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Threshold-Based Relay Selection for Cooperative Wireless Network

THRESHOLD-BASED RELAY SELECTION FOR COOPERATIVE WIRELESS NETWORK

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Copyright Statement

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Abstract

Cooperative communication plays a vital role in the wireless domain recently due to its numerous benefits such as coverage extension, improvement in spectral efficiency, and throughput by increasing the complexity of the system. Furthermore, security becomes a key issue for implementing a cooperative communication system.

In this thesis, the complexity is reduced by employing differential modulation as they do not require complete channel state information (CSI). Different threshold-based relay selection schemes are also proposed to reduce complexity. Furthermore, the security issue in the cooperative wireless network is addressed by enhancing the physical layer security using the proposed double threshold-based optimal relay selection scheme.

List of Publications

Publications during the PhD program:

1. Shamganth, K., & Sibley, M. J. (2020). Relay Selection-Based Physical-Layer Security Enhancement in Cooperative Wireless Network. In Data Communication and Networks (pp. 305-320). Springer, Singapore.
   (Part of this publication is included in Chapter-5 of this thesis)

2. Shamganth, K., & Sibley, M. J. (2018). Complexity analysis of double-threshold based relay selection in D2D cooperative network. J. Wirel. Netw. Commun, 8(1), 1-6.
   (Part of this publication is included in Chapter-4 of this thesis)

3. Shamganth, K., & Sibley, M. J. (2017, August). A survey on relay selection in cooperative device-to-device (D2D) communication for 5G cellular networks. In 2017 International Conference on Energy, Communication, Data Analytics and Soft Computing (ICECDS) (pp. 42-46). IEEE.
   (Part of this publication is included in Chapter-2 of this thesis)

4. Shamganth, K., Al-Ghnimi, S., & Sibley, M. J. (2016). Performance Analysis of Threshold Based Relay Selection Technique in Cooperative Wireless Networks. International Journal of Electronics and Communication Engineering & Technology, 7(1).
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   (Part of this publication is included in Chapter-2 of this thesis)

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List of Abbreviations

3GPP- Third Generation Partnership Project

5G- Fifth Generation

ABER-Average Bit Error Rate

AF-Amplify and Forward

AFbORS- Amplify and Forward based Optimal Relay Selection

BER- Bit Error Rate

BPSK- Binary Phase Shift Key

BS- Base Station

CAGR- Compound Annual Growth Rate

CSI- Channel State Information

D2D- Device-to-Device Communication

DBPSK-Differential BPSK

DF- Decode and Forward

DFbORS-Decode and Forward based Optimal Relay Selection

DiffAF- Differential AF

DQPSK- Differential QPSK

DSTC-Distributed Space Time Coding

DT-GSC- Double Threshold Generalised selection combining

e2e- End-to-End

GSC- Generalised Selection Combining

ISP -Internet Service Providers

LTE-A- LTE-Advanced standard

MER- Mains-to-Eavesdropper Ratio

MGF-Moment Generating Function

MIMO- Multiple-In-Multiple-Out

mMIMO- Massive MIMO

mm-wave- Millimetre Wave

M-PSK-Mary-Phase Shift Keying

MRC-Maximum Ratio Combining

MRS- Multi-Relay-Selection

MS-Mobile Station

MW- Maximum-Weighted matching algorithm

OR- Opportunistic relaying

ORS-Optimal Relay Selection

PARS- Power-Aware Relay Selection

PER- Packet Error Rate

QoS- Quality of Service

QPSK-Quadrature Phase Shift Keying

SER-Symbol Error Rate

SNR- Signal to Noise ratio

SRS- Single Relay Selection

TDMA-Time Division Multiple Access

UE-User Equipment

Chapter 1

Introduction

1.1 Introduction and Motivation

Resource allocation and sharing among multiple relay nodes minimizes power consumption and saves the overall network resources in cooperative wireless networks. Cooperative wireless communication effectively combats fading and provides reliable communication. Relay selection in cooperative wireless communication is an essential technique that improves performance by selecting the best relays and eliminating the relays with a poor signal-to-noise ratio (SNR). There are some critical issues in the relay selection such as the increase in complexity and power consumption by selecting more relays to assist the source transmission. Also, the security threat is one of the critical issues in the existence of an eavesdropper along with the relay node in the cooperative wireless network. Threshold based relay selection can be exploited to overcome the issue of selecting more relays by comparing the SNR at the relays with the pre-set threshold. The complexity in the existing relay selection is high due to the full channel state information (CSI) requirement. This thesis investigates the differential modulation schemes with threshold-based relay selection to reduce the complexity and power consumption. The security issue in cooperative wireless network is addressed in this thesis by enhancing the physical layer security using relay selection. Unlike the existing techniques, the proposed relay selection-based scheme enhances the physical layer security in a cooperative wireless network and offers improved intercept probability performance.

1.2 Main Objectives

- The significant objective of this research is to devise single-, double-, and multi-threshold-based relay selection scheme using differential modulation for cooperative wireless networks and to analyze its performance.
- To improve the physical layer security in cooperative wireless network by the proposed double threshold based optimal relay selection scheme.

1.3 Thesis Contributions

Prior works on the threshold-based relay selection require full channel estimation, which is not possible in fast fading channel conditions. The proposed scheme requires minimal channel estimation as differential modulation is employed. The proposed relaying selection scheme requires a long-term average of the received signal, reducing the full CSI requirement. The proposed method reduces power consumption at the relay node. In addition to threshold-based relay selection the proposed scheme also considers the physical layer security enhancement in a cooperative wireless network.

The major contributions of this thesis are as follows:

1. Single-threshold-based-relay selection with mathematical model using differential modulation applying the distance constraints is proposed. The proposed scheme is studied with amplify and forward (AF) and differential amplify and forward (DiffAF) relaying schemes. Proposed scheme is different from the existing single threshold-based scheme which employs coherent relaying and equal power allocation.
2. Double-threshold-based-multi-relay selection and multi-threshold based proposed with mathematical model using coherent and differential modulation scheme with distance

constraints is also proposed. The complexity analysis of the proposed double- and multi-threshold based scheme is analyzed based on the number of channel estimation and combining branches.

3. The proposed scheme combines the double-threshold scheme with existing optimal relay selection with distance constraints and unequal power allocation to enhance physical layer security in cooperative wireless networks. The BER performance is analyzed for the proposed scheme with different relay scenarios and modulation schemes.

1.4 Thesis Organization

The remainder of this thesis is organised as follows:

- **Chapter 2** – The background concepts of cooperative wireless communication and relay selection in cooperative wireless networks are briefly introduced. A comprehensive survey of relay selection is discussed in this chapter. It also provides a thorough literature review on the relaying techniques, followed by the single- and multi-relay selection techniques and physical layer security for cooperative wireless networks. This chapter also compares the findings of the existing techniques in the literature.
- **Chapter 3** –The proposed single threshold based single relay selection is presented with the mathematical model for cooperative wireless networks. The proposed scheme categorized as Single-Threshold AF and DiffAF relaying with Coherent and differential Modulation schemes. The performance analysis of the single-threshold-based relay selection scheme is discussed. The comparative results for this scheme is presented.
- **Chapter 4** – Mathematical model of the proposed double-threshold based relay selection for double-threshold AF and double-threshold DiffAF relaying with coherent

and differential Modulation schemes is presented. The mathematical model is discussed in this chapter. Furthermore, the performance of the proposed double- and multi-threshold based relay selection schemes is evaluated. Comparative analysis of these schemes is presented.

- **Chapter 5** –Intercept probability analysis of the proposed double threshold based optimal relay selection scheme is presented. In addition, this chapter also presents a comparative BER performance analysis of the proposed scheme with varying numbers of relays and modulation schemes for different distance cases.
- **Chapter 6** – This chapter highlights the summary of the contributions of this thesis and future research directions.

Chapter 2

Background and Related Literature

This chapter provides a comprehensive survey of cooperative wireless communication. A detailed discussion about the relay selection techniques and cooperative relaying protocols in cooperative wireless networks discussed in this chapter. Section 2.1 begins with the theoretical background of cooperative communication followed by the related literature in Section 2.2. The identified research gap is presented in Section 2.3.

Part of this thesis published in “International Conference on Energy, Communication, Data Analytics and Soft Computing (ICECDS)”, (Shamganth & Sibley, 2017) and in “IET Chennai 3rd International on Sustainable Energy and Intelligent Systems (SEISCON 2012)”, (Shamganth.K et al., 2012).

2.1 Theoretical Background

2.1.1 Cooperative Communication

Cooperative communication has drawn significant interest due to the increase in data rate and low-cost network coverage. Low-cost data availability is an essential consideration for multimedia communication systems (Yang et al., 2005). Cooperative relay influences spatial diversity in wireless communication networks without requiring multiple antennas. Device-to-Device (D2D) communication supports the infrastructure-based cellular networks in LTE-Advanced Release 12 standard (K.Shamganth et al., 2016).

The nodes in the wireless network have three main characteristics, such as egoistic, supportive, and cooperative (Dohler & Li, 2010). The egoistic behaviour of the relay node is such that node does not support the transmission of the source information to the destination node (Dohler & Li, 2010). In the case of supportive behaviour of the relay node, it is used only for the unidirectional transmission (Dohler & Li, 2010). The cooperative behaviour of the nodes in a wireless network provides mutual support to the connected nodes in the network (Dohler & Li, 2010). Each node in the cooperative wireless network transmits its data, and at the same time, it will act as a cooperative node for the other nodes in the network (Dohler, M., & Aghvami, A. H, 2008).

Cooperative wireless communication supports direct communication between the nodes in the wireless network in a distributed fashion and it gains similar advantages as that of traditional MIMO based communication. Cooperative communication improves the capacity, speed, and overall performance of the wireless network (Nosratinia et al., 2004). It also extends the network coverage and lifetime (Nosratinia et al., 2004). Cooperative communication mainly depends on the parameters such as resource allocation to the nodes and relay selection. The selected relay node is required to provide optimal performance with the lesser allotted resources (Rege and Abdullah, 2016).

Cooperation between nodes in a wireless network is possible if the number of nodes in the network is three or more, as shown in figure 2.1. The three-node model shown in figure 2.1 involves the source node 'S', the relay node 'R' and the destination node 'D' (Cover and El Gamal., 1979). The source node (S) originates the information, and it intends to send the information to the destination node (D), and the relay node (R) supports the communication between S and D when the link between S and D is weak. Two phases of operation exist in cooperative wireless communication such as Phase-I and Phase-II. The source node ‘S’ transmits the signal and the signal received by the nodes relay node ‘R’ and the destination node ‘D’, and this phase is known as the broadcast phase. The node ‘R’ forwards the information to ‘D’ and this is the multiple access phase.

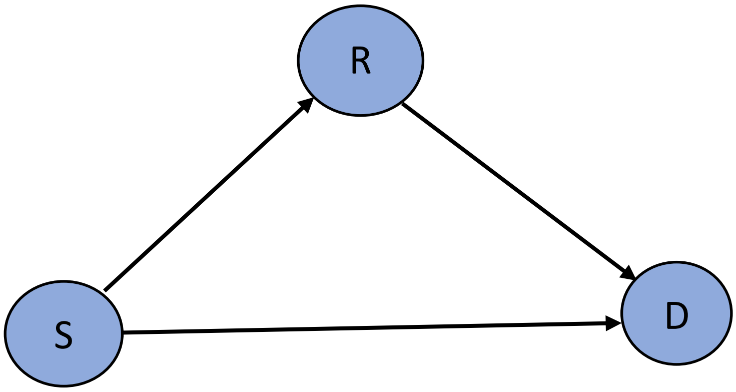

Figure 2.1. Three-node relay model

2.1.1.1 Cooperative Relaying Protocols

The relaying protocols provide the details of the data processing at the relay nodes in a cooperative wireless network. Cooperative relaying protocols are categorized as Fixed and Adaptive relaying protocols (K.J. Ray Liu et al.,2008).

In the fixed relaying the sharing of the channel, resources are deterministic between the source and relay node. The significant benefit of fixed relaying is its more straightforward implementation. Moreover, the limitation of this type of relaying protocol is its degraded bandwidth efficiency due to the resource sharing among relays even though the source to destination link does not suffer from the channel impairments. Limitations of the fixed relaying are overcome by adaptive relaying techniques (Hong et al., 2010).

