline{\gamma}_s X_4}{\overline{\gamma}_1 X_5 + \alpha_2\overline{\gamma}_s X_6 + 1} \tag{3.27}$$

3.3 Nakagami - m Fading Distribution

Cummulative distributive function (CDF) of Nakagami - m fading distribution:

$$F_{X_i}(x) = 1 - exp(-\beta_i x)\sum_{j=0}^{m_i-1}\frac{\beta_i^j x^j}{j!} \tag{3.28}$$

Probability distributive function (PDF) of Nakagami - m fading distribution:

$$f_{X_i}(x) = \frac{\beta_i^{m_i}}{\Gamma(m_i)}x^{m_i-1}exp(-\beta_i x) \tag{3.29}$$

Here $\beta_i = \frac{m_i}{\Omega_i}$, where m is channel fading severity, n is path loss exponent, and Ω is the channel mean power($\Omega_i = E[X_i]$).

3.4 CDF of γ_1

From (3.13), we have

$$\gamma_1 = min(\gamma_{11}, \gamma_{12}) \tag{3.30}$$

Therefore, the CDF of γ_1 can be calculated as

$$\begin{aligned}
F_{\gamma_1}(\gamma) &= pr(min(\gamma_{11}, \gamma_{12}) < \gamma) && (3.31)\\
&= 1 - pr(min(\gamma_{11}, \gamma_{12}) > \gamma) && (3.32)\\
&= 1 - pr(\gamma_{11} > \gamma)pr(\gamma_{12} > \gamma) && (3.33)\\
&= 1 - [1 - pr(\gamma_{11} < \gamma)][1 - pr(\gamma_{12} < \gamma)] && (3.34)\\
&= 1 - [1 - F_{\gamma 11}(\gamma)][1 - F_{\gamma 12}(\gamma)] && (3.35)
\end{aligned}$$

Calculating $F_{\gamma_{11}}(\gamma)$ from (3.9) as follows :-

$$\begin{aligned}
F_{\gamma_{11}}(\gamma) &= pr\left(\frac{\bar{\gamma_s}\alpha_2 X_1}{\bar{\gamma_s}\alpha_1 X_1 + 1} < \gamma\right) && (3.36)\\
&= pr\left(\bar{\gamma_s}\alpha_2 X_1 < \gamma(\bar{\gamma_s}\alpha_1 X_1 + 1)\right) && (3.37)\\
&= pr\left(X_1(\bar{\gamma_s}\left(\alpha_2 - \alpha_1\gamma\right)) < \gamma\right) && (3.38)\\
&= pr\left(X_1 < \frac{\gamma}{\bar{\gamma_s}\left(\alpha_2 - \alpha_1\gamma\right)}\right) && (3.39)
\end{aligned}$$

if $(\alpha_2 - \alpha_1\gamma) > 0$ or $\gamma < \frac{\alpha_2}{\alpha_1}$, we have

$$\begin{aligned}
F_{\gamma_{11}}(\gamma) &= pr\left(X_1 < \frac{\gamma}{\bar{\gamma_s}\left(\alpha_2 - \alpha_1\gamma\right)}\right) && (3.40)\\
&= F_{X_1}\left(\frac{\gamma}{\bar{\gamma_s}\left(\alpha_2 - \alpha_1\gamma\right)}\right) && (3.41)\\
&= 1 - exp(-\beta_1 \frac{\gamma}{\bar{\gamma_s}\left(\alpha_2 - \alpha_1\gamma\right)}) \sum_{j=0}^{m_1-1} \frac{\beta_1^j}{j} \left(\frac{\gamma}{\bar{\gamma_s}\left(\alpha_2 - \alpha_1\gamma\right)}\right)^j && (3.42)
\end{aligned}$$

if $(\alpha_2 - \alpha_1\gamma) \leq 0$ or $\gamma \geq \frac{\alpha_2}{\alpha_1}$, we have

$$\begin{aligned}
F_{\gamma_{11}}(\gamma) &= pr\left(X_1 \geq \frac{\gamma}{\bar{\gamma_s}\left(\alpha_2 - \alpha_1\gamma\right)}\right) && (3.43)\\
F_{\gamma_{11}}(\gamma) &= 1 && (3.44)
\end{aligned}$$

Calculating $F_{\gamma_{12}}(\gamma)$ from (3.9) as follows :-

$$F_{\gamma_{12}}(\gamma) = pr\left(\bar{\gamma_s}\alpha_1 X_1 < \gamma\right) \tag{3.45}$$

$$F_{\gamma_{12}}(\gamma) = pr\left(X_1 < \frac{\gamma}{\bar{\gamma_s}\alpha_1}\right) \tag{3.46}$$

$$F_{\gamma_{12}}(\gamma) = F_{X_1}\left(\frac{\gamma}{\bar{\gamma_s}\alpha_1}\right) \tag{3.47}$$

$$F_{\gamma_{12}}(\gamma) = 1 - exp(-\beta_1\frac{\gamma}{\bar{\gamma_s}\alpha_1})\sum_{k=0}^{m_1-1}\frac{\beta_1^k}{k!}\left(\frac{\gamma}{\bar{\gamma_s}\alpha_1}\right)^k \tag{3.48}$$

Substituting $F_{\gamma_{11}}(\gamma)$ in (3.42) and (3.44), $F_{\gamma_{12}}(\gamma)$ in (3.48) into (3.35), we can calculate $F_{\gamma_1}(\gamma)$ as

$$F_{\gamma_1}(\gamma) = 1 - [1 - F_{\gamma_{11}}(\gamma)][1 - F_{\gamma_{12}}(\gamma)] \tag{3.49}$$

For the case $(\alpha_2 - \alpha_1\gamma) > 0$ or $\gamma < \frac{\alpha_2}{\alpha_1}$, we have

$$\begin{aligned} F_{\gamma_1}(\gamma) = 1 - exp(-\beta_1\frac{\gamma}{\bar{\gamma_s}(\alpha_2 - \alpha_1\gamma)})\sum_{j=0}^{m_1-1}\frac{\beta_1^j}{j!}\left(\frac{\gamma}{\bar{\gamma_s}(\alpha_2 - \alpha_1\gamma)}\right)^j \\ \times exp(-\beta_1\frac{\gamma}{\bar{\gamma_s}\alpha_1})\sum_{k=0}^{m_1-1}\frac{\beta_1^k}{k!}\left(\frac{\gamma}{\bar{\gamma_s}\alpha_1}\right) \end{aligned} \tag{3.50}$$

$$\begin{aligned} F_{\gamma_1}(\gamma) = 1 - exp\left(\frac{-\beta_1\gamma}{\overline{\gamma}_s}\left(\frac{1}{\alpha_2 - \alpha_1\gamma} + \frac{1}{\alpha_1}\right)\right)\sum_{j=0}^{m_1-1}\sum_{k=0}^{m_1-1}\left(\frac{\beta_1\gamma}{\overline{\gamma}_s}\right)^{j+k} \\ \times\left(\frac{1}{(\alpha_2 - \alpha_1\gamma)^j(\alpha_1)^k j!k!}\right) \end{aligned} \tag{3.51}$$

For the case $(\alpha_2 - \alpha_1\gamma) \leq 0$ or $\gamma \geq \frac{\alpha_2}{\alpha_1}$, we have

$$F_{\gamma_1}(\gamma) = 1 - [1 - F_{\gamma_{11}}(\gamma)][1 - F_{\gamma_{12}}(\gamma)] \tag{3.52}$$

$$F_{\gamma_1}(\gamma) = 1 - [1 - 1][1 - F_{\gamma_{12}}(\gamma)] \tag{3.53}$$

$$F_{\gamma_1}(\gamma) = 1 \tag{3.54}$$

3.5 CDF of γ_2

From (3.20), we have

$$\gamma_2 = max(\gamma_{21}, \gamma_{22}) \tag{3.55}$$

Therefore, the CDF of γ_2 can be calculated as

$$F_{\gamma_2}(\gamma) = pr(max(\gamma_{21}, \gamma_{22}) < \gamma) \tag{3.56}$$
$$F_{\gamma_2}(\gamma) = pr(\gamma_{21} < \gamma)pr(\gamma_{22} < \gamma) \tag{3.57}$$
$$F_{\gamma_2}(\gamma) = F_{\gamma 21}(\gamma)F_{\gamma 22}(\gamma) \tag{3.58}$$

Calculating $F_{\gamma_{21}}(\gamma)$ from (3.16) as follows :-

$$F_{\gamma_{21}}(\gamma) = pr\left(\frac{\bar{\gamma}_s\alpha_2 X_2}{\bar{\gamma}_s\alpha_1 x_2 + 1} < \gamma\right) \tag{3.59}$$
$$F_{\gamma_{21}}(\gamma) = pr\left(\bar{\gamma}_s\alpha_2 X_2 < \gamma(\bar{\gamma}_s\alpha_1 x_2 + 1)\right) \tag{3.60}$$
$$F_{\gamma_{21}}(\gamma) = pr\left(X_2 < \frac{\gamma}{\bar{\gamma}_s(\alpha_2 - \alpha_1\gamma)}\right) \tag{3.61}$$

if $(\alpha_2 - \alpha_1\gamma)$ 0 or $\gamma < \frac{\alpha_2}{\alpha_1}$, we have

$$F_{\gamma_{21}}(\gamma) = pr\left(X_2 < \frac{\gamma}{\bar{\gamma}_s(\alpha_2 - \alpha_1\gamma)}\right) \tag{3.62}$$
$$F_{\gamma_{21}}(\gamma) = F_{X_2}\left(\frac{\gamma}{\bar{\gamma}_s(\alpha_2 - \alpha_1\gamma)}\right) \tag{3.63}$$
$$F_{\gamma_{21}}(\gamma) = 1 - exp\left(-\beta_2\frac{\gamma}{\bar{\gamma}_s(\alpha_2 - \alpha_1\gamma)}\right)\sum_{l=0}^{m_2-1}\frac{\beta_2^l}{l!}\left(\frac{\gamma}{\bar{\gamma}_s(\alpha_2 - \alpha_1\gamma)}\right)^l \tag{3.64}$$

if $(\alpha_2 - \alpha_1\gamma) \leq 0$ or $\gamma \geq \frac{\alpha_2}{\alpha_1}$, we have

$$F_{\gamma_{21}}(\gamma) = pr\left(X_2 \geq \frac{\gamma}{\bar{\gamma}_s(\alpha_2 - \alpha_1\gamma)}\right) \tag{3.65}$$
$$F_{\gamma_{21}}(\gamma) = 1 \tag{3.66}$$

Calculating $F_{\gamma_{22}}(\gamma)$ from (3.19) as follows :-

$$F_{\gamma_{22}}(\gamma) = pr\left(\bar{\gamma}_s\alpha_2 X_3 < \gamma\right) \tag{3.67}$$
$$F_{\gamma_{22}}(\gamma) = pr\left(X_3 < \frac{\gamma}{\bar{\gamma}_s\alpha_2}\right) \tag{3.68}$$
$$F_{\gamma_{22}}(\gamma) = F_{X_3}\left(\frac{\gamma}{\bar{\gamma}_s\alpha_2}\right) \tag{3.69}$$
$$F_{\gamma_{22}}(\gamma) = 1 - exp\left(-\beta_3\frac{\gamma}{\bar{\gamma}_s\alpha_2}\right)\sum_{n=0}^{m_3-1}\frac{\beta_3^n}{n!}\left(\frac{\gamma}{\bar{\gamma}_s\alpha_2}\right)^n \tag{3.70}$$

Substituting $F_{\gamma_{21}}(\gamma)$ in (3.64) and (3.66), $F_{\gamma_{22}}(\gamma)$ in (3.70) into (3.58), we can calculate $F_{\gamma_2}(\gamma)$ as

$$F_{\gamma_2}(\gamma) = F_{\gamma 21}(\gamma)F_{\gamma 22}(\gamma) \tag{3.71}$$

For the case $(\alpha_2 - \alpha_1\gamma) > 0$ or $\gamma < \frac{\alpha_2}{\alpha_1}$, we have

$$\begin{aligned} F_{\gamma_2}(\gamma) = 1 - exp\left(-\beta_2 \frac{\gamma}{\overline{\gamma}_s(\alpha_2 - \alpha_1\gamma)}\right) \sum_{l=0}^{m_2-1} \frac{\beta_2^l}{l!} \left(\frac{\gamma}{\overline{\gamma}_s(\alpha_2 - \alpha_1\gamma)}\right)^l - exp\left(-\beta_3 \frac{\gamma}{\overline{\gamma}_s\alpha_2}\right) \\ \times \sum_{n=0}^{m_3-1} \frac{\beta_3^n}{n!} \left(\frac{\gamma}{\overline{\gamma}_s\alpha_2}\right)^n + exp\left(\frac{-\beta_2\beta_3\gamma}{\overline{\gamma}_s}\left(\frac{1}{\alpha_2 - \alpha_1\gamma} + \frac{1}{\alpha_2}\right)\right) \\ \times \sum_{l=0}^{m_2-1} \sum_{n=0}^{m_3-1} \left(\frac{\beta_2^l \beta_3^n \gamma^{l+n}}{\overline{\gamma}_s^{l+n}}\right)\left(\frac{1}{(\alpha_2 - \alpha_1\gamma)^l (\alpha_2)^n l! n!}\right) \end{aligned} \tag{3.72}$$

For the case $(\alpha_2 - \alpha_1\gamma) \leq 0$ or $\gamma \geq \frac{\alpha_2}{\alpha_1}$, we have

$$F_{\gamma_2}(\gamma) = 1 - exp\left(-\beta_3 \frac{\gamma}{\overline{\gamma}_s\alpha_2}\right) \sum_{n=0}^{m_3-1} \frac{\beta_3^n}{n!} \left(\frac{\gamma}{\overline{\gamma}_s\alpha_2}\right)^n \tag{3.73}$$

3.6 CDF of γ_{1E}

From (3.23), we have

$$\gamma_{1E} = \frac{\alpha_2\overline{\gamma}_s X_4}{\alpha_1\overline{\gamma}_s X_4 + \alpha_2\overline{\gamma}_s X_6 + \overline{\gamma}_1 X_5 + 1} \tag{3.74}$$

Here, $\alpha_1\overline{\gamma}_s X_4 + \alpha_2\overline{\gamma}_s X_6 + \overline{\gamma}_1 X_5$ is much larger than 1.

So, (3.74) can be written as

$$\gamma_{1E} = \frac{\alpha_2\overline{\gamma}_s X_4}{\alpha_1\overline{\gamma}_s X_4 + \alpha_2\overline{\gamma}_s X_6 + \overline{\gamma}_1 X_5} \tag{3.75}$$

We calculate CDF of $F_{\gamma_{1E}}(\gamma)$ as :-

$$\begin{aligned} F_{\gamma_{1E}}(\gamma) = \int_0^\infty \int_0^\infty pr(\frac{\alpha_2\overline{\gamma}_s X_4}{\alpha_1\overline{\gamma}_s X_4 + \alpha_2\overline{\gamma}_s X_6 + \overline{\gamma}_1 X_5} < \gamma)_{|(X_5=x_5, X_6=x_6)} \\ \times f_{X_5}(X_5) f_{X_6}(X_6) dX_5 dX_6 \end{aligned} \tag{3.76}$$

$$F_{\gamma_{1E}}(\gamma) = \int_0^\infty \int_0^\infty pr(\frac{\alpha_2\overline{\gamma}_s X_4}{\alpha_1\overline{\gamma}_s X_4 + \alpha_2\overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5} < \gamma) \times f_{X_5}(x_5) f_{X_6}(x_6) dx_5 dx_6 \tag{3.77}$$

Here, $f_{x_5}(x_5)$, $f_{x_6}(x_6)$ are PDF of X_5 and X_6 and defined in (3.29).

$$pr(\frac{\alpha_2\overline{\gamma}_s X_4}{\alpha_1\overline{\gamma}_s X_4 + \alpha_2\overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5} < \gamma) = pr(\alpha_2\overline{\gamma}_s X_4 < \gamma(\alpha_1\overline{\gamma}_s X_4 + \alpha_1\overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5)) \tag{3.78}$$

$$pr(\frac{\alpha_2\overline{\gamma}_s X_4}{\alpha_2\overline{\gamma}_s X_4 + \alpha_1\overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5} < \gamma) = pr((\alpha_2 - \alpha_1\gamma) X_4 \overline{\gamma}_s < \gamma(\alpha_2\overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5)) \tag{3.79}$$

For the $(\alpha_2 - \alpha_1\gamma) > 0$ or $\gamma < \frac{\alpha_2}{\alpha_1}$, we have

$$pr(\frac{\alpha_2\overline{\gamma}_s X_4}{\alpha_1\overline{\gamma}_s X_4 + \alpha_2\overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5 + 1} < \gamma) = pr\left(X_4 < \frac{\gamma(\alpha_2\overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5)}{(\alpha_2 - \alpha_1\gamma)\overline{\gamma}_s}\right) \tag{3.80}$$

$$pr(\frac{\alpha_2\overline{\gamma}_s X_4}{\alpha_1\overline{\gamma}_s X_4 + \alpha_2\overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5 +} < \gamma) = F_{X_4}\left(\frac{\gamma(\alpha_2\overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5)}{(\alpha_2 - \alpha_1\gamma)\overline{\gamma}_s}\right) \tag{3.81}$$

$$F_{X_4}(\gamma) = 1 - exp\left(- \beta_4 \frac{\gamma(\alpha_2\overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5)}{(\alpha_2 - \alpha_1\gamma)\overline{\gamma}_s}\right) \sum_{q=0}^{m_4-1} \frac{\beta_4^q}{q!} \left(\frac{\gamma(\alpha_2\overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5)}{(\alpha_2 - \alpha_1\gamma)\overline{\gamma}_s}\right)^q \tag{3.82}$$

For the case $(\alpha_2 - \alpha_1\gamma) \leq 0$ or $\gamma \geq \frac{\alpha_2}{\alpha_1}$, we have

$$pr(\frac{\alpha_2\overline{\gamma}_s X_4}{\alpha_2\overline{\gamma}_s X_4 + \alpha_1\overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5 +} < \gamma) = pr(X_4 \geq \frac{\gamma(\alpha_2\overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5)}{(\alpha_2 - \alpha_1\gamma)\overline{\gamma}_s}) \tag{3.83}$$

$$pr(\frac{\alpha_2\overline{\gamma}_s X_4}{\alpha_1\overline{\gamma}_s X_4 + \alpha_2\overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5} < \gamma) = 1 \tag{3.84}$$

Calculating $F_{\gamma_{1E}}(\gamma)$ for the case $(\alpha_2 - \alpha_1\gamma) > 0$ or $\gamma < \frac{\alpha_2}{\alpha_1}$ with (3.82), we have

$$F_{\gamma_{1E}}(\gamma) = \int_0^\infty \int_0^\infty \left(1 - exp\left(-\beta_4 \frac{\gamma(\alpha_2\overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5)}{(\alpha_2 - \alpha_1\gamma)\overline{\gamma}_s}\right) \sum_{q=1}^{m_4-1} \frac{\beta_4^q}{q!} \left(\frac{\gamma(\alpha_2\overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5)}{(\alpha_2 - \alpha_1\gamma)\overline{\gamma}_s}\right)^q\right) \times f_{x_5}(x_5) f_{x_6}(x_6) dx_5 dx_6 \tag{3.85}$$

Modifying (3.85), we have

$$F_{\gamma_{1E}}(\gamma) = \int_0^\infty \int_0^\infty f_{x_5}(x_5) f_{x_6}(x_6) dx_5 dx_6 - \int_0^\infty \int_0^\infty exp\Bigg(- \beta_4 \frac{\gamma(\alpha_2 \overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5)}{(\alpha_2 - \alpha_1\gamma)\overline{\gamma}_s} \Bigg) \times \sum_{q=1}^{m_4-1} \frac{\beta_4^q}{q!} \Bigg(\frac{\gamma(\alpha_2 \overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5)}{(\alpha_2 - \alpha_1\gamma)\overline{\gamma}_s} \Bigg)^q \Bigg) f_{x_5}(x_5) f_{x_6}(x_6) dx_5 dx_6 \quad (3.86)$$

$$F_{\gamma_{1E}}(\gamma) = 1 - \int_0^\infty \int_0^\infty exp\Bigg(-\beta_4 \frac{\gamma(\alpha_2 \overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5)}{(\alpha_2 - \alpha_1\gamma)\overline{\gamma}_s} \Bigg) \sum_{q=1}^{m_4-1} \frac{\beta_4^q}{q!} \Bigg(\frac{\gamma(\alpha_2 \overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5)}{(\alpha_2 - \alpha_1\gamma)\overline{\gamma}_s} \Bigg)^q \Bigg) \times f_{x_5}(x_5) f_{x_6}(x_6) dx_5 dx_6 \quad (3.87)$$

$$F_{\gamma_{1E}}(\gamma) = 1 - \int_0^\infty \int_0^\infty exp\Bigg(-\beta_4 \frac{\gamma(\alpha_2 \overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5)}{(\alpha_2 - \alpha_1\gamma)\overline{\gamma}_s} \Bigg) \sum_{q=1}^{m_4-1} \frac{\beta_4^q}{q!} \Bigg(\frac{\gamma(\alpha_2 \overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5)}{(\alpha_2 - \alpha_1\gamma)\overline{\gamma}_s} \Bigg)^q \Bigg) \times \frac{\beta_5^{m_5}}{\Gamma m_6} x_5^{m_5-1} exp(-\beta_5 x_5) \frac{\beta_6^{m_6}}{\Gamma m_6} x_6^{m_6-1} exp(-\beta_6 x_6) dx_5 dx_6 \quad (3.88)$$

Simplifying (3.88) using binomial theorem, we can rewrite $F_{\gamma_{1E}}(\gamma)$

$$F_{\gamma_{1E}}(\gamma) = 1 - \int_0^\infty \int_0^\infty exp\Bigg(- (\frac{\beta_4 \gamma \alpha_2}{\alpha_2 - \alpha_1\gamma} + \beta_6) x_6 \Bigg) exp\Bigg(- (\frac{\beta_4 \overline{\gamma}_1 \gamma}{(\alpha_2 - \alpha_1\gamma)\overline{\gamma}_s} + \beta_5) x_5 \Bigg) \times \frac{\beta_5^{m_5}}{\Gamma m_6} x_5^{m_5-1} \frac{\beta_6^{m_6}}{\Gamma m_6} x_6^{m_6-1} \sum_{q=1}^{m_4-1} \frac{\beta_4^q}{q!} \Bigg(\frac{\gamma \alpha_2 x_6}{\alpha_2 - \alpha_1\gamma} + \frac{\overline{\gamma}_1 \gamma x_5}{(\alpha_2 - \alpha_1\gamma)\overline{\gamma}_s} \Bigg)^q dx_5 dx_6 \quad (3.89)$$

$$F_{\gamma_{1E}}(\gamma) = 1 - \frac{\beta_5^{m_5}}{\Gamma m_5} \frac{\beta_6^{m_6}}{\Gamma m_6} \int_0^\infty \int_0^\infty exp\Bigg(-(\frac{\beta_4 \gamma \alpha_2}{\alpha_2 - \alpha_1\gamma} + \beta_6) x_6 \Bigg) exp\Bigg(-(\frac{\beta_4 \overline{\gamma}_1 \gamma}{(\alpha_2 - \alpha_1\gamma)\overline{\gamma}_s} + \beta_5) x_5 \Bigg) \times x_5^{m_5-1} x_6^{m_6-1} \sum_{q=1}^{m_4-1} \frac{\beta_4^q}{q!} \Bigg(\sum_{a=0}^{q} \frac{q!}{a!(q-a)!} (\frac{\overline{\gamma}_1 \gamma x_5}{(\alpha_2 - \alpha_1\gamma)\overline{\gamma}_s})^a (\frac{\gamma \alpha_2 x_6}{\alpha_2 - \alpha_1\gamma})^{q-a} \Bigg) dx_5 dx_6 \quad (3.90)$$