Fixed Amplify and Forward Relaying

The relay node amplifies and forwards the scaled version of the source node signal to the destination node in the AF relaying protocol (Lanemann et al., 2004). The signal from the source node is received by the relay node and at the destination node. The source signal is received at the relay node, in addition the noise exists in the source to relay link is amplified and forward to the destination. The BS can make a better decision on the detection of the source information based on the two faded version of the signal received (Nosratinia et al., 2004).

Fixed Decode and Forward Relaying

The relay node decodes the source information and forwards the signal to the destination node in the DF relaying (Andrew Sendonaris et al.,2003). It reduces the additive noise effects of the source to relay link, which is the major limitation in AF relaying (Fitzek, F. H.et al.,2006). In Phase-I, the transmitted source signal is received by the relay node and the destination due to the broadcast nature of the source transmission. However, if the decoded signal has the error bits, then the relay will retransmit the erroneous signal, it degrades the received signal quality at the relay node. To overcome the limitation of the erroneous retransmission (Laneman et al.,2004) proposed a hybrid DF protocol.

Adaptive relaying protocols

Fixed relaying protocols suffer from the lower spectral efficiency issue. This limitation is overcome by the adaptive relaying protocols (Hong et al., 2010). Selection relaying is the type of adaptive relaying protocol.

Selection DF relaying

The decode and forward of the source signal at the relay node depends on the SNR threshold condition. If the SNR of the received signal at the relay is above a certain threshold then the relay will be in active mode. If the source to relay link SNR is below the threshold, then the relay will not participate in the communication (Laneman et al.,2004).

2.1.1.2 Need for Relay Selection in Cooperative Wireless Networks

Relay selection plays a vital role in the performance of cooperative wireless networks. Ineffective relay selection in cooperative networks results in performance degradation

(Abdulhadi, S.et al.,2012). The use of distributed virtual antenna terminals from multiple relay nodes improves the reliability in a cooperative wireless communication environment. The relay nodes between the source and the destination node create an additional link to forward the source information to the destination as shown in figure 2.2. The forwarding of the source information depends on the type relaying protocols (Zhang et al., 2016). Relay selection allows the best-selected relay to assist the source transmission to the destination and it reduces the power consumption of the remaining relay nodes (Mohamed et al.,2014).

The existing relay selection scheme in the literature classified into two major categories a centralized relay selection and a distributed relay selection. In a cellular network, the base station communicates with the mobile station using an infrastructure-based network, and in this case, centralized relay selection is used.

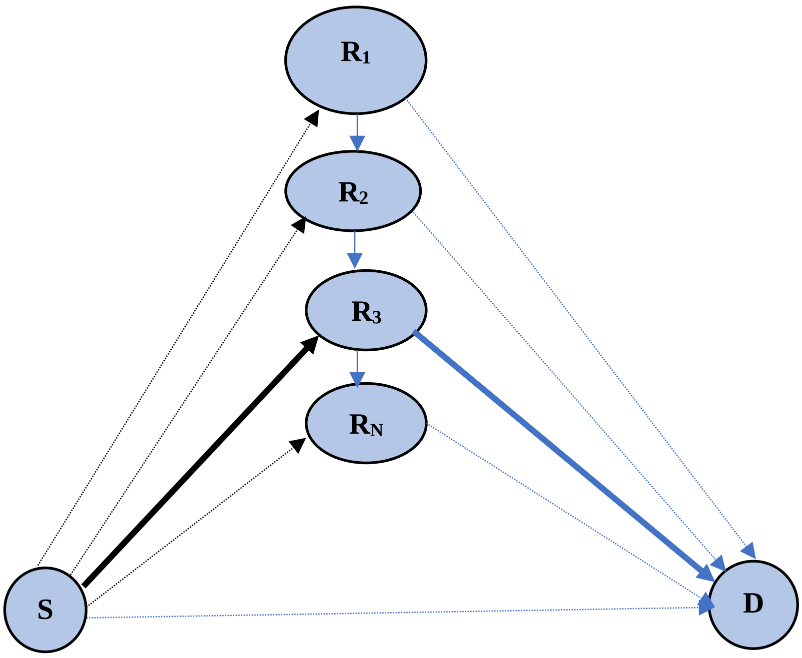

Figure 2.2. Relay selection in Cooperative wireless network

This type of relay selection has the central node that collects the required information from the relays for the communication purpose, as shown in figure 2.3. The type of relay selection proposed by Ibrahim et al., (2008) does not have a central controller and allows each node to decide whether to cooperate with the requested node or not? In this type, each node has the freedom to decide which node to cooperate with based on the control information exchanged between the nodes. The relay selection based on the feedback in the multi-relay cooperative cellular network needs perfect CSI (Kim et al. 2007). Different criteria are used in the relay selection such as SNR, geographical information of the relay node, and so on. The relay with maximum SNR is selected as the best relay in the case of relay selection concerned with SNR. The constraints of the wireless network are based on the different applications for example in cellular network- based data transfer, throughput is one of the major constraints (Bonder et al., 2014). So, in cellular networks, the centralized relay selection is applied in most cases and the relay selection is controlled by the base station and other cellular network elements.

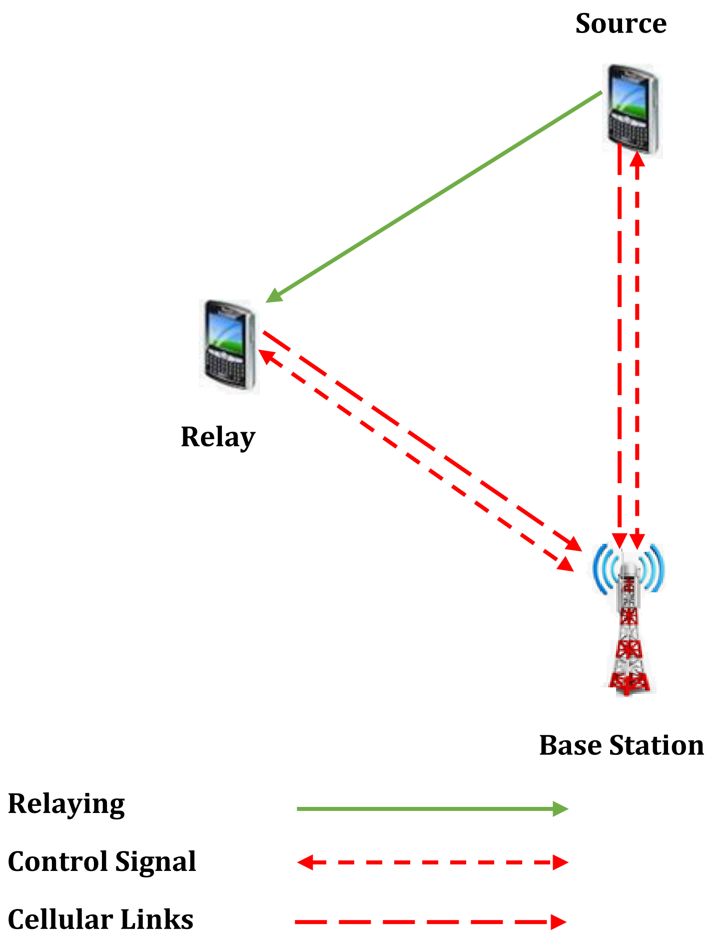

Figure 2.3. Base station controlled relaying

2.2 Related Literature

The wireless network advancements are aiming to match the increasing demand for the mobile subscribers such as increased capacity and high data rate which are essential for multimedia application requirements. The wireless channel impairments such as path loss, shadowing and fading are the major challenges for the service providers in deploying wireless networks. MIMO is one of the prominent techniques to overcome the above-mentioned challenges of the wireless network.

MIMO uses multiple transmit and receive antennas in the network elements, and it improves the reliability of wireless links (Telatar et al., 1999). The multiple antennas and space-time coding at the transmitter and receiver improve the capacity of the communication link. The major issue of the MIMO based network is power consumption and increased complexity (Marzetta et al.,1999).

Berezdivin et al. (2002) stated in his work that the relays using the time-domain relaying technique apply time-division multiplexing to access the channel and this allows the relay node to communicate with other nodes in the network. The relay uses different timeslots for transmitting and receiving the signals. In the case of frequency domain relaying, different frequency is assigned for the uplink and downlink for the relays to transmit and receive the signals from other nodes simultaneously.

Zhang et al. (2012) reported that MIMO cannot be applied to the types of network such as wireless sensor and Ad-hoc networks due to the size and power limitations of the nodes in these types of networks. Ahmed, Q. Z et al. (2012) developed the low-complexity receiver for cooperative wireless sensor networks.

2.2.1 Wireless Relay Networks

Distributed MIMO in a wireless network is formed by using multiple single-antenna nodes in the distributed fashion. The space-time coding applied to the single- antenna nodes in the work of Jing et al. (2006). In this work the author applied distributed space-time coding (DSTC) to the single-antenna nodes. This study shows similar diversity achieved as that of traditional MIMO systems. This work applies two-phase transmission in Phase-I signal transmitted to the relay and in Phase-II the relay converts the signal into linear dispersion space time code. This work assumes that full CSI is available at the receiver node.

Genc V. et al. (2008) proposed the wireless relay networking, and this technique achieves diversity without implementing multiple antennas in the user terminal. Sadek et al. (2010) developed the virtual antenna array using the multiple-single antenna nodes to communicate with other nodes. The major limitation exists on the selection of multiple single antenna relay nodes. If the relay node selection is not proper, then it leads to the overall network performance degradation.

Gang Liu et al. (2011) developed cooperative relaying that improves the relay-based wireless network performance, and, in this technique, multiple relay nodes transmit the data to the base station. The authors also reported the path management in IEEE 802.16j network between the nodes.

2.2.2 Cooperative Wireless Communication

Edward C.Van Der Meulen (1971) first introduced the relay channel, and in this work, the three-terminal communication channel capacity is obtained based on the timesharing approach, which is a pioneering work in the field of relaying and cooperative transmission which led to the enormous amount of theoretical and practical work published by many other researchers in this field.

The work of Cover and El Gamal. (1979) serves as the fundamental idea for cooperative wireless communication and in this study three-node model was analyzed. Furthermore, the author developed theorems to calculate the capacity of the three-node model.

Andrew Sendonaris et al. (2003) introduced the type of spatial diversity, and it achieves the diversity gains through the cooperation of mobile users in their two-part paper. The user cooperation strategy was analyzed in Part-I and performance analysis and implementation issues discussed in Part-II.

Nicholas Laneman et al. (2003) developed a technique that achieves cooperative diversity by applying DSTC, but the limitation is the complexity of the coding scheme. This issue was addressed in the later work by Laneman et al. (2004) and proposed cooperative diversity with less complexity. Timer-based single relay selection proposed in this work, the source node send the ready to transmit (RTS) to the destination and it is overheard by the relays. The clear to send message by the destination node is send as a reply to the source and all the relays in the coverage area to adjust the power level based on the defined policy. The timer is set at the relays and the relay with less timer value is selected. This work reports relaying techniques such as amplify-and-forward, decode-and-forward, and selection relaying.

To resolve the complexity of the scheme proposed by Nicholas Laneman et al. (2003), Aggelos Blestas et al. (2006) proposed the opportunistic relaying (OR) that selects the best relay to assist the source transmission. This study reported the issue of packet collision in distributed relay selection and more channel estimation and increased complexity in centralized relay selection. Aggelos Bletsas et al. (2006) proposed the multi-relay beamforming and destination-based relay selection. This study reported an increase in diversity order and reduction in transmission power. The major limitation of this study was the training overhead that depends on the number of relays.

Li et al. (2008) developed the carrier frequency offset (CFO) mitigation for orthogonal frequency division multiplexing (OFDM), and the CFO mitigation is critical in OFDM since the small CFO may lead to degraded performance. The findings of this study show that cyclic prefix (CP) has a significant role in mitigating the CFO. Mitigation performance is improved based on the CP length. Choosing the CP length has its impact on the power and bandwidth efficiencies as well. This study uses the extended CP, and this affects the processing gain. The limitation of this study includes the complete CFO removal result in bandwidth efficiency degradation.

The CFO mitigation for the cooperative and non-cooperative networks was analyzed by Shamganth. K et al. (2011). This study shows the improvement in the mitigation performance depends on the CP length. The performance of the CFO mitigation algorithm differs from CP. Thus, the study shows that long CP is required to improve the transmission efficiency, and it differs from the CP mitigation technique (Li et al. 2008). This study shows improved performance and avoids the degradation of bandwidth efficiency. Ahmed, Q.Z et al. (2015) developed the transmitter with limited processing capability at the receiver.

2.2.2.1 Relay Selection

Zhao, Adve, and Lim (2007) revisited the work of Laneman (2004) and proposed the Optimal Power Allocation (OPA) algorithm for the all-participate-amplify-and-forward (AP-AF) to minimize the outage probability for the multiple relay node scenario. Also, by this OPA scheme, the author proved that SER is minimized. The performance of the AP-AF scheme degrades if the cooperating nodes are more for larger network scenarios. To overcome this overhead in this work author introduced selection based amplify and forward (S-AF) in which only the best node is chosen as the relay node. This single relay selection is different from the work of Aggelos Bletsas et al. (2006) since it is not based on the delay process at the relays. In this work, the relay selection is combined with OPA.

In the distributed relay selection technique, there is no feedback to the central controller node involved in the distributed relay selection. Moreover, the nodes participating in information transmission has the details of the received SNR. Different types of distributed relay selection are simple selection, fixed priority selection, and relay selection based on outage probability. Categories of distributed relay selection are single-relay selection (SRS) and multi-relay selection (MRS).

Opportunistic relaying (OR) scheme developed by Aggelos Blestas et al. (2006) does not consider power allocation at the relay nodes. Findings of Chen Y et al. (2006) addressed the limitations in the relay selection scheme "Power-Aware Relay Selection" (PARS), the power constraint added to the OR scheme in this scheme and it uses “Optimal Power Allocation” (OPA) to minimize the total transmitted power. Total power is minimized by the channel measurement performed by the relays. The network lifetime extension by 100% is achieved by combining the PARS with the OR scheme. But there is a limitation of collision in combining the PARS and OR if the timer expiry is at the same time for two relays. In this scheme, during the relay selection, there is a CSI requirement of all the links, and it increases the complexity. This limitation is addressed in the work of Kyu-Sung Hwang et al. (2007) "Switch and Examine node selection" (SENS). It is a multi-hop relay protocol, and the relay is selected if the link SNR is above the threshold. In this scheme, the relay remains selected until the link SNR is less than the threshold. SENS has less complexity compared to the OR scheme. There is no requirement of all the relays in the listening mode all the time due to this approach power consumption is less. In SENS, the switching concept introduced with the sub-optimal relay selection algorithm switch between the nodes if the node performance is degraded based on the channel conditions.

Tajer et al. (2007) developed an opportunistic cooperation method to minimize the information exchange between the cooperating nodes. It requires less CSI feedback, but the diversity multiplexing trade-off (DMT) is the same as DSTC. They also studied the relation between the diversity multiplexing trade-off and bandwidth allocation between the source node and its partner node in a cooperative wireless network. Limitation in this scheme is many relays are in listening mode and decode the source node transmitted signal, so the power consumption is high. To overcome this limitation Aggelos Blestas et al. (2007) proposed an opportunistic AF relaying with feedback and this scheme is simple and has increased diversity order and less power consumption. In this scheme ARQ is combined with OR for the feedback from the destination node. The selected relay will be active, only if the destination node could not decode the source node signal correctly. Due to the feedback from the destination, there is a limitation of additional overhead in this scheme.

"Geographical information based relaying selection" developed by Wang et al. (2009) this scheme selects the best relay among the multiple nodes based on the location information of the nodes in a cooperative wireless network. The data is transmitted between the cooperative clusters and this scheme has less symbol error probability (SEP). It also increases spectral efficiency and less overhead required. The major limitation in this method is the geographical information requirement of all the nodes.

Relay Selection Schemes for Cooperative D2D Communication

This section summarizes the relay selection schemes suitable for Cooperative D2D communication shown in table 2.1 (Shamganth & Sibley, 2017). The table presented below published in “International Conference on Energy, Communication, Data Analytics and Soft Computing (ICECDS)” (Shamganth & Sibley, 2017).

Table 2.1 Summary of Relay selection schemes for Cooperative D2D Communication (Shamganth & Sibley, 2017)

Citation	Relay selection scheme	Main idea
(Ma et al., 2012)	Distributed Relay Selection Method for Relay Assisted D2D Communication	This algorithm mainly studied the relay selection problem for D2D communication underlaying cellular network.
(Miao et al., 2014)	Cross-Layer Relay Selection Algorithm for D2D	The main focus of this algorithm is to overcome the limited buffer capacity issue of the traditional relay selection schemes.
(Zhang et al., 2015)	Joint Relay Selection and Resource allocation	An efficient resource allocation scheme and a low complexity relay selection strategy proposed for D2D enabled cellular networks, where a D2D UE can act as a source as well as a potential relay for other UEs.
(Panigrahi et al., 2016)	Dynamic Relay Selection for LTE-D2D Communication	A joint solution proposed in this scheme for dynamic selection of an optimal relay UE and adaptive modulation based D2D scheduling
(Ansari, R. I et al.,2016)	Energy Efficient Relay Selection in Multi-hop D2D network	In this scheme, the energy-efficient relay selection for cooperative multi-hop device-to-device (D2D) networks studied.

2.2.2.2 Threshold based Relay Selection

Yang & Alouini (2005) proposed the Output Threshold MRC (OT-MRC). In this output threshold-based scheme, the destination node adaptively combines the diversity paths and test the output SNR with a preselected threshold.

W. Pam Siriwongpairat et al. (2006) proposed the multiple relay selection scheme that has two phases: the quality of the signal received at the relay is compared with a threshold in the first phase. During the second phase, the relay that satisfies threshold requirements is selected. This scheme aims to reduces the channel estimation and compares it to the scheme without threshold where all relays will participate in the relayed transmission. But it has the limitation of an increased number of channel estimations if more relays meet the threshold requirements. This is due to the fixed threshold does not react to the channel conditions.

In DF relaying scheme the error propagation occurs if the relay has the detection errors and forward it to the destination then SNR will be degraded during combining. (T. Wang et al., 2006) introduced the type of digital relaying named as link adaptive relaying (LAR) at the relay to achieve full diversity. In this method the adaptive relay transmits power at the relay with respect to link SNR. This method is suitable for both coded and un-coded cooperative networks. The power scaling factor (α) used in this method archives performance improvement in terms of average bit error probability. Also, this method is more robust to feedback and quantization errors.

The threshold digital relaying (TDR) technique achieves cooperative diversity in a cooperative network with detection errors at the relays (P. Herhold et al.2007). In this scheme the relay with high SNR meeting the threshold requirement will retransmit the received signal from the source node and other relays remain idle (P. Herhold et al.2007). The threshold is selected in this scheme using the power fraction of the source and the relay. The power fraction is determined using a numerical optimization technique. A. Adinoyi et al. 2007 examine the effect of using multi-antenna in distributed fixed relays. The effect of using a larger number of relays with fewer antennas and a lesser number of relays with a greater number of antennas are studied. The findings of this study showed that performance is improved in the network with lesser relays and more antennas.

Onat et al. (2007) examined the SNR based selective digital relaying with an optimal threshold. In this scheme, the relay will decide whether to forward the signal to the destination or to remain idle based on the instantaneous SNR of the source to relay link. The threshold rule formulated in this work to minimize the average BER. The optimal threshold proposed in this study depends on the average SNR of the relay to destination and the direct link between source to destination.

Prakash Ponnaluri et al. (2007) studied the achievable diversity order of un-coded cooperative relaying. Hard-decision adaptive decode and forward protocol is used in this study. They also showed the change in threshold with respect to average SNR provides the performance improvement.

Kyu-Sung Hwang et al. (2007) devised a sub-optimal threshold-based relay selection scheme with the predetermined threshold fixed at the relay and the destination node. This scheme addresses the complexity and power consumption limitations in OR (Aggelos Blestas et al. 2006) for the large number of relays in the cooperative network. In this scheme, only the relay with the SNR above the threshold will be in listening mode and all the other relays are in silent mode. So, the channel estimation is less, and the power consumption is less compared to OR. This scheme addresses the limitation of the SENS (Kyu-Sung Hwang et al. 2007) i.e., the degradation in the BER performance in the low SNR regions. To overcome this limitation the switched diversity with post-selection (Yang et al. 2006) is applied in this scheme and it reduces the number of channel estimations.

Onat et al. (2008) studied the impact of SNR based selective digital relaying in minimizing the BER. This study analyses different models with the availability of source -destination, relay-destination, and source-relay instantaneous and average SNR. The findings of this study show that the relaying decision is improved by the knowledge of instantaneous SNR of the source-destination link and it reduces the end-to-end (e2e) BER. This study also suggests the hybrid schemes that employ selective digital relaying at the relay combined with the efficient detection technique shows performance improvement.

Lioumpas et al., (2008) combines the features of Minimum Selection-Generalized Selection Combining (MS-GSC) and Normalized Threshold (NT-GSC) in the proposed Absolute Threshold Generalized Selection Combining (AT-GSC). Moreover, this scheme achieves better adaption to channel conditions without increasing the system complexity.

Liu et al. (2010) proposed double testing with TDR. The limitation in the TDR is the error detection at the relay is not done. Without error detections, relays may transmit incorrect information despite threshold use. Hence, it is important that the threshold value can minimize end-to-end performance, considering error propagation. W. Pam Siriwongpairat et al. (2006) applied optimal threshold detection at the source-relay link. Ban et al.(2007) applied the optimal threshold at the relay-destination link. But in the proposed double testing method the relay measures the channel quality of both source-relay and relay to the destination during the retransmission to the destination. So, the error propagation is minimized (Liu et al., 2010).

Amarasuriya et al. (2010) developed the output-threshold multiple-relay-selection (OT-MRS) for the multi-branch cooperative networks. In this method threshold testing is done at the destination. This method uses orthogonal channeling and maximum ratio combining (MRC) at the relays. The scheme outperforms the single relay selection and generalized selection combining (GSC) based MRS.

Hao Niu et al. (2010) studied the threshold-based relay selection algorithm. This scheme is based on the threshold-based relay selection scheme proposed by Kyu-Sung Hwang et al. 2007. In the work of Hao Niu et al. (2010), the outage probability analysis of the threshold-based relay selection algorithm conceived by Hao Niu et al. (2010) is performed. The expression of the closed-form outage probability is derived. This scheme achieves the same diversity as the OR scheme (Aggelos Blestas et al., 2006) and reduces the number of channel estimations.

Liu et al., (2010) devised a threshold-based hybrid relay selection scheme. In this scheme the relays are divided into AF and DF relay groups. This scheme considers the grouping of relays based on the method of error detection that depends on the SNR threshold. Also, frame detection is used and not the symbol detection. The relay that has the instantaneous SNR above threshold is placed in the DF relay group and other relays are placed in the AF relay group. The relay with maximum instantaneous SNR is placed in both AF and DF relay groups. This scheme is a combination of hybrid relaying and relay selection. Liu et al., (2010) analyzed the frame error rate performance of the hybrid relay selection with convolutional coding at the source node. In this work, the improved SNR threshold-based FER approximation model was developed. This model applied to the hybrid relay selection to derive average FER expression at high SNR.

Park et al., (2011) proposed an Adaptive Threshold-based relay selection scheme (ATRS). In this method, the source selects the best relay among the multiple relays in the network if the relay-destination instantaneous SNR is above the threshold. There is a notable difference observed between the relay selection scheme proposed by Onat et al. (2008) and this scheme as follows; the source selects the relay in the work of Park et al., (2011) and the destination selects the relay in the scheme proposed by Onat et al. (2008). Also, there is no control message exchange in the Park et al., (2011) relay selection scheme but there exists the control message exchange by Onat et al. (2008). The complexity and the power consumption is less in the relay selection scheme proposed by Park et al., (2011) as compared to Onat et al. (2008).

Gharanjik & Mohamed-Pour (2011) analyzed the "switch-and-stay partial-relay selection" (SS-PRS). The outage probability and average (ABER) performance is evaluated SS-PRS scheme. The SS-PRS has a similar outage performance of the PRS scheme proposed by Krikidis et al. (2008) but the SS-PRS scheme has less complexity compared to the PRS.