$$F_{\gamma_{1E}}(\gamma) = 1 - \frac{\beta_5^{m_5}}{\Gamma m_5} \frac{\beta_6^{m_6}}{\Gamma m_6} \sum_{q=0}^{m_4-1} \sum_{q=0}^{q} \frac{q!}{a!(q-a)!} \frac{\beta_4^q \gamma^q}{q!} \Bigg(\frac{\overline{\gamma}_1}{(\alpha_2 - \alpha_1\gamma)\overline{\gamma}_s} \Bigg)^a \Bigg(\frac{\alpha_2}{\alpha_2 - \alpha_1\gamma} \Bigg)^{q-a} \times \int_0^\infty exp\Bigg(- (\frac{\beta_4 \overline{\gamma}_1 \gamma}{(\alpha_2 - \alpha_1\gamma)\overline{\gamma}_s} + \beta_5) x_5 \Bigg) x_5^{(a+m_5-1)} dx_5 \times \int_0^\infty exp\Bigg(- (\frac{\beta_4 \gamma \alpha_2}{\alpha_2 - \alpha_1\gamma} + \beta_6) x_6 \Bigg) x_6^{(q-a+m_6-1)} dx_6 \quad (3.91)$$

$$F_{\gamma_{1E}}(\gamma) = 1 - \frac{\beta_5^{m_5}}{\Gamma m_5}\frac{\beta_6^{m_6}}{\Gamma m_6}\sum_{q=0}^{m_4-1}\sum_{c=0}^{r}\frac{q!}{a!(q-a)!}\frac{\beta_4^q\gamma^q}{q!}\left(\frac{\overline{\gamma}_1}{(\alpha_2-\alpha_1\gamma)\overline{\gamma}_s}\right)^a\left(\frac{\alpha_2}{\alpha_2-\alpha_1\gamma}\right)^{q-a}$$
$$\times \frac{\Gamma(a+m_5)}{(\frac{\beta_4\overline{\gamma}_1\gamma}{(\alpha_2-\alpha_1\gamma)\overline{\gamma}_s}+\beta_5)(a+m_5)}\frac{\Gamma(q-a+m_6)}{(\frac{\beta_4\gamma\alpha_2}{\alpha_1-\alpha_2\gamma}+\beta_6)(q-a+m_6)} \tag{3.92}$$

3.7 CDF of γ_{2E}

From (3.27), we have

$$\gamma_{2E} = \frac{\alpha_1\overline{\gamma}_s X_4}{\overline{\gamma}_1 X_5 + \alpha_2\overline{\gamma}_s X_6 + 1} \tag{3.93}$$

Here, $(\overline{\gamma}_1 X_5 + \alpha_2\overline{\gamma}_s X_6)$ is much larger than 1.

So, (3.93) can be written as

$$\gamma_{2E} = \frac{\alpha_1\overline{\gamma}_s X_4}{\overline{\gamma}_1 X_5 + \alpha_2\overline{\gamma}_s X_6} \tag{3.94}$$

$$F_{\gamma_{2E}}(\gamma) = \int_0^\infty\int_0^\infty pr(\frac{\alpha_1\overline{\gamma}_s X_4}{\overline{\gamma}_1 X_5 + \alpha_2\overline{\gamma}_s X_6} < \gamma)_{|(X_5=x_5,X_6=x_6)} f_{X_5}(X_5) f_{X_6}(X_6) dX_5 dX_6 \tag{3.95}$$

$$F_{\gamma_{2E}}(\gamma) = \int_0^\infty\int_0^\infty pr(\frac{\alpha_1\overline{\gamma}_s X_4}{\overline{\gamma}_1 x_5 + \alpha_2\overline{\gamma}_s x_6} < \gamma) f_{x_5}(x_5) f_{x_6}(x_6) dx_5 dx_6 \tag{3.96}$$

Here, $f_{x_5}(x_5)$, $f_{x_6}(x_6)$ are PDF of x_5 and x_6

$$pr\left(\frac{\alpha_1\overline{\gamma}_s X_4}{\overline{\gamma}_1 x_5 + \alpha_2\overline{\gamma}_s x_6} < \gamma\right) = pr\left(\alpha_1\overline{\gamma}_s X_4 < \gamma(\alpha_2\overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5)\right) \tag{3.97}$$

$$pr\left(\frac{\alpha_1\overline{\gamma}_s X_4}{\overline{\gamma}_1 x_5 + \alpha_2\overline{\gamma}_s x_6} < \gamma\right) = pr\left(X_4 \le \frac{\gamma(\alpha_2\overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5)}{\alpha_1\overline{\gamma}_s}\right) \tag{3.98}$$

$$pr\left(\frac{\alpha_1\overline{\gamma}_s X_4}{\overline{\gamma}_1 x_5 + \alpha_2\overline{\gamma}_s x_6} \le \gamma\right) = F_{X_4}\left(\frac{\gamma(\alpha_2\overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5)}{\alpha_1\overline{\gamma}_s}\right) \tag{3.99}$$

$$F_{X_4}\left(\frac{\gamma(\alpha_2\overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5)}{\alpha_1\overline{\gamma}_s}\right) = 1 - exp\left(-\beta_4\frac{\gamma(\alpha_2\overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5)}{\alpha_1\overline{\gamma}_s}\right)$$
$$\times\sum_{q=1}^{m_4-1}\frac{\beta_4^q}{q!}\left(\frac{\gamma(\alpha_2\overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5)}{\alpha_1\overline{\gamma}_s}\right)^q \tag{3.100}$$

$$F_{\gamma_{2E}}(\gamma) = \int_0^\infty \int_0^\infty f_{x_5}(x_5) f_{x_6}(x_6) dx_5 dx_6 - \int_0^\infty \int_0^\infty exp\bigg(- \beta_4 \frac{\gamma(\alpha_2 \overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5)}{\alpha_1 \overline{\gamma}_s}\bigg) \times \sum_{r=1}^{m_4-1} \frac{\beta_4^r}{r!} \Bigg(\frac{\gamma(\alpha_2 \overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5)}{\alpha_1 \overline{\gamma}_s} \Bigg)^r f_{x_5}(x_5) f_{x_6}(x_6) dx_5 dx_6 \tag{3.101}$$

Calculating $F_{\gamma_{2E}}(\gamma)$ with (3.100) :-

$$F_{\gamma_{2E}}(\gamma) = 1 - \int_0^\infty \int_0^\infty exp\bigg(- \beta_4 \frac{\gamma(\alpha_2 \overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5)}{\alpha_1 \overline{\gamma}_s}\bigg) \sum_{r=1}^{m_4-1} \frac{\beta_4^r}{r!} \Bigg(\frac{\gamma(\alpha_2 \overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5)}{\alpha_1 \overline{\gamma}_s} \Bigg)^r \times \frac{\beta_5^{m_5}}{\Gamma m_6} x_5^{m_5-1} exp(-\beta_5 x_5) \frac{\beta_6^{m_6}}{\Gamma m_6} x_6^{m_6-1} exp(-\beta_6 x_6) dx_5 dx_6 dx_5 dx_6 \tag{3.102}$$

$$F_{\gamma_{2E}}(\gamma) = 1 - \int_0^\infty \int_0^\infty exp\bigg(- \beta_4 \frac{\gamma(\alpha_2 \overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5)}{\alpha_1 \overline{\gamma}_s}\bigg) exp(-\beta_5 x_5) exp(-\beta_6 x_6) \times \frac{\beta_5^{m_5}}{\Gamma m_6} x_5^{m_5-1} \frac{\beta_6^{m_6}}{\Gamma m_6} x_6^{m_6-1} \sum_{r=1}^{m_4-1} \frac{\beta_4^r}{r!} \Bigg(\frac{\gamma(\alpha_2 \overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5)}{\alpha_1 \overline{\gamma}_s} \Bigg)^r dx_5 dx_6 dx_5 dx_6 \tag{3.103}$$

$$F_{\gamma_{2E}}(\gamma) = 1 - \int_0^\infty \int_0^\infty exp\bigg(- (\beta_4 \gamma + \beta_6) x_6 \bigg) exp\bigg(- (\frac{\beta_4 \overline{\gamma}_1 \gamma}{\alpha_1 \overline{\gamma}_s} + \beta_5) x_5 \bigg) \times \frac{\beta_5^{m_5}}{\Gamma m_6} x_5^{m_5-1} \frac{\beta_6^{m_6}}{\Gamma m_6} x_6^{m_6-1} \sum_{r=1}^{m_4-1} \frac{\beta_4^r}{r!} \Bigg(\frac{\gamma(\alpha_2 \overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5)}{\alpha_1 \overline{\gamma}_s} \Bigg)^r dx_5 dx_6 \tag{3.104}$$

Simplifying (3.104) using binomial theorem, we can rewrite $F_{\gamma_{2E}}(\gamma)$

Here,

$$\Bigg(\frac{\gamma(\alpha_2 \overline{\gamma}_s x_6 + \overline{\gamma}_1 x_5)}{\alpha_1 \overline{\gamma}_s} \Bigg)^r = \sum_{c=0}^{r} \frac{r!}{c!(r-c)!} (\frac{\gamma \overline{\gamma}_1 x_5}{\alpha_1 \overline{\gamma}_s})^c (\gamma x_6)^{r-c} \tag{3.105}$$

After simplifying the equation (3.101) [1]

$$F_{\gamma_{2E}}(\gamma) = 1 - \frac{\beta_5^{m_5}}{\Gamma m_5}\frac{\beta_6^{m_6}}{\Gamma m_6}\int_0^{\infty}\int_0^{\infty} exp\Big(-(\beta_4\gamma+\beta_6)x_6\Big)exp\Big(-(\frac{\beta_4\overline{\gamma}_1\gamma}{\alpha_1\overline{\gamma}_s}+\beta_5)x_5\Big) \times x_5^{m_5-1}x_6^{m_6-1}\sum_{r=1}^{m_4-1}\frac{\beta_4^r}{r!}\Bigg(\sum_{c=0}^{r}\frac{r!}{c!(r-c)!}(\frac{\gamma\overline{\gamma}_1 x_5}{\alpha_1\overline{\gamma}_s})^c(\gamma x_6)^{r-c}\Bigg)dx_5dx_6 \tag{3.106}$$

$$F_{\gamma_{2E}}(\gamma) = 1 - \frac{\beta_5^{m_5}}{\Gamma m_5}\frac{\beta_6^{m_6}}{\Gamma m_6}\sum_{r=0}^{m_4-1}\sum_{c=0}^{r}\frac{r!}{c!(r-c)!}\frac{\beta_4^r\gamma^r}{r!}\Bigg(\frac{\overline{\gamma}_1}{\alpha_1\overline{\gamma}_s}\Bigg)^c\int_0^{\infty} exp\Big(-(\frac{\beta_4\overline{\gamma}_1\gamma}{\alpha_1\overline{\gamma}_s}+\beta_5)x_5\Big) \times x_5^{(c+m_5-1)}dx_5\int_0^{\infty} exp\Big(-(\beta_4\gamma+\beta_6)x_6\Big)x_6^{(r-c+m_6-1)}dx_6 \tag{3.107}$$

$$F_{\gamma_{2E}}(\gamma) = 1 - \frac{\beta_5^{m_5}}{\Gamma m_5}\frac{\beta_6^{m_6}}{\Gamma m_6}\sum_{r=0}^{m_4-1}\sum_{c=0}^{r}\frac{r!}{c!(r-c)!}\frac{\beta_4^r\gamma^r}{r!}\Bigg(\frac{\overline{\gamma}_1}{\alpha_1\overline{\gamma}_s}\Bigg)^c\frac{\Gamma(c+m_5)}{(\frac{\beta_4\overline{\gamma}_1\gamma}{\alpha_1\overline{\gamma}_s}+\beta_5)(c+m_5)} \times \frac{\Gamma(r-c+m_6)}{(\beta_4\gamma+\beta_6)(r-c+m_6)} \tag{3.108}$$

3.8 Outage Probability

Here, we are finding the outage probabilities for UE_1 and UE_2. If both UE_1 and UE_2 meet the decoding criteria to decode their respective signals transmitted from S, then no outage occurs. UE_1's decoding threshold level is represented with $\gamma_{th,1}$, and UE_2's decoding threshold level is represented with $\gamma_{th,2}$. If the SINR is larger than or equal to the decoding threshold level $\gamma_{th,1}$ and $\gamma_{th,2}$, UE_1 and UE_2 will be able to decode their signals $x_1$and x_2.