Kyu-Sung Hwang et al. (2012) developed the incremental relay combining with output threshold (IRC-OT). This scheme is the type of multiple relay selection combined with incremental relaying to achieve spectral efficiency and diversity gain. This scheme has less complexity and improved BER performance compared with incremental relaying and all-participate relaying schemes.

Herath et al., (2012) proposed the "distributed switch-and-examine combining with threshold-based relay selection" (DSEC-T). This scheme is the combination of the switch-and-examine combining (Yang et al., 2003) and threshold-based relay selection. The relay is selected based on the source-relay link SNR. The relay selection process is stopped if the SNR at the relay is above the threshold. AF relaying is applied at the relay to forward source information to the destination. Ahmed, Q. Z et al. (2012) developed the minimum bit error rate detector for AF relaying as the noise was not Gaussian.

Salhab & Zummo, (2013) proposed the sub-optimal relay selection scheme. The switching threshold scheme used in the scheme gives optimum performance in terms of bit-error-probability (BEP) in contrast to the relay selection scheme proposed by Hwang et al. (2007). In the proposed scheme the author showed the selection of relay is based on the switching threshold if the e2e SNR is above the switching threshold then the relay will be selected. The channel estimations and the power consumption at the relay are less compared to the switch and examine combining scheme. Ahmed, Q. Z et al. (2014) studied the channel estimation error in threshold-based detection for AF networks.

Xie et al. (2014) developed the diversity combining scheme based on generalized selection combining with the double threshold. This scheme is developed for the multi-channel communication system. Ahmed, Q. Z et al. (2014) developed the combining scheme for cooperative wireless sensor networks using channel shortening technique.

Aydm, et al. (2015) proposed the optimum threshold-based relay selection algorithm based on MRC, cooperative MRC (Yi et al., 2008) and virtual noise considered for DF relaying. This scheme considers in Nakagami-m fading channel distribution for the direct link between source to destination and the relayed links source to relay and relay to destination.

Zhiquan Bai et al. (2015) proposed "Incremental Hybrid Decode Amplify Forward Relaying" (IHDAF) it is a three-node cooperative relaying scheme. This scheme combines the hybrid Decode Amplify Forward Relaying developed by Duy & Kong, (2012) and incremental relaying by Laneman et.al,(2004). In this scheme the relay adaptively decides to transmit the source signal or to remain in a silent mode based on the link quality between the source-destination, source-relay, and relay- destination nodes. The relay also decides on the type of relaying to apply whether AF or DF based on the SNR. This study applies cooperative mode not based on the SNR threshold at the destination and at the relay. Further, in this study the influence of power allocation, relay location, and SNR threshold with respect to the outage probability is analyzed. The findings of this study show the outage and BER performance improvement of IHDAF in comparison with incremental-selective DF (ISDF) relaying and incremental DF (IDF). Ahmed, Q. Z et al. (2013) studied the optimal linear detector and Ahmed, Q. Z et al. (2014) developed the optimal transceiver for non-orthogonal AF relaying and findings of the two study shows the diversity order improvement.

Nagarajan et al. (2017) proposed multiple relay selection based on DF relaying protocol. This method overcomes the limitations of detection errors in the selection combining scheme by using an optimal threshold at the relays. Nevertheless, as the number of relays in the network increases, the efficiency of finding the best relay for forwarding the data decreases. The authors studied the error rate of the multiple relay DF scheme in a flat Rayleigh fading environment. The findings of this study indicate that the instantaneous SNR threshold at the relays has its impact on the symbol error probability. Ahmed, Q. Z et al. (2015) developed the new symbol error rate detector to minimize the symbol error.

Dayanidhy & Kumar, (2017) proposed selection combining with full CSI. This scheme overcomes the performance degradation experienced due to the detection errors in multi-relay DF networks. The proposed selection combining scheme in this study has improved symbol error probability (SEP) compared to the conventional Selection Combining (SC) techniques.

S.S. Nam et al. (2018) extended the ATRS scheme proposed by Park et al., (2011) and analyze the SER performance based on limited feedback. The extended ATRS scheme proposed by S.S. Nam et al. (2018) overcome the performance degradation of discarding the better relay to destination links due to minimum feedback in Park et al., (2011) by 1-bit increase in feedback data rate in the type II relay environment.

Ferdi Kara et al. (2019) proposed Threshold based Selective Cooperative Non-Orthogonal Multiple Access (TBS-C-NOMA) to improve the data reliability and to overcome the error propagation issue in the conventional cooperative NOMA based network. In this scheme the cell edge user will receive the forwarded signal from the user near to the base station if the signal to interference plus noise ratio (SINR) is above the threshold and this avoids the error propagation.

Ferdi Kara et al. (2020) analyzed the outage probability and ergodic capacity of TBS-C-NOMA scheme proposed in Ferdi Kara et al. (2019). In this work the authors derived the closed form expressions of outage probability and ergodic capacity and applied to symmetric and asymmetric channel conditions. Furthermore, there is a tradeoff identified between the BER performance and outage and ergodic capacity. The joint power allocation and threshold selection proposed in this work provides performance improvement in terms of both BER and ergodic capacity.

2.2.3 Differential Modulation based Cooperative Communication

The relay selection scheme with coherent modulation assumes the CSI is estimated at the destination and the relay nodes. However, in the real-time fading environment, the CSI estimation in the cooperative wireless network with multiple relay nodes is challenging. The differential modulation scheme does not require CSI at the relay and the destination nodes. Depends on the type of modulation we select there will be a requirement of partial or full CSI. Coherent detection requires the CSI of both the direct link and the source-relay and relay to destination nodes. However, for differential modulation, there is no requirement of CSI. The scheme combining the differential modulation and relay selection exists in the literature are as follows:

Qing Zhao et al. (2005) proposed the AF relaying suitable for differential modulation in cooperative wireless networks. This scheme does not require instantaneous channel estimates as it is required in coherent modulation schemes. In this work, the closed-form expression of probability density function (PDF) of the SNR and the average bit error rate derived. The findings of this study show improved performance for AF based differential modulation compared to the non-cooperative differential PSK modulation.

Poramate Tarasak et al. (2005) developed the two-user cooperative diversity technique using differential modulation. In this scheme, if two users want to communicate to the same destination the information of the first user mapped in the in-phase (I-axis) and another user is mapped to the quadrature-phase axis (Q-axis) to ensure both users information decodable at the destination. In this study, the performance of DF and selection relaying protocol is evaluated for both symmetric and asymmetric cases. This study shows that DF achieves high-performance gain for symmetric scenarios. Furthermore, this study also shows that higher performance gain is achieved for selection of the relaying protocols for the asymmetric inter-user channels.

Himsoon et al. (2005) proposed the differential AF transmission scheme for a two-user cooperative communication system. This scheme with DQPSK modulation provides performance improvement compared to DBPSK modulation with direct transmission.

Himsoon et al. (2006) proposed a differential AF scheme for multi-node cooperative wireless networks. The limitation in the study of Himsoon et al. (2005) is the optimum power allocation not examined extensively for the two-user scenario. In this study, the closed-form optimum power allocation is evaluated for a single relay scenario and extended for the multi-relay scenario as approximate power allocation. The findings of this study is source node should be allotted with more power as compared to other nodes in the network to achieve better performance. The relay location also plays a significant role to achieve the performance of optimum power allocation the gain increases if all the relays are nearer to the destination.

The binary differential transmission schemes developed by Qiang Zhao et al. (2007) are differential amplify and forward (DAF) and differential decode and forward (DDF). This study analyzed the BER performance of DPSK in a single relay-based cooperative wireless network. The analytical framework developed in this study calculates the outage probability and for the PDF of the instantaneous SNR and average BER in the Rayleigh fading channel for the DAF and DDF schemes presented for single relay schemes. This study also shows the performance improvement obtained in cooperative DAF and DDF schemes in terms of cooperative diversity compared to the conventional non-cooperative differential modulation schemes.

Thanongsak Himsoon et al. (2008) analyze the differential modulation schemes for multimode cooperative wireless networks scenario named as multi-node differential amplify and forward scheme (DiffAF) and multi-node differential decode and forward scheme (DiffDF). In this study, the performance of the DiffDF scheme is enhanced by Joint optimization of power allocation and decision threshold which minimize the BER.

Chu et al. (2008) proposed the differential modulation based on an estimate and forward relaying. In this study, the selective combining is used at the destination, and it reduces the complexity. Maximum Likelihood (ML) algorithm used to estimate the signal at the destination. This scheme overcomes the limitations of Qiang Zhao et al. (2007) in which the estimate-and-forward relaying with the PL algorithm. The findings in the study of Chu et al. (2008) showed that the ML algorithm with the differential estimate and forward relaying has improved performance compared to the PL algorithm with the differential estimate and forward relaying.

Chu et al. (2008) also developed the differential modulation with relay selection in combination with the detect-and-forward relaying protocol. In this scheme, differentially modulated signals from the source received by the relays. Moreover, the best relay can detect the source signal correctly; then it will forward the source signal to the destination node. Findings of this scheme show that the proposed scheme outperforms the differential AF scheme and worse than differential perfect detect and forward scheme. However, the limitation in this scheme compared to the non-cooperative scheme is the degraded spectral efficiency.

Fang et al. (2009) proposed the differential modulation scheme generalized differential modulation (GDM) with AF relaying. This scheme bridges the performance gap between the differential modulation and the coherent detection experienced in the schemes proposed in the work of Qiang Zhao et al. (2007) and Himsoon et al. (2006). The differential modulation scheme in the work of Fang et al. (2009) divides the transmitted frame into many small blocks. The first symbol in the block is referred to as the reference symbol, and the remaining symbols are normal. The reference symbol in each block is encoded differentially based on the preceding reference symbol, while the regular symbols are encoded differentially based on the reference symbol in the same block. The findings of this study show that more transmit power to the reference symbol leads to reliable transmission.

Zhu et al. (2010) investigated the differential modulation and demodulation of a multi-relay cooperative wireless network using DF and selective relaying (SR) protocol. The relay in this scheme uses the instantaneous BEP of the source- relay node to decide on whether to forward or to remain in silent mode. A maximum-likelihood detector for DF protocol is derived, and a piecewise linear (PL) detector proposed in this study. The error performance of a multi-relay system operating with the SR protocol is analyzed. It shows that SR protocol achieves full space diversity in terms of error probability perspective.

Kim et al. (2011) developed the selection cooperation with double differential modulation using AF relaying (DDAF). The carrier offset problem in DDAF occurs due to the difference of oscillator frequency between the transmitter and the receiver and overcome by using a double differential modulation scheme (Bhatnagar et al., 2008). This scheme overcomes the limitations of DAF due to the carrier offset and provides improved performance.

Gao et al., (2011) analyzed the performance of differential modulation-based relay selection in the multi-relay cooperative wireless network. This scheme employed detect-and-forward relaying. The same relaying technique is used in Chu et al., (2008) and the closed-form BER approximation with BPSK. However, in this scheme, the closed-form BER approximation with MPSK is derived. The closed-form solution obtained in this study achieves full diversity order.

Avendi et al. (2013) analyzed the performance of multi-relay selection for differential M-PSK modulation with AF relaying over fast fading channels. In this study, the performance of the system analyzed using optimum MRC weights, and that result is used for the lower bound error performance. Moreover, the new combining weights proposed at the destination based on the autocorrelation values. The findings of the study show a degradation in the error performance relates to the fading rate. The proposed combining weights shows better performance compared to conventional combining weights.

Avendi & Nguyen. (2013) analyzed the differential AF relaying with slow-fading channel using post-detection selection combining at the destination. The findings of this study show that the complexity of selection combining is less compared to MRC with similar performance. Avendi & Nguyen. (2014) analyzed the differential AF relaying with a fast-fading channel using post-detection selection combining at the destination. The study in (Avendi & Nguyen, 2013) is valid for a slow fading environment, and it is not suitable for highly mobile users. In this study, DBPSK modulation with fixed gain at the relay is used along with a non-coherent detection scheme. Furthermore, the per-frame transmission is assumed in this scheme to avoid switching between the transmission and reception required for symbol-by-symbol transmission. The findings of this study show that BER performance depends on the fading rates of the channel.