The Outage Probability of UE_1

$$P_{O1} = F_{\gamma_1}(\gamma_{th,1}) \tag{3.109}$$

The Outage Probability of UE_2

$$P_{O2} = F_{\gamma_2}(\gamma_{th,2}) \tag{3.110}$$

The outage probability of the NOMA system can be written as

$$P_O = P_{O1}P_{O2} \tag{3.111}$$

3.9 Channel Capacity of UE$_1$

According to Shannon's theory [34], the channel capacity C_{UE_1} is calculated as

$$C_{UE_1} = \int_{\gamma_{th,1}}^{\infty} \log_2(1+\gamma) f_{\gamma_1}(\gamma) d\gamma \tag{3.112}$$

Here, in the system γ of UE$_1$ is always lesser than (α_2/α_1) and the Threshold level of UE$_1$ is $\gamma_{th,1}$.

$$C_{UE_1} = \int_{\gamma_{th,1}}^{\frac{\alpha_2}{\alpha_1}} \log_2(1+\gamma) f_{\gamma_1}(\gamma) d\gamma \tag{3.113}$$

Applying integration by parts to solve (3.113), the channel capacity of UE$_1$ can be calculated as

$$C_{UE_1} = \left[\frac{\ln(1+\gamma)F_{\gamma_1}(\gamma)}{\ln(2)}\right]_{\gamma_{th,1}}^{\frac{\alpha_2}{\alpha_1}} - \frac{1}{\ln(2)} \int_{\gamma_{th,1}}^{\frac{\alpha_2}{\alpha_1}} \frac{F_{\gamma_1}(\gamma)}{1+\gamma} \tag{3.114}$$

Substituting the upper and lower limits to (3.114), we have

$$C_{UE_1} = \left[\frac{\ln(1+\frac{\alpha_2}{\alpha_1})F_{\gamma_1}(\frac{\alpha_2}{\alpha_1}) - \ln(1+\gamma_{th,1})F_{\gamma_1}(\gamma_{th,1})}{\ln(2)}\right] - \frac{1}{\ln(2)} \int_{\gamma_{th,1}}^{\frac{\alpha_2}{\alpha_1}} \frac{F_{\gamma_1}(\gamma)}{1+\gamma} \tag{3.115}$$

Substituting (3.51) and (3.54) in (3.115), we have

$$\begin{aligned} C_{UE_1} =& \frac{1}{\ln(2)}\Bigg[\ln(1+\frac{\alpha_2}{\alpha_1}) - \ln(1+\gamma_{th,1})[1 - exp\left(\frac{-\beta_1\gamma}{\overline{\gamma}_s}\left(\frac{1}{\alpha_2-\alpha_1\gamma} + \frac{1}{\alpha_1}\right)\right) \\ &\times \sum_{j=0}^{m_1-1}\sum_{k=0}^{m_1-1}\left(\frac{\beta_1\gamma}{\overline{\gamma}_s}\right)^{j+k}\left(\frac{1}{(\alpha_2-\alpha_1\gamma)^j(\alpha_1)^k j!k!}\right)]\Bigg] - \frac{1}{\ln(2)} \\ &\times \int_{\gamma_{th,1}}^{\frac{\alpha_2}{\alpha_1}} \frac{\left[1 - exp\left(\frac{-\beta_1\gamma}{\overline{\gamma}_s}\left(\frac{1}{\alpha_2-\alpha_1\gamma} + \frac{1}{\alpha_1}\right)\right)\sum_{j=0}^{m_1-1}\sum_{k=0}^{m_1-1}\left(\frac{\beta_1\gamma}{\overline{\gamma}_s}\right)^{j+k}\left(\frac{1}{(\alpha_2-\alpha_1\gamma)^j(\alpha_1)^k j!k!}\right)\right]}{1+\gamma} d\gamma \end{aligned} \tag{3.116}$$

After solving (3.116), we have

$$C_{UE_1} = \frac{1}{\ln(2)} \Bigg[\ln(1+\frac{\alpha_2}{\alpha_1}) - \ln(1+\gamma_{cth,1})[1 - exp\Bigg(\frac{-\beta_1\gamma}{\overline{\gamma}_s}\Bigg(\frac{1}{\alpha_2-\alpha_1\gamma}+\frac{1}{\alpha_1}\Bigg)\Bigg)$$
$$\times \sum_{j=0}^{m_1-1}\sum_{k=0}^{m_1-1}\left(\frac{\beta_1\gamma}{\overline{\gamma}_s}\right)^{j+k}\left(\frac{1}{(\alpha_2-\alpha_1\gamma)^j(\alpha_1)^k j!k!}\right)]\Bigg] - \frac{1}{\ln(2)}\int_{\gamma_{cu,1}}^{\frac{\alpha_2}{\alpha_1}}\frac{1}{1+\gamma}d\gamma + \frac{1}{\ln(2)}$$
$$\times \int_{\gamma_{th,1}}^{\frac{\alpha_2}{\alpha_1}} \frac{\Bigg[exp\Bigg(\frac{-\beta_1\gamma}{\overline{\gamma}_s}\Bigg(\frac{1}{\alpha_2-\alpha_1\gamma}+\frac{1}{\alpha_1}\Bigg)\Bigg)\sum_{j=0}^{m_1-1}\sum_{k=0}^{m_1-1}\left(\frac{\beta_1\gamma}{\overline{\gamma}_s}\right)^{j+k}\left(\frac{1}{(\alpha_2-\alpha_1\gamma)^j(\alpha_1)^k j!k!}\right)\Bigg]}{1+\gamma}d\gamma \tag{3.117}$$

$$C_{UE_1} = \frac{1}{\ln(2)} \Bigg[\ln(1+\frac{\alpha_2}{\alpha_1}) - \ln(1+\gamma_{th,1})[1 - exp\Bigg(\frac{-\beta_1\gamma}{\overline{\gamma}_s}\Bigg(\frac{1}{\alpha_2-\alpha_1\gamma}+\frac{1}{\alpha_1}\Bigg)\Bigg)$$
$$\times \sum_{j=0}^{m_1-1}\sum_{k=0}^{m_1-1}\left(\frac{\beta_1\gamma}{\overline{\gamma}_s}\right)^{j+k}\left(\frac{1}{(\alpha_2-\alpha_1\gamma)^j(\alpha_1)^k j!k!}\right)]\Bigg]$$
$$- \frac{1}{\ln(2)}|\ln(1+\gamma_{cu,1}) - \ln(1+\frac{\alpha_2}{\alpha_1}) + \Delta_1| \tag{3.118}$$

Where Δ_1 is defined as

$$\Delta_1 = \int_{\gamma_{th,1}}^{\frac{\alpha_2}{\alpha_1}} \frac{\Bigg[exp\Bigg(\frac{-\beta_1\gamma}{\overline{\gamma}_s}\Bigg(\frac{1}{\alpha_2-\alpha_1\gamma}+\frac{1}{\alpha_1}\Bigg)\Bigg)\sum_{j=0}^{m_1-1}\sum_{k=0}^{m_1-1}\left(\frac{\beta_1\gamma}{\overline{\gamma}_s}\right)^{j+k}\left(\frac{1}{(\alpha_2-\alpha_1\gamma)^j(\alpha_1)^k j!k!}\right)\Bigg]}{1+\gamma}d\gamma \tag{3.119}$$

3.10 Channel Capacity of UE_2

The Threshold level of UE_2 is $\gamma_{th,2}$. According to Shannon's theory [34], the channel capacity C_{UE_2} is calculated as

$$C_{UE_2} = \int_{\gamma_{th,2}}^{\infty} \log_2(1+\gamma) f_{\gamma_2}(\gamma) d\gamma \tag{3.120}$$

$$C_{UE_2} = \int_{\gamma_{th,2}}^{\frac{\alpha_2}{\alpha_1}} \log_2(1+\gamma) f_{\gamma_2}(\gamma) d\gamma \tag{3.121}$$

$$C_{UE_2} = \left[\frac{\ln(1+\gamma)F_{\gamma_2}(\gamma)}{\ln(2)}\right]_{\gamma_{th,2}}^{\frac{\alpha_2}{\alpha_1}} - \frac{1}{\ln(2)}\int_{\gamma_{th,2}}^{\frac{\alpha_2}{\alpha_1}} \frac{F_{\gamma_2}(\gamma)}{1+\gamma} \tag{3.122}$$

After applying integration by parts and substituting upper and lower limits to (3.121)

$$C_{UE_2} = \left[\frac{\ln(1+\frac{\alpha_2}{\alpha_1})F_{\gamma_2}(\frac{\alpha_2}{\alpha_1}) - \ln(1+\gamma_{th,2})F_{\gamma_2}(\gamma_{th,2})}{\ln(2)}\right] - \frac{1}{\ln(2)}\int_{\gamma_{th,3}}^{\frac{\alpha_2}{\alpha_1}} \frac{F_{\gamma_2}(\gamma)}{1+\gamma} \tag{3.123}$$

Substituting (3.72) and (3.73) in (3.123), we have

$$\begin{aligned}C_{UE_2} =& \frac{1}{\ln(2)}\Bigg[\Bigg[\ln(1+\frac{\alpha_2}{\alpha_1})1 - exp\left(-\beta_3\frac{\gamma}{\bar{\gamma}_s\alpha_2}\right)\sum_{n=0}^{m_3-1}\frac{\beta_3^n}{n!}\left(\frac{\gamma}{\bar{\gamma}_s\alpha_2}\right)^n)\Bigg] - \Bigg[\ln(1+\gamma_{th,2})(1\\
&- exp\left(-\beta_2\frac{\gamma}{\bar{\gamma}_s(\alpha_2-\alpha_1\gamma)}\right)\sum_{l=0}^{m_2-1}\frac{\beta_2^l}{l!}\left(\frac{\gamma}{\bar{\gamma}_s(\alpha_2-\alpha_1\gamma)}\right)^l - exp\left(-\beta_3\frac{\gamma}{\bar{\gamma}_s\alpha_2}\right)\\
&\times\sum_{n=0}^{m_3-1}\frac{\beta_3^n}{n!}\left(\frac{\gamma}{\bar{\gamma}_s\alpha_2}\right)^n + exp\left(\frac{-\beta_2\beta_3\gamma}{\bar{\gamma}_s}\left(\frac{1}{\alpha_2-\alpha_1\gamma}+\frac{1}{\alpha_2}\right)\right)\sum_{l=0}^{m_2-1}\sum_{n=0}^{m_3-1}\left(\frac{\beta_2^l\beta_3^n\gamma^{l+n}}{\bar{\gamma}_s^{l+n}}\right)\\
&\times\left(\frac{1}{(\alpha_2-\alpha_1\gamma)^l(\alpha_2)^n l!n!}\right))\Bigg]\Bigg] - \frac{1}{\ln(2)}\int_{\gamma_{th,2}}^{\frac{\alpha_2}{\alpha_1}}\frac{1}{1+\gamma}\Bigg[1 - exp\left(-\beta_2\frac{\gamma}{\bar{\gamma}_s(\alpha_2-\alpha_1\gamma)}\right)\\
&\times\sum_{l=0}^{m_2-1}\frac{\beta_2^l}{l!}\left(\frac{\gamma}{\bar{\gamma}_s(\alpha_2-\alpha_1\gamma)}\right)^l - exp\left(-\beta_3\frac{\gamma}{\bar{\gamma}_s\alpha_2}\right)\sum_{n=0}^{m_3-1}\frac{\beta_3^n}{n!}\left(\frac{\gamma}{\bar{\gamma}_s\alpha_2}\right)^n\\
&+ exp\left(\frac{-\beta_2\beta_3\gamma}{\bar{\gamma}_s}\left(\frac{1}{\alpha_2-\alpha_1\gamma}+\frac{1}{\alpha_2}\right)\right)\sum_{l=0}^{m_2-1}\sum_{n=0}^{m_3-1}\left(\frac{\beta_2^l\beta_3^n\gamma^{l+n}}{\bar{\gamma}_s^{l+n}}\right)\left(\frac{1}{(\alpha_2-\alpha_1\gamma)^l(\alpha_2)^n l!n!}\right)\Bigg]d\gamma\end{aligned} \tag{3.124}$$