2.2.4 Physical Layer Security in Cooperative Communication

The physical layer security in cooperative wireless networks studied by Zou, Y et al. (2013). In this work the author developed the optimal relay selection schemes to enhance the physical security through AF and DF relaying protocols; proposed AF based optimal relay selection (P-AFbORS) and proposed DF based optimal relay selection (P-DFbORS).

Cooperative beamforming with physical layer security and partial relay selection is developed by Qian, M. et al. (2016). The author has considered source-destination pair and number of DF relays along with the eavesdropper node and two relay strategies; linear-complexity relay ordering, and exponential complexity exhaustive search used for the performance analysis. Findings of this study show that high secrecy capacity exists as compared to existing search schemes. An enhanced relay selection scheme named as proposed source relay selection (PSRS) along with physical layer security is developed by Shim, K. et al. (2017). The author has investigated the privacy performance of the opportunistic scheduling in multi-relay cooperative modelling.

The optimal sequential deployment is analyzed and the measurement-based optimal technique for the dual-hop wireless relay network was developed by Ghosh, A. et al. (2017). The author used multi-connectivity approach in the individual system by providing effective communication amongst individual node and the neighboring node.

Khyati Chopra et al., (2018) studied the secrecy outage performance of threshold-based DF scheme with direct link and in the absence of direct link between source to eavesdropper and source to destination nodes. Unlike the other existing works in the literature the author does not assume that all the relays will correctly decode the source information. Findings of this work shows the link quality source, relay and destination affect the outage performance. Also, the eavesdropper link quality and the secrecy rate requirement have its effect in the outage performance.

From the literature review, it is observed that still issues exist in terms of physical layer security improvement for cooperative D2D networks. Moreover, the chances of eavesdropping effect are high if more relays with poor received signal quality were selected.

2.3 Research Gap

Since relay selection selects the best relay to assist the source transmission, identification of an effective relay selection technique is essential to improve the overall performance of the cooperative wireless network, considering the network's security aspects.

The constraints of the wireless networks depend on the application for example node power is the major limitation in sensor networks, whereas, in cellular mobile communication, mobility is the major constraint. The transmission protocols that consider the SNR, error performance, interference, secured transmission, and power consumption at the nodes need special attention. Thus, methods for direct communication between the nodes in the network without using the base station must be introduced to enhance connectivity in a multi-relay cooperative wireless network.

Security in cooperative wireless networks is one of the major challenges and improving security in cooperative network need special focus. The security issue arises due to the eavesdropping attack in the cooperative network due to the broadcast nature of the source signal. The signal transmitted by the source is received by the multiple relays and the eavesdropper node, so the security is a major issue cooperative wireless network.

Threshold-based relay selection techniques in cooperative wireless networks draw more attention, and the present works mainly focus on coherent modulation with the AF and DF relaying protocols. However, the channel estimation of the source to relay and relay to destination link adds more complexity which is overcome by the differential modulation schemes. Differential modulation with AF and DF does not require instantaneous channel information which in turn reduce the complexity of the overall system. Existing works apply the threshold at the relay and at the destination applying DF relaying at the relays. Among the relaying schemes AF and DF, the AF and the differential AF are more attractive due to its lesser complexity at the relay and the destination. However, the threshold-based differential AF scheme is not studied extensively in cooperative wireless networks. Moreover, there is a need for double threshold-based relay selection in cooperative D2D communication operating in out-band. In the double threshold scheme threshold set at the relay based on the location of the relay is also essential during power allocation at the source and the relay nodes. Moreover, the threshold at the combiner output is required to improve e2e performance. As an extension to the double threshold relay selection scheme introducing threshold at the input to the combiner is also essential, and this scheme is multi-threshold based multi-relay selection. This extended model will select the signal from the relay-destination link if the SNR at the input to the combiner is above the combiner input threshold. The proposed double-threshold and Multi-threshold scheme with differential modulation are not studied in the literature. Also, the application of double threshold-based differential AF to enhance the physical layer security in the cooperative wireless network is not studied in the literature.

Chapter 3

Single Threshold based Relay Selection

3.1 Introduction

Distributed relay selection in the cooperative network is categorized based on the number of relay nodes assisting the source node transmission to the destination node (Abdulhadi et al.,2012), i.e., Single relay selection and Multi-Relay Selection. In this chapter, the single-relay selection is widely discussed with the proposed threshold-based relay selection. The related literature of single-relay selection is discussed in chapter 2. Threshold-based relay selection exists in the literature mostly for the DF relaying (Thanongsak Himsoon et al. 2008). In this chapter, single threshold-based relay selection is widely studied with the AF relaying and Differential AF (DiffAF) relaying protocols. This chapter investigates the two variants by applying single threshold such as threshold only at the relays with the SER and BER performance for AF, and DiffAF protocols and threshold deployed only at the destination. Besides, the power allocation also plays a significant role in the performance of the system. The effect of power allocation plays a vital role in distributed relay selection. The two methods of power allocation scheme exist in the literature are adapted for the study of the threshold-based relay selection performance such as Equal Power allocation (Laneman et al.,2004) and Optimum Power allocation (Su et al., 2008). This chapter has two major parts that discuss the effect of Single-Relay selection with AF relaying protocol and single-relay selection with DiffAF relaying protocol for coherent and differential modulation schemes.

Moreover, in this chapter, the proposed single threshold-based relay selection with AF relaying and DiffAF relaying protocol is analyzed with coherent and differential modulation schemes. This chapter also presents the mathematical model of the proposed threshold-based relay selection for cooperative D2D out-band autonomous mode with single-threshold AF and Differential AF relaying using coherent and differential modulation schemes. In this chapter, comparative analysis of Single-Threshold based AF and DiffAF relaying using coherent modulation and comparison of Single-Threshold based AF and DiffAF using differential modulation also discussed. Part of the work presented in this chapter published in "International Journal of Electronics and Communication Engineering & Technology" (Shamganth, K. et al., 2016) and in "International Journal of Advanced Research in Computer Science and Software Engineering" (Shamganth, K. et al., 2014).

3.2 Single Threshold based AF with Coherent Modulation

Single threshold-based relay selection employs the received instantaneous SNR at the relay or the destination to select a relay. The fixing of threshold improves the received signal quality and reduces the power consumption of the relay nodes. Based on whether the threshold is fixed at the relay or at the destination it is categorized as destination-based relay selection and source-based relay selection.

3.2.1 Proposed Single Threshold-based Relay Selection Scheme

In the proposed single threshold-based relay selection scheme, the SNR threshold is fixed at the relay. The received SNR at the relay is tested and if the threshold is met the relay is selected. (Shamganth, K. et al., 2016).

Step 1: The relay located in the coverage area of the source receive the source signal.

Step 2: Relay node use AF relaying protocol. The input SNR threshold (γ_{iT}) is fixed at the relay.

Step 3: If the instantaneous SNR at the relay (γ_{sr}) is above the input SNR threshold (γ_{iT}) then the relay will be in active mode and is ready to amplify and forward the source signal to the destination. If this condition is not satisfied, then the relay will be in the sleep mode.

Step 4: If the threshold condition in step 3 is not satisfied at the relay, then signal from the direct link S-D will be used at the destination for detection.

Step 5: Maximum ratio combining (MRC) is used at the destination to combine the signal from the direct link and the relayed link.

3.2.2 System Model of Single-Threshold based Relay Selection

Single threshold-based relay selection scheme is investigated with AF relaying (Shamganth, K. et al., 2016). In this scheme, the selected relay amplifies the source signal and forward it to the destination node. The system model of the proposed scheme is shown in figure 3.1.

In the system model, the dual-hop scenario is considered, the transmitted signal from the user follows two orthogonal phases by using TDMA. The system model assumes that all the nodes consist of single-antenna, and the transmission is half-duplex (Shamganth, K. et al., 2016).

Information bits are converted in the format of binary phase-shift keying (BPSK). The transmitted signal from the source given is by Nguyen, H et al. (2009)

$$x(t) = m(t) * c(t), \tag{3.1}$$

with the phase either 0 or π radians.

The transmitted BPSK signal is given by

$$\begin{cases} x_1(t) = -A\cos(2\pi f_c t) \;\; if\ the\ information\ bit\ is\ '0' \\ x_2(t) = +A\cos(2\pi f_c t) \;\; if\ the\ information\ bit\ is\ '1' \end{cases} for\ 0 \le t \le T_b.$$

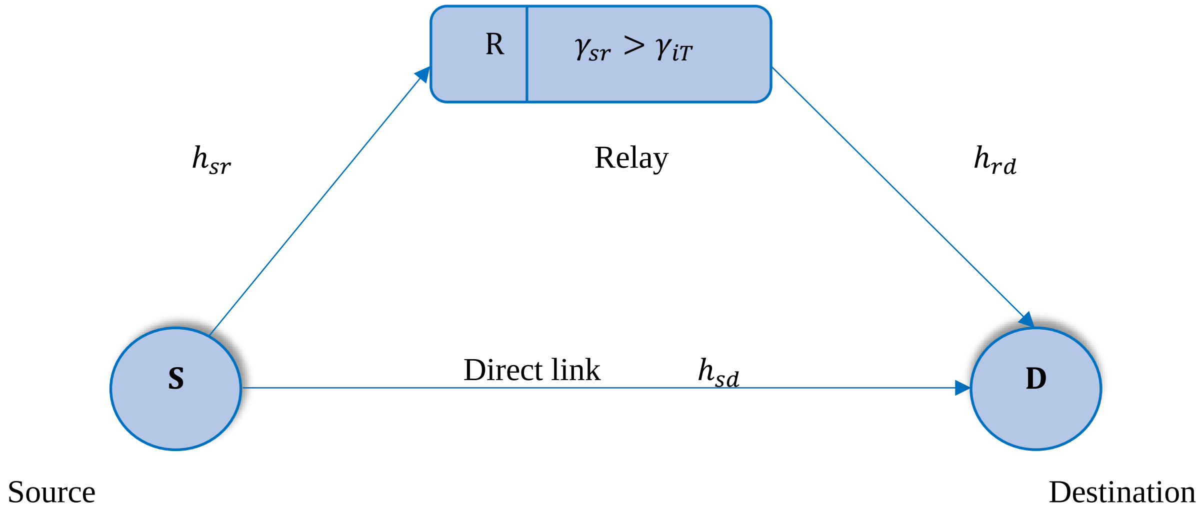

Figure 3.1. System Model Single-Threshold based Relay Selection.

In Phase-I, the source node transmits the signal to the destination node, and the relay nodes overhears the source signal due to its broadcast's nature (Shamganth, K. et al.,2016).

The signal received at the relay in Phase-I given as:

$$y_{sr} = \sqrt{P_s} h_{sr} x + n_{sr}. \tag{3.2}$$

The signal received at the destination node in the direct link S-D in Phase-I given as:

$$y_{sd} = \sqrt{P_s} h_{sd} x + n_{sd}, \tag{3.3}$$

where P_s denotes the average source power of the transmitted signal, n_{sr} *and* n_{sd} denotes the complex additive white Gaussian noise with zero-mean and variance N_0 and x denotes the transmitted information symbol. The channel between source and relay node (S-R), relay to the destination node (R-D) and the direct link source to destination (S-D) follows Rayleigh fading conditions.

The channel coefficients between the source to relay and the source to destination link has zero-mean and variance and is given by

$h_{sr} \sim CN(0, \sigma_{sr}^2)$, and

$h_{sd} \sim CN(0, \sigma_{sd}^2)$, respectively.

During the Phase-II the relay with SNR above the input threshold (γ_{iT}) is selected to amplify and forward the source signal to the destination. In Phase-II, the relay amplifies the signal from the source and forwards it to the destination (Shamganth, K. et al.,2016).