$$\begin{aligned}C_{UE_2} =& \frac{1}{\ln(2)}\Bigg[\Bigg[\ln(1+\frac{\alpha_2}{\alpha_1})(1 - exp\left(-\beta_3\frac{\gamma}{\bar{\gamma}_s\alpha_2}\right)\sum_{n=0}^{m_3-1}\frac{\beta_3^n}{n!}\left(\frac{\gamma}{\bar{\gamma}_s\alpha_2}\right)^n)\Bigg] - \Bigg[\ln(1+\gamma_{th,2})(1\\
&- exp\left(-\beta_2\frac{\gamma}{\bar{\gamma}_s(\alpha_2-\alpha_1\gamma)}\right)\sum_{l=0}^{m_2-1}\frac{\beta_2^l}{l!}\left(\frac{\gamma}{\bar{\gamma}_s(\alpha_2-\alpha_1\gamma)}\right)^l - exp\left(-\beta_3\frac{\gamma}{\bar{\gamma}_s\alpha_2}\right)\\
&\times\sum_{n=0}^{m_3-1}\frac{\beta_3^n}{n!}\left(\frac{\gamma}{\bar{\gamma}_s\alpha_2}\right)^n + exp\left(\frac{-\beta_2\beta_3\gamma}{\bar{\gamma}_s}\left(\frac{1}{\alpha_2-\alpha_1\gamma}+\frac{1}{\alpha_2}\right)\right)\\
&\times\sum_{l=0}^{m_2-1}\sum_{n=0}^{m_3-1}\left(\frac{\beta_2^l\beta_3^n\gamma^{l+n}}{\bar{\gamma}_s^{l+n}}\right)\left(\frac{1}{(\alpha_2-\alpha_1\gamma)^l(\alpha_2)^n l!n!}\right))\Bigg]\Bigg] - \frac{1}{\ln(2)}\int_{\gamma_{th,2}}^{\frac{\alpha_2}{\alpha_1}}\frac{1}{1+\gamma}\Bigg[1\\
&- exp\left(-\beta_2\frac{\gamma}{\bar{\gamma}_s(\alpha_2-\alpha_1\gamma)}\right)\sum_{l=0}^{m_2-1}\frac{\beta_2^l}{l!}\left(\frac{\gamma}{\bar{\gamma}_s(\alpha_2-\alpha_1\gamma)}\right)^l - exp\left(-\beta_3\frac{\gamma}{\bar{\gamma}_s\alpha_2}\right)\\
&\times\sum_{n=0}^{m_3-1}\frac{\beta_3^n}{n!}\left(\frac{\gamma}{\bar{\gamma}_s\alpha_2}\right)^n + exp\left(\frac{-\beta_2\beta_3\gamma}{\bar{\gamma}_s}\left(\frac{1}{\alpha_2-\alpha_1\gamma}+\frac{1}{\alpha_2}\right)\right)\\
&\times\sum_{l=0}^{m_2-1}\sum_{n=0}^{m_3-1}\left(\frac{\beta_2^l\beta_3^n\gamma^{l+n}}{\bar{\gamma}_s^{l+n}}\right)\left(\frac{1}{(\alpha_2-\alpha_1\gamma)^l(\alpha_2)^n l!n!}\right)\Bigg]d\gamma\end{aligned} \tag{3.125}$$

$$C_{UE_2} = \frac{1}{\ln(2)} \Bigg[\Bigg[\ln(1+\frac{\alpha_2}{\alpha_1})(1 - exp\left(-\beta_3 \frac{\gamma}{\bar{\gamma}_s \alpha_2}\right) \sum_{n=0}^{m_3-1} \frac{\beta_3^n}{n!} \left(\frac{\gamma}{\bar{\gamma}_s \alpha_2}\right)^n) \Bigg] - \Bigg[\ln(1+\gamma_{th,2})(1 - exp\left(-\beta_2 \frac{\gamma}{\bar{\gamma}_s(\alpha_2 - \alpha_1\gamma)}\right) \sum_{l=0}^{m_2-1} \frac{\beta_2^l}{l!} \left(\frac{\gamma}{\bar{\gamma}_s(\alpha_2-\alpha_1\gamma)}\right)^l - exp\left(-\beta_3 \frac{\gamma}{\bar{\gamma}_s\alpha_2}\right) \times \sum_{n=0}^{m_3-1} \frac{\beta_3^n}{n!} \left(\frac{\gamma}{\bar{\gamma}_s\alpha_2}\right)^n + exp\left(\frac{-\beta_2\beta_3\gamma}{\bar{\gamma}_s}\left(\frac{1}{\alpha_2-\alpha_1\gamma} + \frac{1}{\alpha_2}\right)\right) \sum_{l=0}^{m_2-1}\sum_{n=0}^{m_3-1} \left(\frac{\beta_2^l\beta_3^n\gamma^{l+n}}{\bar{\gamma}_s^{l+n}}\right) \times \left(\frac{1}{(\alpha_2-\alpha_1\gamma)^l(\alpha_2)^n l!n!}\right)) \Bigg] \Bigg] - \frac{1}{\ln(2)} |\ln(1+\gamma_{th,2}) - \ln(1+\frac{\alpha_2}{\alpha_1}) + \Delta_2| \tag{3.126}$$

Where Δ_2 is defined as

$$\Delta_2 = \int_{\gamma_{th,2}}^{\frac{\alpha_2}{\alpha_1}} \Bigg[\left(\frac{1}{1+\gamma}\right) \Bigg(exp\left(-\beta_2 \frac{\gamma}{\bar{\gamma}_s(\alpha_2-\alpha_1\gamma)}\right) \sum_{l=0}^{m_2-1} \frac{\beta_2^l}{l!} \left(\frac{\gamma}{\bar{\gamma}_s(\alpha_2-\alpha_1\gamma)}\right)^l - exp\left(-\beta_3\frac{\gamma}{\bar{\gamma}_s\alpha_2}\right) \times \sum_{n=0}^{m_3-1} \frac{\beta_3^n}{n!}\left(\frac{\gamma}{\bar{\gamma}_s\alpha_2}\right)^n + exp\left(\frac{-\beta_2\beta_3\gamma}{\bar{\gamma}_s}\left(\frac{1}{\alpha_2-\alpha_1\gamma}+\frac{1}{\alpha_2}\right)\right) \times \sum_{l=0}^{m_2-1}\sum_{n=0}^{m_3-1}\left(\frac{\beta_2^l\beta_3^n\gamma^{l+n}}{\bar{\gamma}_s^{l+n}}\right)\left(\frac{1}{(\alpha_2-\alpha_1\gamma)^l(\alpha_2)^n l!n!}\right)\Bigg)\Bigg] d\gamma \tag{3.127}$$

3.11 Channel Capacity of UE$_{1E}$

According to Shannon's theory [34], the channel capacity $C_{UE_{1E}}$ is calculated as

$$C_{1E} = \int_{\gamma_{th,3}}^{\infty} \log_2(1+\gamma) f_{\gamma_{1E}}(\gamma) d\gamma \tag{3.128}$$

Here, in the system γ of UE$_1$ is always lesser than (α_2/α_1) and the Threshold level of the eavesdropper is $\gamma_{th,3}$

$$C_{1E} = \int_{\gamma_{th,3}}^{\frac{\alpha_2}{\alpha_1}} \log_2(1+\gamma) f_{\gamma_{1E}}(\gamma) d\gamma \tag{3.129}$$

Applying integration by parts to solve (3.129), the channel capacity of UE$_{1E}$ can be calculated as

$$C_{1E} = \left[\frac{\ln(1+\gamma)F_{\gamma_{1E}}(\gamma)}{\ln(2)}\right]_{\gamma_{th,3}}^{\frac{\alpha_2}{\alpha_1}} - \frac{1}{\ln(2)} \int_{\gamma_{th,3}}^{\frac{\alpha_2}{\alpha_1}} \frac{F_{\gamma_{1E}}(\gamma)}{1+\gamma} \tag{3.130}$$

Substituting the upper and lower limits to (3.130), we have

$$C_{1E} = \left[\frac{\ln(1+\frac{\alpha_2}{\alpha_1})F_{\gamma_{1E}}(\frac{\alpha_2}{\alpha_1}) - \ln(1+\gamma_{th,3})F_{\gamma_{1E}}(\gamma_{cu,3})}{\ln(2)}\right] - \frac{1}{\ln(2)}\int_{\gamma_{th,3}}^{\frac{\alpha_2}{\alpha_1}} \frac{F_{\gamma_{1E}}(\gamma)}{1+\gamma} \quad (3.131)$$

Substituting (3.84) and (3.92) in (3.131), we have

$$\begin{aligned} C_{1E} =& \frac{1}{\ln(2)}\Bigg[\ln(1+\frac{\alpha_2}{\alpha_1}) - \ln(1+\gamma_{th,3})[1 - \frac{\beta_5^{m_5}}{\Gamma m_5}\frac{\beta_6^{m_6}}{\Gamma m_6}\sum_{q=0}^{m_4-1}\sum_{c=0}^{r}\frac{q!}{a!(q-a)!}\frac{\beta_4^q\gamma^q}{q!}\left(\frac{\overline{\gamma}_1}{(\alpha_2-\alpha_1\gamma)\overline{\gamma}_s}\right)^a \\ &\times \left(\frac{\alpha_2}{\alpha_2-\alpha_1\gamma}\right)^{q-a}\frac{\Gamma(a+m_5)}{(\frac{\beta_4\overline{\gamma}_1\gamma}{(\alpha_2-\alpha_1\gamma)\overline{\gamma}_s}+\beta_5)(a+m_5)}\frac{\Gamma(q-a+m_6)}{(\frac{\beta_4\gamma\alpha_2}{\alpha_2-\alpha_1\gamma}+\beta_6)(q-a+m_6)}] - \frac{1}{\ln(2)}\int_{\gamma_{th,3}}^{\frac{\alpha_2}{\alpha_1}}\frac{1}{1+\gamma} \\ &\times \Bigg[1 - \frac{\beta_5^{m_5}}{\Gamma m_5}\frac{\beta_6^{m_6}}{\Gamma m_6}\sum_{q=0}^{m_4-1}\sum_{c=0}^{r}\frac{q!}{a!(q-a)!}\frac{\beta_4^q\gamma^q}{q!}\left(\frac{\overline{\gamma}_1}{(\alpha_2-\alpha_1\gamma)\overline{\gamma}_s}\right)^a\left(\frac{\alpha_2}{\alpha_2-\alpha_1\gamma}\right)^{q-a} \\ &\times \frac{\Gamma(a+m_5)}{(\frac{\beta_4\overline{\gamma}_1\gamma}{(\alpha_2-\alpha_1\gamma)\overline{\gamma}_s}+\beta_5)(a+m_5)}\frac{\Gamma(q-a+m_6)}{(\frac{\beta_4\gamma\alpha_2}{\alpha_2-\alpha_1\gamma}+\beta_6)(q-a+m_6)}\Bigg]d\gamma \end{aligned} \quad (3.132)$$

$$\begin{aligned} C_{1E} =& \frac{1}{\ln(2)}\Bigg[\ln(1+\frac{\alpha_2}{\alpha_1}) - \ln(1+\gamma_{th,3})[1 - \frac{\beta_5^{m_5}}{\Gamma m_5}\frac{\beta_6^{m_6}}{\Gamma m_6}\sum_{q=0}^{m_4-1}\sum_{c=0}^{r}\frac{q!}{a!(q-a)!}\frac{\beta_4^q\gamma^q}{q!}\left(\frac{\overline{\gamma}_1}{(\alpha_2-\alpha_1\gamma)\overline{\gamma}_s}\right)^a \\ &\times \left(\frac{\alpha_2}{\alpha_2-\alpha_1\gamma}\right)^{q-a}\frac{\Gamma(a+m_5)}{(\frac{\beta_4\overline{\gamma}_1\gamma}{(\alpha_2-\alpha_1\gamma)\overline{\gamma}_s}+\beta_5)(a+m_5)}\frac{\Gamma(q-a+m_6)}{(\frac{\beta_4\gamma\alpha_2}{\alpha_2-\alpha_1\gamma}+\beta_6)(q-a+m_6)}] - \frac{1}{\ln(2)}\int_{\gamma_{th,3}}^{\frac{\alpha_2}{\alpha_1}}\frac{1}{1+\gamma} \\ &\times \Bigg[1 - \frac{\beta_5^{m_5}}{\Gamma m_5}\frac{\beta_6^{m_6}}{\Gamma m_6}\sum_{q=0}^{m_4-1}\sum_{c=0}^{r}\frac{q!}{a!(q-a)!}\frac{\beta_4^q\gamma^q}{q!}\left(\frac{\overline{\gamma}_1}{(\alpha_2-\alpha_1\gamma)\overline{\gamma}_s}\right)^a\left(\frac{\alpha_2}{\alpha_2-\alpha_1\gamma}\right)^{q-a} \\ &\times \frac{\Gamma(a+m_5)}{(\frac{\beta_4\overline{\gamma}_1\gamma}{(\alpha_2-\alpha_1\gamma)\overline{\gamma}_s}+\beta_5)(a+m_5)}\frac{\Gamma(q-a+m_6)}{(\frac{\beta_4\gamma\alpha_2}{\alpha_2-\alpha_1\gamma}+\beta_6)(q-a+m_6)}\Bigg]d\gamma \end{aligned} \quad (3.133)$$

$$\begin{aligned} C_{1E} =& \frac{1}{\ln(2)}\Bigg[\ln(1+\frac{\alpha_2}{\alpha_1}) - \ln(1+\gamma_{th,3})[1 - \frac{\beta_5^{m_5}}{\Gamma m_5}\frac{\beta_6^{m_6}}{\Gamma m_6}\sum_{q=0}^{m_4-1}\sum_{c=0}^{r}\frac{q!}{a!(q-a)!}\frac{\beta_4^q\gamma^q}{q!}\left(\frac{\overline{\gamma}_1}{(\alpha_2-\alpha_1\gamma)\overline{\gamma}_s}\right)^a \\ &\times \left(\frac{\alpha_2}{\alpha_2-\alpha_1\gamma}\right)^{q-a}\frac{\Gamma(a+m_5)}{(\frac{\beta_4\overline{\gamma}_1\gamma}{(\alpha_2-\alpha_1\gamma)\overline{\gamma}_s}+\beta_5)(a+m_5)}\frac{\Gamma(q-a+m_6)}{(\frac{\beta_4\gamma\alpha_2}{\alpha_2-\alpha_1\gamma}+\beta_6)(q-a+m_6)}]\Bigg] \\ &- \frac{1}{\ln(2)}|\ln(1+\gamma_{th,3}) - \ln(1+\frac{\alpha_2}{\alpha_1}) + \Delta_{1E}| \end{aligned} \quad (3.134)$$

Where Δ_{1E} is defined as

$$\Delta_{1E} = 1 - \frac{\beta_5^{m_5}}{\Gamma m_5}\frac{\beta_6^{m_6}}{\Gamma m_6}\sum_{q=0}^{m_4-1}\sum_{c=0}^{r}\frac{q!}{a!(q-a)!}\frac{\beta_4^q\gamma^q}{q!}\left(\frac{\overline{\gamma}_1}{(\alpha_2-\alpha_1\gamma)\overline{\gamma}_s}\right)^a \times \left(\frac{\alpha_2}{\alpha_2-\alpha_1\gamma}\right)^{q-a}\frac{\Gamma(a+m_5)}{(\frac{\beta_4\overline{\gamma}_1\gamma}{(\alpha_2-\alpha_1\gamma)\overline{\gamma}_s}+\beta_5)(a+m_5)}\frac{\Gamma(q-a+m_6)}{(\frac{\beta_4\gamma\alpha_2}{\alpha_2-\alpha_1\gamma}+\beta_6)(q-a+m_6)} \tag{3.135}$$

3.12 Channel Capacity of UE_{2E}

According to Shannon's theory [34], the channel capacity C_{UE_1} is calculated as

$$C_{2E} = \int_{\gamma_{th,3}}^{\infty}\log_2(1+\gamma)f_{\gamma_{2E}}(\gamma)d\gamma \tag{3.136}$$

Here, in the system γ of UE_1 is always lesser than (α_2/α_1) and the Threshold level of the eavesdropper is $\gamma_{th,3}$

$$C_{2E} = \int_{\gamma_{th,3}}^{\frac{\alpha_2}{\alpha_1}}\log_2(1+\gamma)f_{\gamma_{2E}}(\gamma)d\gamma \tag{3.137}$$

Applying integration by parts to solve (3.113), the channel capacity of UE_{2E} can be calculated as

$$C_{2E} = \left[\frac{\ln(1+\gamma)F_{\gamma_{2E}}(\gamma)}{\ln(2)}\right]_{\gamma_{th,3}}^{\frac{\alpha_2}{\alpha_1}} - \frac{1}{\ln(2)}\int_{\gamma_{th,3}}^{\frac{\alpha_2}{\alpha_1}}\frac{F_{\gamma_{2E}}(\gamma)}{1+\gamma} \tag{3.138}$$

$$C_{2E} = \left[\frac{\ln(1+\frac{\alpha_2}{\alpha_1})F_{\gamma_{2E}}(\frac{\alpha_2}{\alpha_1}) - \ln(1+\gamma_{th,3})F_{\gamma_{2E}}(\gamma_{th,3})}{\ln(2)}\right] - \frac{1}{\ln(2)}\int_{\gamma_{th,3}}^{\frac{\alpha_2}{\alpha_1}}\frac{F_{\gamma_{2E}}(\gamma)}{1+\gamma} \tag{3.139}$$

Substituting (3.108) in (3.139), we have

$$C_{2E} = \frac{1}{\ln(2)}\Bigg[\ln(1+\frac{\alpha_2}{\alpha_1}) - \ln(1+\gamma_{th,3})[1 - \frac{\beta_5^{m_5}}{\Gamma m_5}\frac{\beta_6^{m_6}}{\Gamma m_6}\sum_{r=0}^{m_4-1}\sum_{c=0}^{r}\frac{r!}{r!(r-c)!}\frac{\beta_4^r\gamma^r}{r!}\left(\frac{\overline{\gamma}_1}{\alpha_1\overline{\gamma}_s}\right)^c \times \frac{\Gamma(c+m_5)}{(\frac{\beta_4\overline{\gamma}_1\gamma}{\alpha_1\overline{\gamma}_s}+\beta_5)(c+m_5)}\frac{\Gamma(r-c+m_6)}{(\beta_4\gamma+\beta_6)(r-c+m_6)}]\Bigg] - \frac{1}{\ln(2)}\int_{\gamma_{th,3}}^{\frac{\alpha_2}{\alpha_1}}\frac{1}{1+\gamma}\Bigg[1 - \frac{\beta_5^{m_5}}{\Gamma m_5}\frac{\beta_6^{m_6}}{\Gamma m_6} \times \sum_{r=0}^{m_4-1}\sum_{c=0}^{r}\frac{r!}{c!(r-c)!}\frac{\beta_4^r\gamma^r}{r!}\left(\frac{\overline{\gamma}_1}{\alpha_1\overline{\gamma}_s}\right)^c\frac{\Gamma(c+m_5)}{(\frac{\beta_4\overline{\gamma}_1\gamma}{\alpha_1\overline{\gamma}_s}+\beta_5)(c+m_5)}\frac{\Gamma(r-c+m_6)}{(\beta_4\gamma+\beta_6)(r-c+m_6)}\Bigg]d\gamma \tag{3.140}$$

$$C_{2E} = \frac{1}{\ln(2)}\Bigg[\ln(1+\frac{\alpha_2}{\alpha_1}) - \ln(1+\gamma_{th,3})[1 - \frac{\beta_5^{m_5}}{\Gamma m_5}\frac{\beta_6^{m_6}}{\Gamma m_6}\sum_{r=0}^{m_4-1}\sum_{c=0}^{r}\frac{r!}{r!(r-c)!}\frac{\beta_4^r\gamma^r}{r!}\left(\frac{\overline{\gamma}_1}{\alpha_1\overline{\gamma}_s}\right)^c$$
$$\times \frac{\Gamma(c+m_5)}{(\frac{\beta_4\overline{\gamma}_1\gamma}{\alpha_1\overline{\gamma}_s}+\beta_5)(c+m_5)}\frac{\Gamma(r-c+m_6)}{(\beta_4\gamma+\beta_6)(r-c+m_6)}] - \frac{1}{\ln(2)}|\ln(1+\gamma_{th,3})$$
$$- \ln(1+\frac{\alpha_2}{\alpha_1}) + \Delta_{2E}| \tag{3.141}$$

Where Δ_{2E} is defined as

$$\Delta_{2E} = 1 - \frac{\beta_5^{m_5}}{\Gamma m_5}\frac{\beta_6^{m_6}}{\Gamma m_6}\sum_{r=0}^{m_4-1}\sum_{c=0}^{r}\frac{r!}{c!(r-c)!}\frac{\beta_4^r\gamma^r}{r!}\left(\frac{\overline{\gamma}_1}{\alpha_1\overline{\gamma}_s}\right)^c$$
$$\times \frac{\Gamma(c+m_5)}{(\frac{\beta_4\overline{\gamma}_1\gamma}{\alpha_1\overline{\gamma}_s}+\beta_5)(c+m_5)}\frac{\Gamma(r-c+m_6)}{(\beta_4\gamma+\beta_6)(r-c+m_6)} \tag{3.142}$$

3.13 Secrecy Capacity

The secrecy capacity of UE_1 is the difference between the channel capacity of UE_1 and the channel capacity of an eavesdropper decoding UE_1's signal.

$$C_{S,1} = C_{UE_1} - C_{2E} \tag{3.143}$$

The secrecy capacity of UE_2 is the difference between the channel capacity of UE and the channel capacity of an eavesdropper decoding UE_2's signal.

$$C_{S,2} = C_{UE_2} - C_{1E} \tag{3.144}$$

The secrecy capacity of the system is the sum of the secrecy capacity of UE_1 and UE_2.

$$C_{System} = C_{S,1} + C_{S,2} \tag{3.145}$$

Chapter 4

Results and Analysis

In this section, let's observe the system performance of the NOMA system operating in full-duplex relaying mode with the help of MATLAB simulations.

In the deployed NOMA system, the S delivers signals to UE_1 and UE_2, respectively. The normalized distances between S to UE_1, S to UE_2, UE_1 to UE_2, S to E, UE_1 to E, and UE_2 to E are 0.3, 1.2, 1.3, 0.5, 0.3, and 2, respectively, with power allocation coefficients α_1=0.2 and α_2=0.8. The transmit power range of 0 dB to 20 dB and the UE_1 transmits relay signal with power $\alpha_2 P_s$. The threshold levels $\gamma_{th,1}$, $\gamma_{th,2}$, and $\gamma_{th,E}$ are set to 2 dB. Here, UE_2 sends jamming signals with power P_1=15 dB, the fading severity(m) is set to 2, and the path loss exponent(n) is set to 3.