The instantaneous SNR of the source to relay link given as

$$\gamma_{sr} = \frac{P_s|h_{sr}|^2}{N_0}. \tag{3.4}$$

Threshold testing at the relay based on the following conditions (Shamganth, K. et al.,2016):

$$\begin{cases} if\ \gamma_{sr} > \gamma_{iT}\ then\ relay\ will\ be\ in\ active\ mode \\ if\ \gamma_{sr} < \gamma_{iT}\ then\ relay\ will\ be\ in\ sleep\ mode \end{cases}. \tag{3.5}$$

The signal from the relay amplified and forwarded to the destination node D with an amplification factor of A (Laneman et al.,2004).

$$A = \sqrt{\frac{P_r}{P_s|h_{sr}|^2 + N_0}}. \tag{3.6}$$

The signal received at the destination D in Phase-II is (Shamganth, K. et al.,2014)

$$y_{rd} = A\, h_{rd} y_{sr} + n_{rd}, \tag{3.7}$$

where n_{rd} is the noise components in the relay to the destination channel and is given as

$$n_{rd} \sim CN(0,1). \tag{3.8}$$

The channel coefficient between the R-D link has zero-mean and variance (Shamganth, K. et al.,2014) and is given by

$$h_{rd} \sim CN(0, \sigma_{rd}^2). \qquad (3.9)$$

Substituting the amplification factor in equation (3.6) to equation (3.7) gives

$$y_{rd} = \sqrt{\frac{P_r}{P_s|h_{sr}|^2 + N_0}}\, h_{rd} y_{sr} + n_{rd}. \qquad (3.10)$$

Substituting equation (3.2) in equation (3.10) yields (Shamganth, K. et al.,2016)

$$y_{rd} = \sqrt{\frac{P_r}{P_s|h_{sr}|^2 + N_0}}\, h_{rd}\left(\sqrt{P_s} h_{sr} x + n_{sr}\right) + n_{rd}, \qquad (3.11)$$

$$y_{rd} = \sqrt{\frac{P_r P_s}{P_s|h_{sr}|^2 + N_0}}\, h_{rd} h_{sr} x + \sqrt{\frac{P_r}{P_s|h_{sr}|^2 + N_0}} h_{rd} n_{sr} + n_{rd}, \qquad (3.12)$$

$$y_{rd} = \sqrt{\frac{P_r P_s}{P_s|h_{sr}|^2 + N_0}}\, h_{rd} h_{sr} x + n'_{rd}, \qquad (3.13)$$

$$n'_{rd} = \sqrt{\frac{P_r}{P_s|h_{sr}|^2 + N_0}} h_{rd} n_{sr} + n_{rd}, \qquad (3.14)$$

where h_{rd} denotes the channel coefficient from the relay to the destination and n_{rd} denotes the complex additive white Gaussian noise between the relay and destination path.

Assume the noise components n_{sr} and n_{rd}, are independent and the equivalent noise n'_{rd}, is zero-mean, complex Gaussian random variable with variance N_0.

$$N'_0 = N_0\left(\frac{P_r|h_{rd}|^2}{P_s|h_{sr}|^2 + N_0} + 1\right), \qquad (3.15)$$

where N'_0 in (W/Hz) is the power spectral density of AWGN (Liu et al. .2008).

The instantaneous SNR of the source to destination direct link (Shamganth, K. et al.,2016) is given as

$$\gamma_{sd} = \frac{P_s}{N_0}|h_{sd}|^2. \tag{3.16}$$

The destination node receives the source signal through the direct link S-D and the relayed link R-D. Maximum ratio combiner (MRC) maximizes the overall SNR (Brennan, D. G., 2003) and the coherent detector with the knowledge of all channel coefficients is required. The MRC output is equal to the sum of the received SNR from both direct link S-D and the relay to destination link R-D.

The instantaneous SNR of the relayed link R-D (Shamganth, K. et al.,2016) is given by

$$\gamma_{rd} = \frac{P|h_{rd}|^2}{N_0}. \tag{3.17}$$

For the calculation of the mutual information between source to the destination node, the total instantaneous SNR at the destination is required. The SNR received at the destination node is the sum of the SNR of the direct link S-D and the equivalent instantaneous SNR relay link (Qiang Zhao et al. 2005).

The equivalent instantaneous SNR of the S-R-D relayed link (Shamganth, K. et al.,2016) is given by

$$\gamma_r = \frac{P_s P_r |h_{sd}|^2 |h_{rd}|^2}{N_0(P_s|h_{sd}|^2 + P_r|h_{rd}|^2 + N_0)}. \tag{3.18}$$

The average SNR of the S-R and S-D link (Shamganth, K. et al.,2016) is given by

$$\overline{\gamma_{sr}} = \frac{\sigma_{sr}^2}{N_0}, \tag{3.19}$$

$$\overline{\gamma_{sd}} = \frac{\sigma_{sd}^2}{N_0}. \tag{3.20}$$

The detected signal at the destination node obtained by applying the minimum Euclidean distance detection (J. G. Proakis et al.,2000) using the optimal detection rule given as

$$\hat{x} = \arg\min|\varepsilon - x| \quad (x_1, x_2) \in x. \tag{3.21}$$

The channel coefficient h_{sd} of the direct link S-D follows the exponential distribution, so the instantaneous SNR of the S-D link is also exponentially distributed.

$$p(\gamma_{sd}) = \frac{1}{\overline{\gamma_{sd}}} exp\left(-\frac{\gamma_{s,d}}{\overline{\gamma_{s,d}}}\right). \tag{3.22}$$

The channel coefficient h_{rd} of the relay link R-D follows the exponential distribution, the instantaneous SNR of the relay to destination link is also exponentially distributed and given as

$$p(\gamma_{rd}) = \frac{1}{\overline{\gamma_{rd}}} exp\left(-\frac{\gamma_{rd}}{\overline{\gamma_{rd}}}\right). \tag{3.23}$$

3.2.3 SER Analysis of Single-Relay Selection Scheme

With the knowledge of the channel state information (CSI), the output of the MRC combiner at the destination stated in (K.J Ray et al.,2008, pp 219, pp123) as

$$y_d = \alpha_s y_{sd} + \alpha_r y_{rd}, \tag{3.24}$$

where $\alpha_s = \frac{\sqrt{P_s} h_{sd}^*}{N_0}$ and $\alpha_r = \frac{\sqrt{\frac{P_s P_r}{P_s |h_{sr}|^2 + N_0}} h_{sr}^* h_{rd}^*}{\left(\frac{P_r |h_{rd}|^2}{P_s |h_{sr}|^2 + N_0} + 1\right) N_0}$.

The transmitted symbol 'x' is assumed to have an average energy $E_s = 1$, the output SNR at the MRC combiner (Shamganth, K. et al.,2014) given as,

$$\gamma_c = \gamma_{sd} + \gamma_r, \tag{3.25}$$

where $\gamma_{sd} = \frac{P_s}{N_0}|h_{sd}|^2$ and $\gamma_r = \frac{\gamma_{sr}\gamma_{rd}}{\gamma_{sr} + \gamma_{rd} + 1}$.

The conditional SER of single-relay cooperative AF systems with M-PSK (K.J Ray et al.,2008) is given as

$$P_{MPSK}^{h_{sd,}h_{sr}h_{rd}} \approx \frac{1}{\pi}\int_0^{\frac{(M-1)\pi}{M}} exp\left(-\frac{b_{PSK}(\gamma_{sd}+\gamma_r)}{sin^2\theta}\right) d\theta, \tag{3.26}$$

where $b_{PSK} = sin^2\left(\frac{\pi}{M}\right)$.

The MGF of a random variable Z is given as

$$M_Z = \int_{-\infty}^{\infty} \exp(-sz)\, P_Z(Z) dZ. \tag{3.27}$$

Averaging the conditional SER in equation (3.26) over the Rayleigh fading channels $h_{sd,}h_{sr}\ and\ h_{rd}$, the SER of the MPSK signals is given in terms of MGF $M_{\gamma_{sd}}$and $M_{\gamma_r}$is given as (K.J Ray et al.,2008, pp 219)

$$P_{SER} \approx \frac{1}{\pi}\int_0^{\frac{(M-1)\pi}{M}} M_{\gamma_{sd}}\left(\frac{b_{PSK}}{sin^2\theta}\right)\prod_{i=1}^{N} M_{\gamma_r}\left(\frac{b_{PSK}}{sin^2\theta}\right) d\theta. \tag{3.28}$$

The asymptotic tight SER expression for AF cooperative system using M-PSK for high SNR derived in (Su et al., 2008) as

$$P_{SER} \approx \frac{DN_0^2}{b^2}\cdot\frac{1}{P_s\sigma_{sd}^2}\left(\frac{1}{P_s\sigma_{sr}^2} + \frac{1}{P_r\sigma_{rd}^2}\right), \tag{3.29}$$

where $b = sin^2\left(\frac{\pi}{M}\right)$.

$$D = \frac{3(M-1)}{8M} + \frac{sin\left(\frac{2\pi}{M}\right)}{4\pi} - \frac{sin\left(\frac{4\pi}{M}\right)}{32\pi}. \tag{3.30}$$

The SER expression in equation (3.29) and equation (3.30) for AF relaying with coherent modulation is considered as the benchmark to compare it with the simulation results in the upcoming section.

Motivation

Power allocation plays a vital role in cooperative wireless network performance. The effect of power allocation in the proposed scheme with unequal power allocation and equal power allocation scheme was studied in this section. Existing literature mostly focuses on equal power allocation of the source and the relay, and in some literature, the joint power allocation and relay selection investigated; however, the complexity is high. So, there is a need to study the power allocation of the source and the relay with the proposed threshold-based relay selection. Su et al. (2008) proposed the optimum power allocation, and three cases based on the distance between source to relay and destination is considered in the simulation. Threshold fixed at the relay for the different distance cases presented in this section.

The total power is given by

$$P_t = P_s + P_r, \tag{3.31}$$

The optimum power allocation for AF with M-PSK modulation for high SNR stated in (Theorem 5.3.4, Liu et al. .2008) as

$$P_s = \frac{\sigma_{sr}+\sqrt{\sigma_{sr}^2+8\sigma_{rd}^2}}{3\sigma_{sr}+\sqrt{\sigma_{sr}^2+8\sigma_{rd}^2}} P_t, \tag{3.32}$$

$$P_r = \frac{2\sigma_{sr}}{3\sigma_{sr}+\sqrt{\sigma_{sr}^2+8\sigma_{rd}^2}} P_t. \tag{3.33}$$

The single-relay AF cooperative network with the power allocation based on the optimum power ratios mentioned in equation (3.32) and (3.33) is analyzed for three different cases. The link quality plays a significant role in power allocation. The power allocation also depends on the distance between the source to relay (S-R) and relay to the destination (R-D). In this study, the distance-based power allocation and fixing threshold at the relay is combined to arrive at three different cases.

Case(i): The channel link quality of the S-R link and R-D link are equal, i.e., $\sigma_{sr}^2 = 1$ and $\sigma_{rd}^2 = 1$. Relay is assumed to be at the center of the source and the relay, so the distance between S-R and R-D is same.

$d(S,R) = d(R,D)$.

Case(ii): The channel link quality of the R-D link is good compared to the S-R link.

i.e., $\sigma_{sr}^2 = 1$ and $\sigma_{rd}^2 = 10$. In this case, the relay is assumed to be closer to the destination node. Therefore, the power allocation at the source node is more compared to the relay node. Threshold at the relay is less in this case. The optimum power ratios based on equation (3.32) and (3.33) is $P_s = 0.8333P_t$ and $P_r = 0.16777P_t$, and

$d(S,R) \gg d(R,D)$.

Case(iii): The channel link quality of the S-R link is good as compared to the R-D link.

$d(S,R) < d(R,D)$.

In this case, the relay is assumed to be nearer to the source and the distance is more from the destination node. Therefore, the power allocation at the source node is less compared to the relay node. Threshold fixed at the relay is more in this case due to less distance from the source node. The optimum power ratios based on equation (3.32) and (3.33) is $P_s = 0.5394P_t$ and $P_r = 0.4605P_t$.