4.1 SINR

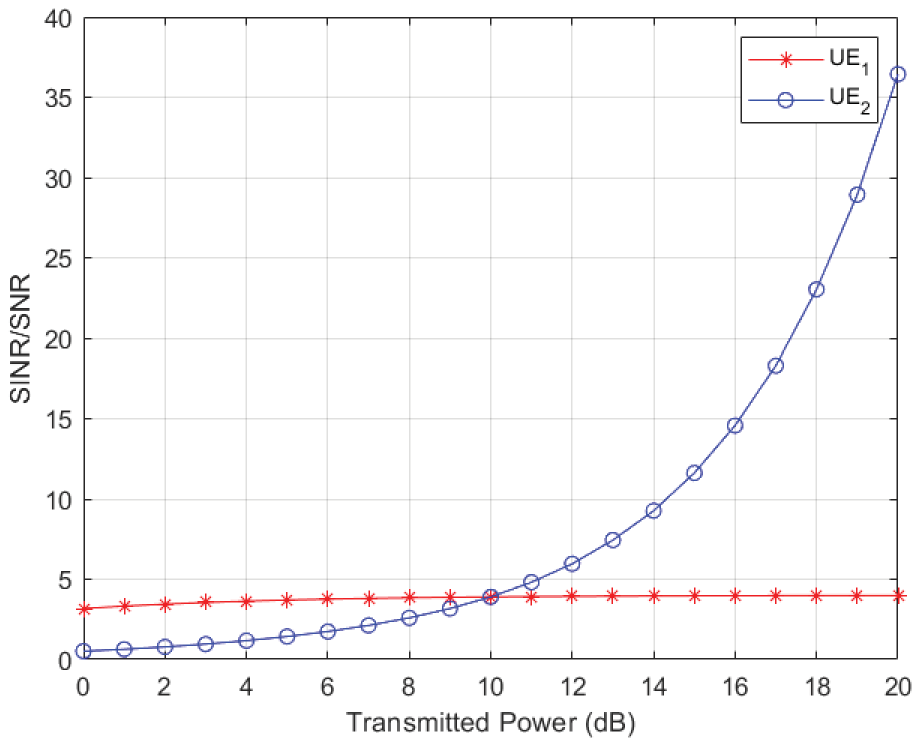

Figure 4.1: Transmitted Power Versus SINR/SNR of UE_1 and UE_2.

In figure 4.1, we can observe that the SINR/SNR of UE_1 and UE_2 increases with an increase in transmitted power. SINR/SNR of UE_1 is higher than UE_2 at low power levels, as the transmission power increases the SINR/SNR of UE_2 also gradually increases. This increase in the SINR/SNR of UE_2 is due to the relay link between UE_1 and UE_2. UE_1 decodes and forwards the data signals of UE_1 with power $\alpha_2 P_s$, which is equal to the power allocated for UE_2 at S. This relay link data signal doesn't have any interference, so the increase in the SINR/SNR of UE_2 is higher than the SINR/SNR of UE_1 with an increase in transmitted power.

4.2 Outage Probability

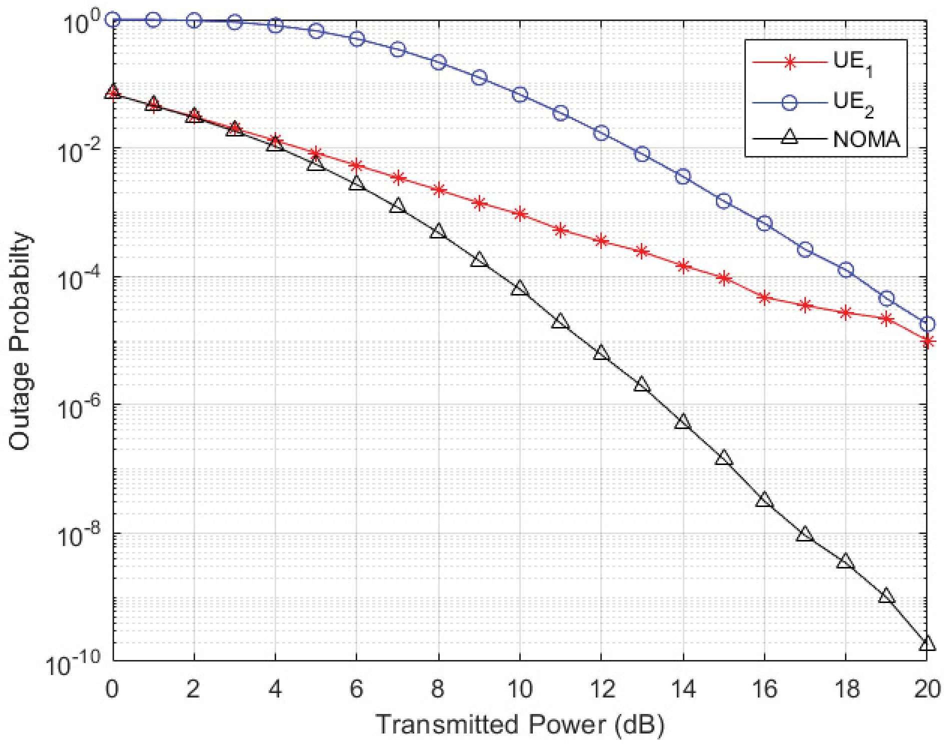

Figure 4.2: Transmitted Power Versus Outage Probability of UE_1, UE_2, and NOMA.

In figure 4.2, the outage probability of the NOMA system decreases with an increase in transmitted power. The outage probability of UE_1 is less than the outage probability of UE_2. This is because the distance between UE_1 and S is smaller than the distance between UE_2 and S. The relay link between UE_1 and UE_2 increases the SINR/SNR of UE_2, which leads to a decrease in outage probability of UE_2. Here, we can say that the outage probability of the NOMA system decreases with an increase in transmitted power

4.3 Secrecy Capacity of The System with Varying Distance between S and E

In the NOMA system, we are varying the distance between S and E. The power at source P_s is set to 20 dB.

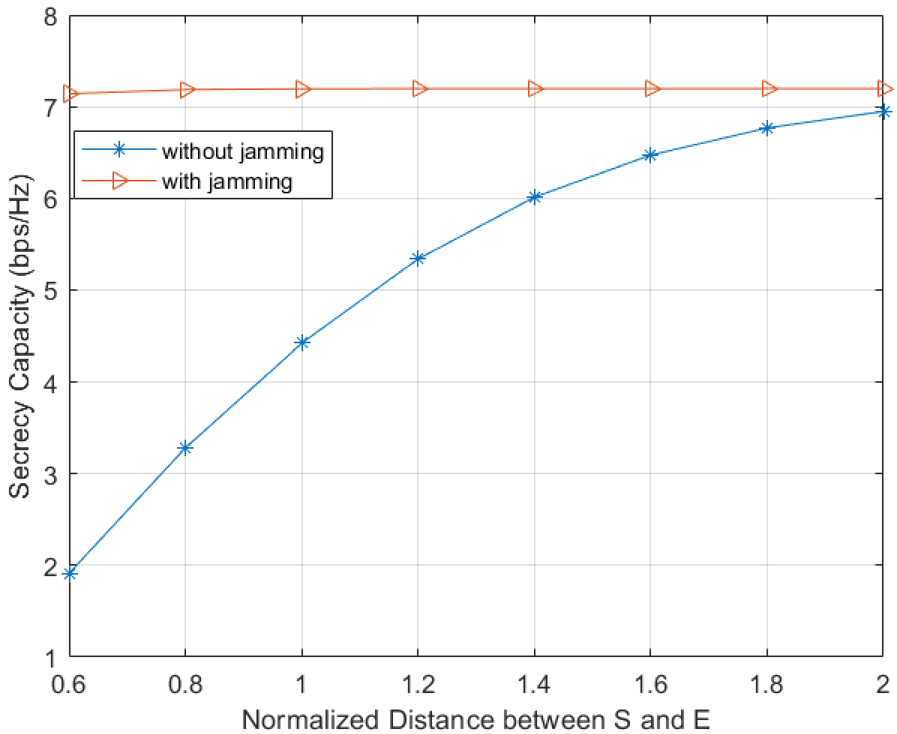

Figure 4.3: Normalized Distance Versus Secrecy Capacity of NOMA System with Active Jamming and Without Active Jamming.

In figure 4.3, the secrecy capacity of the NOMA system deployed with active jamming is higher than the secrecy capacity of the ordinary NOMA system. In the NOMA system, the secrecy capacity of the system increases with an increase in the distance between S and E. In the NOMA system deployed with active jamming, the secrecy capacity of the system is consistent and higher than the ordinary NOMA system with an increase in distance between S and E. Increasing the distance decreases the eavesdropper channel capacity, which leads to an increase in secrecy capacity of the system. In the case of the NOMA system deployed with active jamming, the jamming signals will affect the eavesdropper's channel capacity, which leads to a higher secrecy capacity of the system even when the distances between the S and E are less. From this section, we can conclude that deploying active jamming increases the secrecy capacity of the NOMA system.

4.4 Secrecy Capacity of The System with Varying Distance between UE_2 and E

In the NOMA system, we are varying the distance between UE_2 to E. The power at source P_s is set to 20 dB.

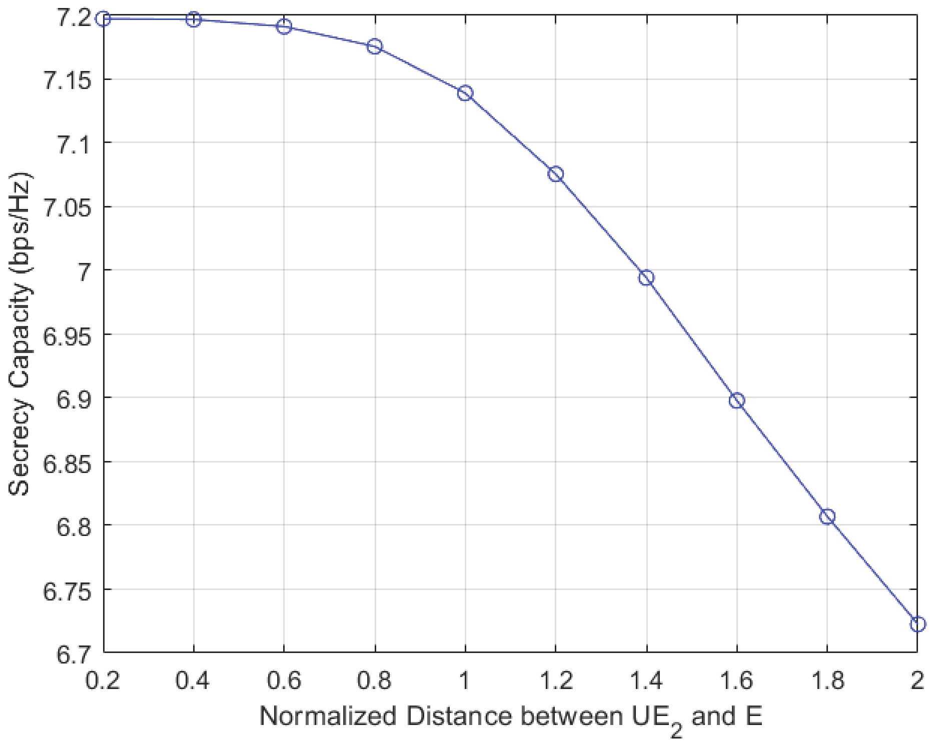

Figure 4.4: Normalized Distance Versus Secrecy capacity of the NOMA System deployed with Active Jamming

In figure 4.4, we can observe the simulated results. The secrecy capacity of the system decreases with an increase in distance between UE_2 and E. The UE_2 in the system transmits jamming signals to affect the performance of the eavesdropper. If the distance between the eavesdropper and UE_2 increases, the power of the jamming signals decreases, which leads to a decrease in the secrecy capacity of the system.