Simulation Setup

In this section the simulation setup for testing the single threshold based single relay selection model for cooperative network is presented. The SER results of the single relay selection scheme with equal power allocation and unequal power allocation is presented in the next section. Simulation parameters consists of 10^5 random bits with 4-PSK and 16-PSK modulation with AF relaying based cooperative network is considered in the simulation. The noise variance is assumed as $N_0 = 1.$ The source to destination and relay to destination channel is modeled as Rayleigh fading channels. In figure 3.2(a) the simulation parameters consist of the total power is $P_t = 1$, and the source node power is set as $P_s = 0.67$ and the relay node power is $P_r = 0.33P_t$. In case(i) the relay node is assumed to be equidistant from the source and relay so $\sigma_{sr}^2 = 1$ and $\sigma_{rd}^2 = 1$ applied in equation (3.32) and (3.33) and this gives the optimum power ratios $P_s = \frac{2}{3}P_t$ and $P_r = \frac{1}{3}P_t$ since the total power, $P_t = 1$ we have $P_s = \frac{2}{3}$ and $P_r = \frac{1}{3}$. In figure 3.2(b) the simulation for case(ii) assumes the relay is at less distance from the destination and more distance from the source. The channel link for this case is $\sigma_{sr}^2 = 1$ and $\sigma_{rd}^2 = 10$ applied in equation (3.32) and (3.33) and this gives the optimum power ratios $P_s = 0.8333P_t$ and $P_r = 0.16777P_t$. In figure 3.2(c) the power ratios considered are $P_s = 0.5394P_t$ and $P_r = 0.4605P_t$. In figure 3.2(d) the power ratios considered for the simulation are $P_s = 0.16777P_t$ and $P_r = 0.8333P_t$. The simulation of figure 3.3 consists of 16-PSK with the optimum power ratios of $P_s = \frac{2}{3}P_t$ and $P_r = \frac{1}{3}P_t$. The SER tight upper bound results of equation (3.29) and (3.30) is presented with the simulation SER results of cooperative AF. The parameters applied in equation (3.29) for the SER calculation consists of M=4 and $P_s = \frac{1}{2}P_t$, $P_r = \frac{1}{2}P_t$ and the noise variance $N_0 = 1$ and $\sigma_{sd}^2 = \sigma_{sr}^2 = \sigma_{rd}^2 = 1$ for the equal power allocation in figure 3.4.

Simulation Results and Discussion

The simulation results of the proposed threshold-based relay selection scheme for the cooperative network with different relay distance scenarios are presented. Figure3.2 shows the SER performance of the single relay AF systems with QPSK. The equal power allocation with QPSK modulation scheme compared with the unequal power allocation at the source and the relay node.

Figure 3.2(a) presents that SER performance of unequal power allocation that is marginally better than equal power allocation with the performance improvement of 1dB.

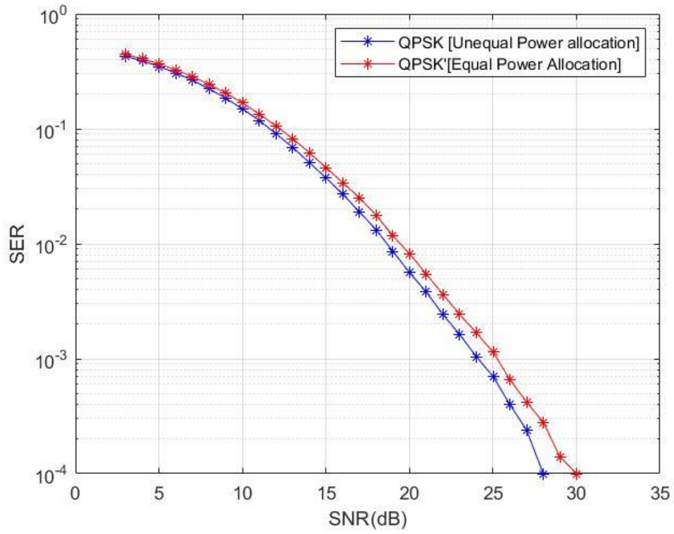

Figure 3.2 (a). Performance of Single relay AF with $P_s = \frac{2}{3}P_t$ and $P_r = \frac{1}{3}P_t$.

Figure 3.2(b) shows the SER performance of unequal power allocation outperforms the equal power allocation with the performance improvement of more than 2dB, i.e., $\sigma_{sr}^2 = 1$ and $\sigma_{rd}^2 = 10$. In this case, less distance assumed between the relay and the destination node, and more distance between the source to relay. Therefore, the power allocation at the relay node is less compared to the source.

Similar performance is observed in unequal power allocation and the equal power allocation schemes as in figure 3.2(c). It is observed that reducing the source node power and increasing the relay power degrades the SER performance of unequal power allocation scheme. It is also observed that in figure 3.2(d), for $P_s = 0.16777P_t$ and $P_r = 0.8333P_t$ there is 1dB performance degradation of unequal power allocation compared to the equal power allocation scheme. From figure 3.2(a),3.2(b),3.2(c) and 3.2(d) it is observed that if the channel quality link ratios $\frac{\sigma_{sr}^2}{\sigma_{rd}^2}$ is high then unequal power allocation outperforms equal power allocation.

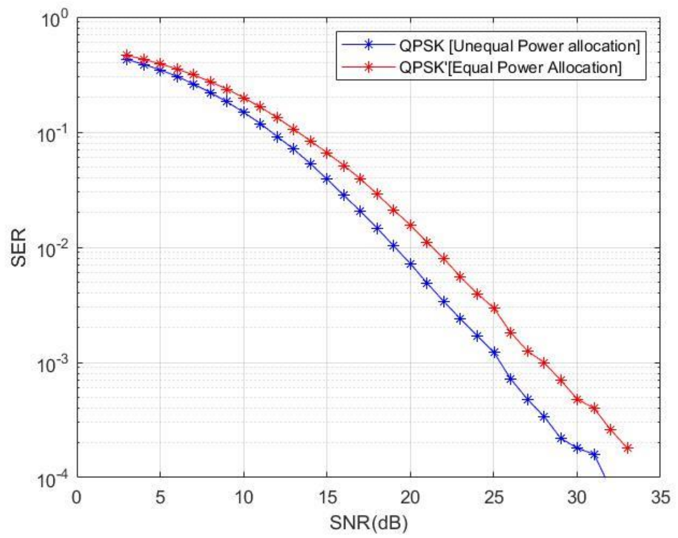

Figure 3.2 (b). SER Performance of Cooperative Single relay AF with $P_s = 0.8333P_t$ and $P_r = 0.16777P_t$

To analyze the optimum power ratio and the SER performance of unequal power allocation is modulation dependent, the simulation performed with 16-PSK in figure 3.3. The performance improvement of 3dB observed in figure 3.3 with unequal power allocation compared to equal power allocation.

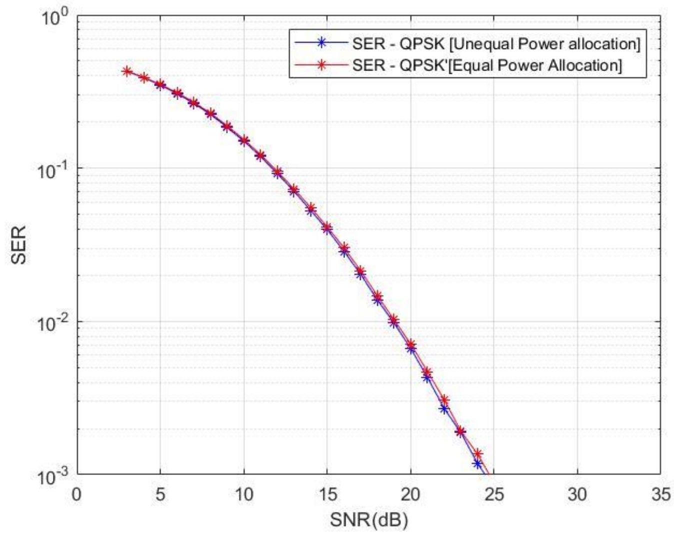

Figure 3.2 (c). SER Performance of Cooperative Single relay AF with $P_s = 0.5394P_t$ and $P_r = 0.4605P_t$

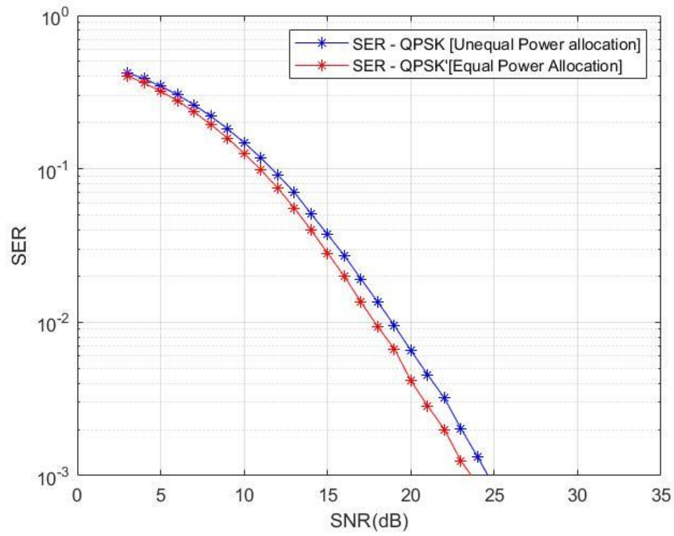

Figure 3.2 (d). SER Performance of Cooperative Single relay AF with $P_s = 0.16777P_t$ and $P_r = 0.8333P_t$

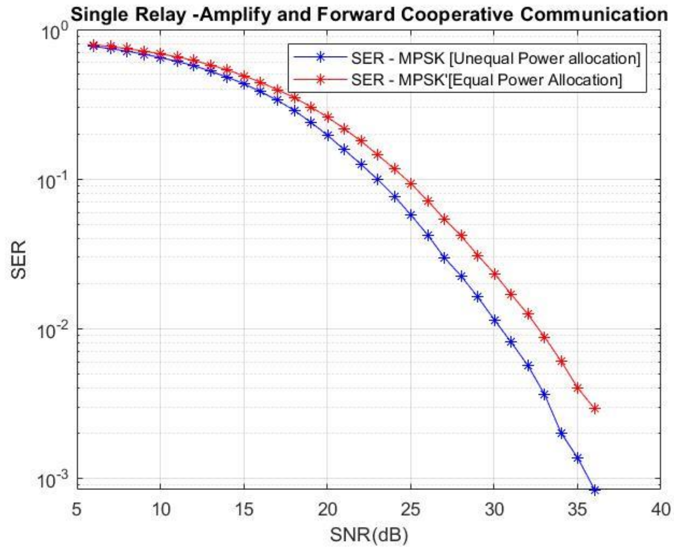

Figure 3.3. SER Performance of Cooperative Single relay AF with 16-PSK: $P_s = \frac{2}{3}P_t$ and $P_r = \frac{1}{3}P_t$

Figure 3.4 presents the single relay cooperative AF network with the optimum power ratios of $P_s = 0.8333P_t$ and $P_r = 0.16777P_t$. There is a performance improvement of 1dB is observed in the theoretical result using equation (3.29) of optimum power compared to the theoretical SER performance of equal power allocation. Furthermore, there is a performance difference of 2dB observed between theoretical SER performance with optimum power and the simulation results. Moreover, the performance improvement observed with optimum power allocation simulation results compared equal power allocation scheme. Furthermore, the SER performance of optimum power allocation simulation shown in figure 3.4 with $P_s = 0.8333P_t$, $P_r = 0.1677P_t$ performance improvement is obtained.

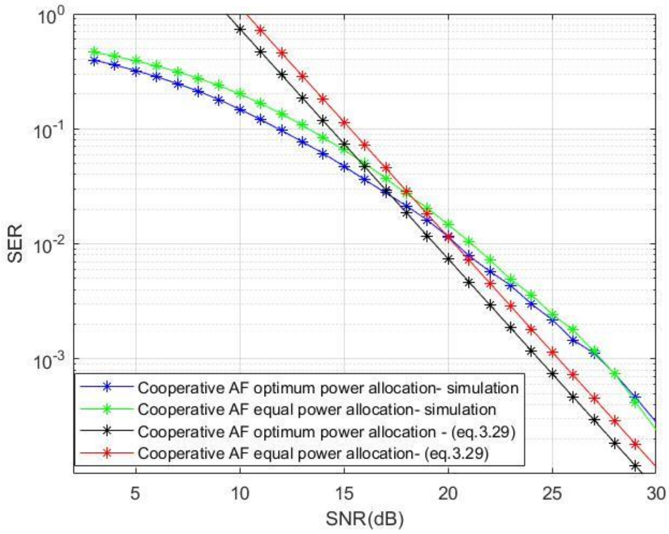

Figure 3.4. SER Performance of Cooperative Single relay AF with $P_s = 0.8333P_t$ and $P_r = 0.16777P_t$

Single-Relay Selection based Cooperative AF with Single-Threshold at Relay

Single-Threshold based relay selection is discussed in this section with the threshold at the relay. The fixing threshold at the relay enhances spectral efficiency due to selecting the relay based on the S-R link quality. In the single threshold-based relay selection, two variations exist such as fixing threshold at the relays and threshold at the destination. This study compares fixing single threshold at the relay and the destination.