4.5 Secrecy Capacity of The System for Various Degrees of Fading Severity

To investigate the impact of fading severity parameter (m) on the system, we are varying the fading severity parameter with three different values. Here the fading severity is set to 1 is a Rayleigh fading environment, which has a non-line-of-sight communication between transmitter and receiver. The fading severity is set to 2 and 3 is a fading environment that has multi-path communication, line-of-sight-

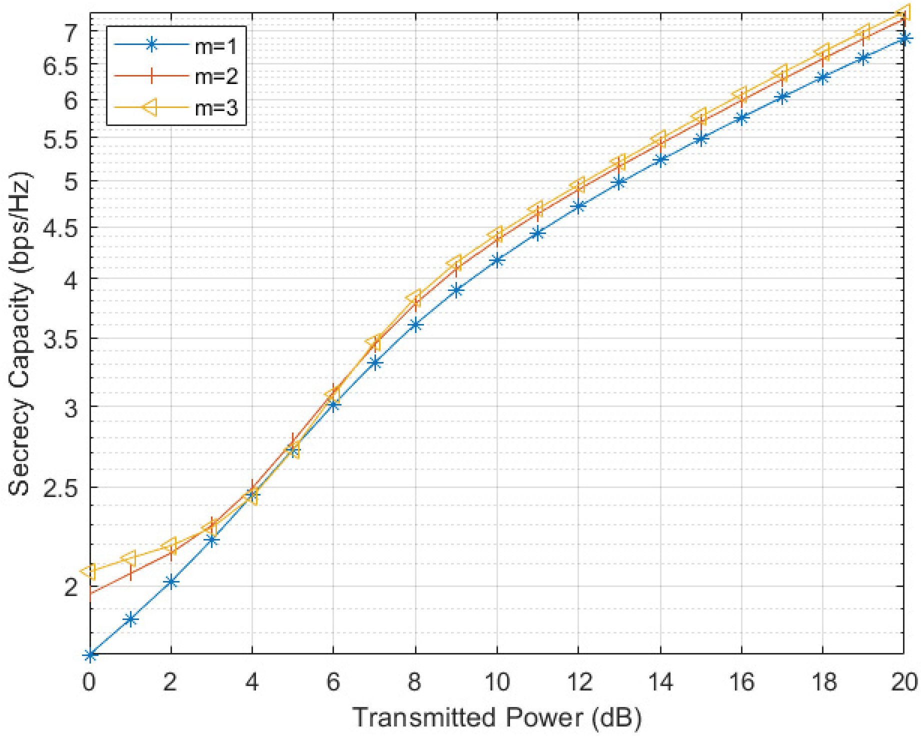

Figure 4.5: Transmitted Power Versus Secrecy Capacity of the System with Different Fading Severity.

communication, etc between transmitter and receiver.

In figure 4.5, we can observe the simulated results. The environment with fading severity value set to 1 has less secrecy capacity because of the non-line-of-sight communication between the transmitter and receiver, which leads to high attenuation in the system. The environment with fading severity values set to 2 and 3 has high secrecy capacity comparatively because of the line-of-sight communication, multi-path communication, etc between the transmitter and receiver, which leads to low attenuation in the system. From the observations, we can conclude that the secrecy capacity of the system increases with an increase in fading severity parameter.

4.6 The System's Secrecy Capacity for Various Degrees of Path Loss Exponent

To investigate the impact of path loss exponent(n), we are varying the path loss exponent factor with four different values. Here the path loss exponent set to 2 represents a free space environment with a line-of-sight communication between transmitter and receiver. The path loss exponent factor is set to 3, which represents an environment with a few obstacles in the line-of-sight communication between transmitter and receiver. The path loss exponent factor set to 4 represents an environment with moderate obstacles between the transmitter and the receiver. The path loss exponent when set to 5 represents a denser environment with large amounts of obstacles between the transmitter and receiver. So the transmitter and receiver will have non-line-of-sight communication.

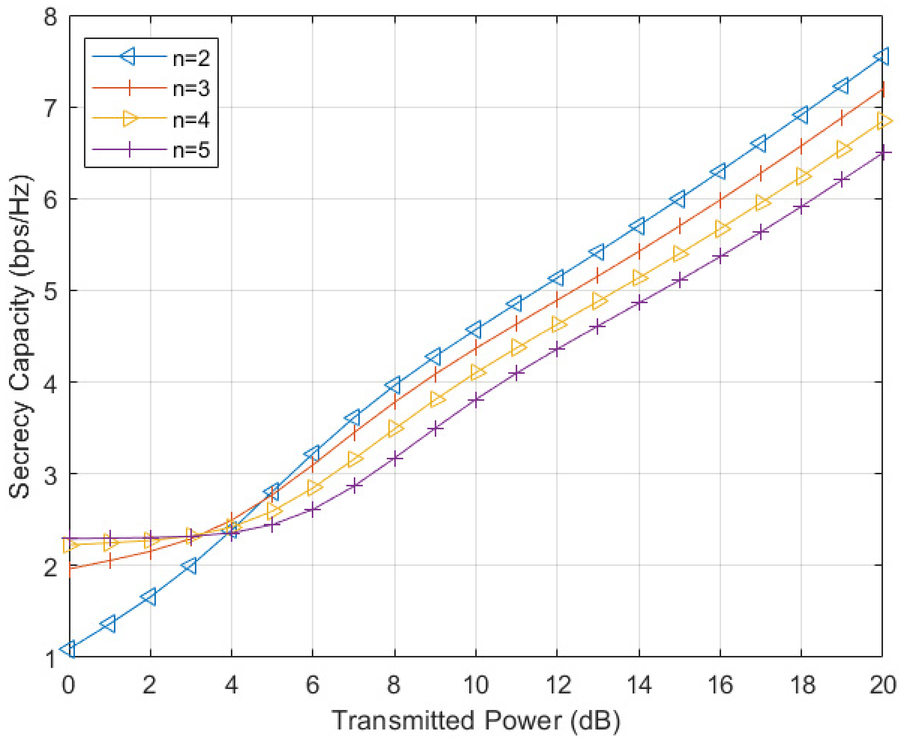

Figure 4.6: Transmitted Power Versus Secrecy Capacity for Different Path Loss Exponent

In figure 4.6, we can observe the simulated results. The environment with a path loss exponent value set to 5 has less secrecy capacity because of the non-line-of-sight communication between the transmitter and receiver, which leads to high attenuation in the system. The environment with a path loss exponent value set to 2 has high secrecy capacity comparatively because of the line-of-sight communication between the transmitter and receiver, which leads to low attenuation in the system. The secrecy capacity of those with a high path loss exponent has higher secrecy capacity at lower power levels because in the denser environment eavesdropper can't receive the data signals with low power, which lead to an increase in the secrecy capacity of the system. From the observations, we can conclude that the secrecy capacity of the system decreases with an increase in path loss exponent.

Chapter 5

Discussion

In Mathematical analysis, we derived the expressions for performance metrics such as outage probability and secrecy capacity. To get the expressions for the performance metrics we first need to get the signal expressions, SINR, PDF, and CDF for UE1 and UE2 based on the system model. In the simulation, we generated channel coefficients of the Nakagami-m fading environment with gamma distribution using fading severity and channel mean power. We used these channel coefficients in the derived SINR expressions and generated the secrecy capacity and outage probability of users in the system.

- **RQ1:** What is the response of outage probability of the NOMA system and the users in the NOMA system?

  Ans: The outage probability of the NOMA system decreases with an increase in transmitted power. The outage probability of UE_1 is less than the outage probability of UE_2. The outage probability of $UE_1 < UE_2$ because the UE_1 is near to S than UE_2. The relay link between UE_1 and UE_2 increases the SINR/SNR of UE_2 with an increase in transmitted power, which leads to a decrease in outage probability of UE_2. In section (4.2), we discussed the outage probability of the NOMA system.

- **RQ2:** How does the implementation of the active jamming technique improve the secrecy performance of the power domain NOMA system?

  Ans: After implementing active jamming in a full-duplex relay NOMA system, the jamming signals will be transmitted across the system. The users will receive the data signals from the source along with jamming signals. Here in the proposed system, the users are legitimate, so they know about the jamming signals. The users will first eliminate the jamming signal in the received data signal. After eliminating the jamming signal from the received data signal the users will decode the leftover data signal. As the users are legitimate, there will be no effect of jamming on the user's channel. In the case of Eavesdropper, who is illegitimate and doesn't know about the deployment of jamming in the system. The eavesdropper find's it difficult to decode the received signal because the eavesdropper is unaware of the jamming signals and can't eliminate the jamming signals. The jamming signals in the system will interfere with the eavesdropper's channel due to this the eavesdropper's performance is decreased. The increased secrecy capacity of the NOMA system with active jamming is due to the effect of jamming on the eavesdropper's channel capacity. From the figure 4.3, we can observe the impact of the active jamming technique in the system.

- **RQ3:** What is the response of secrecy capacity of the full-duplex relay PD-NOMA system with active jamming by varying fading severity and path loss exponent parameters?

  Ans: An increase in the path-loss exponent (n) decreases the secrecy capacity of the system. An increase in path loss exponent makes the environment denser, which leads to an increase in attenuation. The secrecy capacity of those with a high path loss exponent has higher secrecy capacity at lower power levels because the eavesdropper can't receive the data signals with low power in the denser environment. The increase in fading severity(m) increases the secrecy capacity of the system. When fading severity is set to 1, it represents a Rayleigh fading environment. In the Rayleigh fading environment, the secrecy capacity is low because of the non-line-of-sight communication between the transmitter and receiver. As fading severity parameter becomes greater than 1, the secrecy capacity of the system increases because of the line-of-sight communication between transmitter and receiver. In sections (4.5) and (4.6), we discussed the effect of the secrecy capacity of the system by varying the fading severity and path loss exponent parameters separately and illustrated the simulation results.

5.1 Validity

We implemented a computational model using MATLAB software and gathered the measurements for secrecy capacity and outage probability for the designed model. We simulated the channel as Nakagami-m fading based on the derived cumulative distribution function (CDF) and probability density function (PDF) distributions in (3.28) and (3.29). We simulated the outage probability and secrecy capacity of the system based on the derived expressions of the SNR/SINR in (3.13), (3.20), (3.23), and (3.27) in the analytical parts. To validate the obtained secrecy capacity and outage probability of the computational model, we need to implement the system model in the real world and gather the measurements according to the parameters of the computational model. After obtaining measurements of both experimental and computational implementations, we need to verify them. In verification, we need to perform statistical measures for the gathered measurements. Further, we should observe the differences between computational and experimental data.

5.2 Contribution of Thesis

It is crucial to have reliable and effective wireless communication networks given the rapid advancement in the usage and applications of wireless communications. Channel capacity and spectral efficiency for future wireless networks have to be very high due to an increase in the user base, data traffic, etc. NOMA is one of the multiple access techniques that can be suitable to deliver the current requirements. Security has been a priority factor for future wireless networks as the number of users and the data that has been transmitted between them has been drastically increasing.

Many kinds of research have been done on NOMA systems using relay networks, rayleigh fading, and many physical layer security techniques. The active jamming technique is also a physical layer security technique that is not much explored along with a relay network in various fading environments. Most research regarding NOMA is done either by implementing a relay network or by implementing active jamming in a Rayleigh fading environment. Which is why we have deployed an active jamming technique with decode and forward relay in Nakagami-m fading to observe the performance of the NOMA system with a combination of relay network and active jamming. In this study, the links are operated in a full duplex mode in which the relay can transmit and receive at the same time to further enhance the spectrum efficiency. Nakagami-m fading is taken into account since it is well-known that this generalized distribution can be used to represent a variety of fading scenarios, including rayleigh, gaussian, and rician fading, among others [17].

Chapter 6

Conclusions and Future Work

We deployed a full-duplex relay PD-NOMA in a Nakagami -m fading environment and investigated the secrecy capacity and outage probability of the system. We implemented the active jamming technique because it was observed as one of the better ways to increase the security of the NOMA system's physical layer and its ability for secrecy. We derived the theoretical expressions of SINR/SNR for users UE_1, UE_2, and eavesdropper. Calculated CDF and PDF theoretically to observe the system's outage probability and secrecy capacity. The outage probability of the near user is less than the far user because the distance between S and UE_1 is less than the distance between S and UE_2. The relay link in the system enhances the SINR/SNR of far users, which decreases the outage probability of far users. The increase in transmission power from the source decreases the outage probability for near and far users. Calculated the outage probability, and secrecy capacity theoretically, and generated data for the simulated system.

To affect the eavesdropper's performance, we deployed active jamming in the system. The implementation of active jamming decreased the performance of the eavesdropper, which leads to an increase in the secrecy capacity of the system. In sections (4.3) and (4.4), we can observe the secrecy capacity of the NOMA system before and after deploying the active jamming technique and the response of the system with varying distances between E to S and E to UE_2. We have considered the Nakagami-m fading environment for the system, and the secrecy capacity of the system increases with an increase in fading severity and decreases with an increase in the path loss exponent of the NOMA system.

We mainly focused on the implementation of active jamming in a single-cell multi-user model, we carried out a secrecy performance analysis of the system. In this study, the UE_2 will transmit the jamming signal throughout the system. The drawback of this implementation of active jamming is that it drains the power of users as they require additional power to transmit the jamming signals. The future work can mainly be focused on implementing active jamming in a multi-cell multi-user environment and optimizing the jamming power in users so that we can obtain higher secrecy performance with less power and observe the secrecy performance metrics of the users and the system.

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