In figure 3.5, the cooperative AF with the single threshold at the relay SER simulation is compared with the analytical results of equal power and optimum power without a threshold and with equal power simulation is presented. In this case, the optimum power assigned to the source and relay node is $P_s = 0.8333P_t$ and $P_r = 0.1677P_t$, moreover, it is assumed that distance between the S-R link is more than the R-D link in this scenario and threshold at the relay fixed as 4.7dB. The single threshold scheme has outperformed the other AF schemes without threshold at an SNR of 15dB. It matches the cooperative AF with optimized power analytical result without a threshold and 1dB performance improvement observed at an SNR of 17dB. Also, there is a difference of 3dB between threshold-based simulation and the analytical result without threshold.

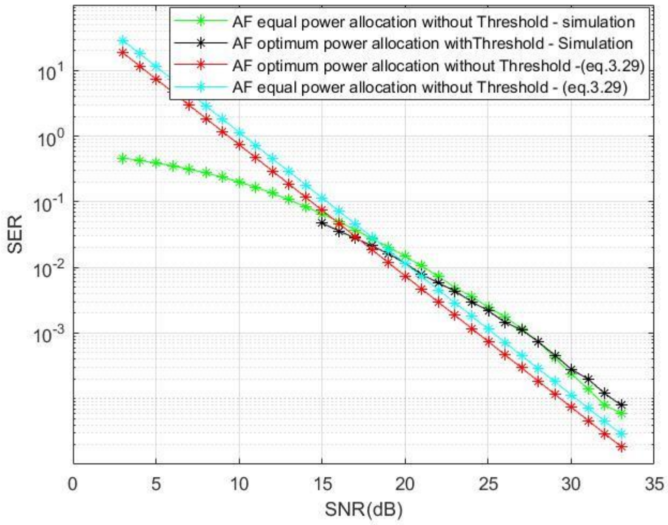

Figure 3.5. Single relay AF with Threshold at Relay with $P_s = 0.8333P_t$ and $P_r = 0.1677P_t$

Simulation Results and Discussion of Cooperative AF with Differential Modulation

Performance of single relay cooperative AF with differential modulation scheme analyzed in this section, the analytical result of (Su, W., Sadek, A. K., & Ray Liu, K. J. 2008) is used as a benchmark and compared with differential modulation schemes with equal and unequal power allocation scenarios.

Case(i): The channel link quality of the S-R link is inferior to the R-D link. Moreover, the distance of the S-R link is assumed to be more than the R-D link.

Figure 3.6 presents the comparative SER performance for cooperative AF with DBPSK for unequal power allocation and equal power allocation schemes. There is a performance improvement of more than 2dB at SER of 10^{-3} is observed for unequal power allocation scheme compared to equal power allocation.

For the same scenario, the SER performance is analyzed with the DQPSK modulation scheme in Figure 3.6 (a) with the optimum power of $P_s = 0.8P_t$ and $P_r = 0.2P_t$. Similar performance observed as that of DBPSK. However, the analysis shows that the unequal power allocation scheme is not modulation dependent.

In Figure 3.6 (b) the DQPSK modulation is used with cooperative AF relaying protocol and the optimum power at the source, and the relay node is $P_s = 0.7P_t$ and $P_r = 0.3P_t$. In this case, unequal power allocation outperforms the equal power allocation with the performance improvement of 1dB at the SER of 10^{-3}. Comparing the results in figure 3.6 (a) and figure 3.6 (b) performance improvement is observed on increasing the source node power. In figure 3.6 (a) and 3.6 (b), the difference of 1dB is observed, and it is due to the source node power.

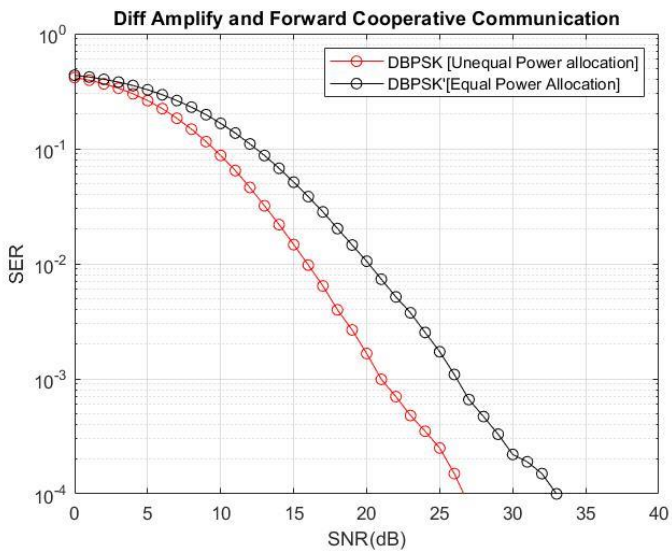

Figure 3.6. Comparison of SER Performance of Cooperative Single relay AF with DBPSK with $P_s = 0.8P_t$ and $P_r = 0.2P_t$

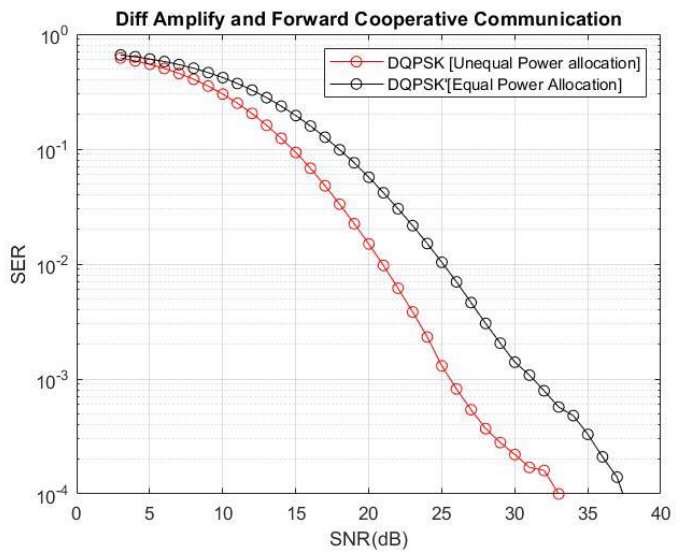

Figure 3.6 (a). Comparison of SER Performance of Cooperative Single relay AF with DQPSK with $P_s = 0.8P_t$ and $P_r = 0.2P_t$

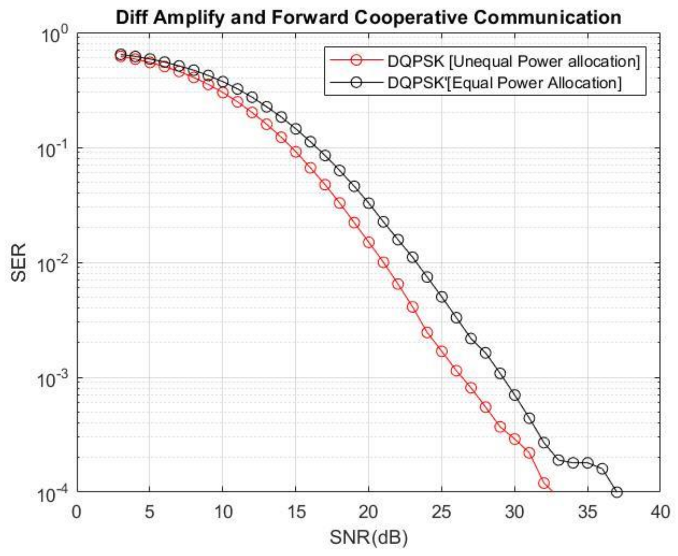

Figure 3.6 (b). Comparison of SER Performance of Cooperative Single relay AF with DQPSK with $P_s = 0.7P_t$ and $P_r = 0.3P_t$

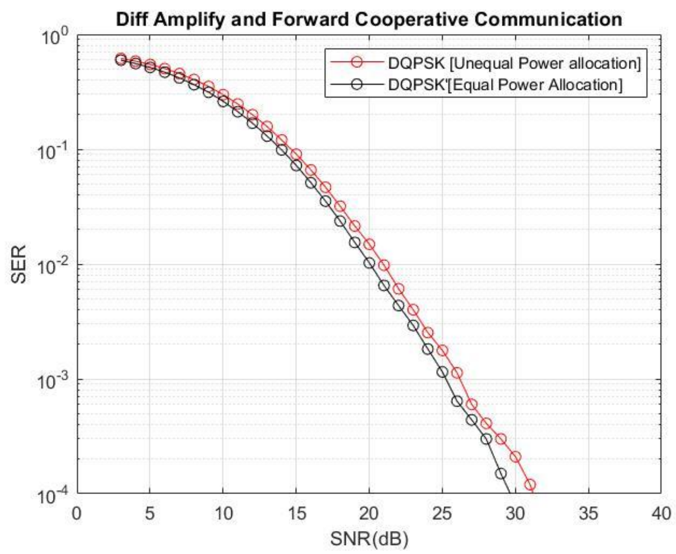

Figure 3.6 (c). Comparison of SER Performance of Cooperative Single relay AF with DQPSK with $P_s = 0.3P_t$ and $P_r = 0.7P_t$

Case(ii): The channel link quality of the S-R link is good as compared to the R-D link.

The distance between relay and destination node is assumed to be more in this case, and the distance between the source and relay is less. Therefore, the power allocation at the relay node is more compared to the source. In figure 3.6(c), there is a performance degradation of unequal power allocation compared to the equal power allocation scheme.

Simulation Results and Discussions of DiffAF with Differential Modulation

Figure 3.7 shows the single relay cooperative DiffAF SER performance of DBPSK with the power ratios of $P_s = 0.8P_t$ and $P_r = 0.2P_t$. Simulation results show the performance improvement of 2dB at the SER of 10^{-3} for unequal power allocation with DiffAF protocol compared to the equal power allocation scheme. Furthermore, the performance improvement of more than 3dB observed at the SER of 10^{-4}. Furthermore, comparing the simulation results of cooperative DiffAF with DBPSK in figure 3.7 with cooperative AF based DBPSK in figure3.6 shows a performance improvement for the cooperative DiffAF scheme of more than 1dB at the SER of 10^{-4}.

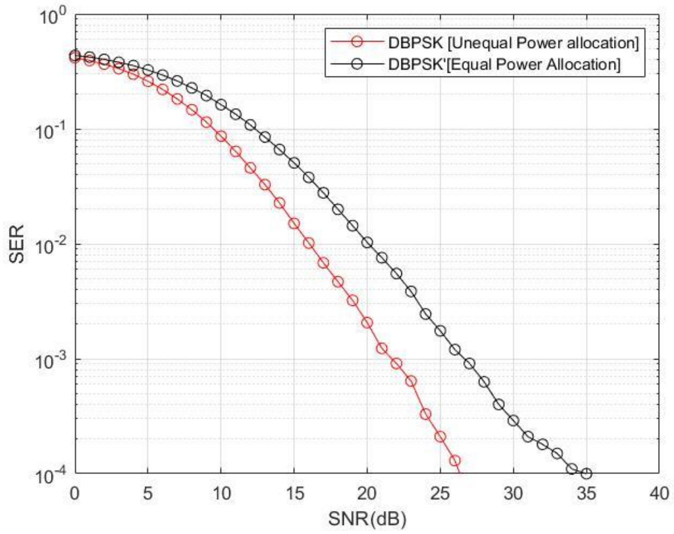

Figure 3.7. Comparison of SER Performance of Cooperative Single-relay DiffAF protocol with $P_s = 0.8P_t$ and $P_r = 0.2P_t$

3.2.4 BER Analysis of Single Relay Cooperative DiffAF

The conditional BER of DiffAF relaying (Liu, K., Sadek, A., Su, W., & Kwasinski, A. 2008) is given by

$$P_{b|\gamma} = \frac{1}{16\pi} \int_{-\pi}^{\pi} f(\theta)\, exp[-\alpha(\theta)\gamma]\, d\theta, \tag{3.35}$$

where,

$f(\theta) = \frac{b^2(1-\beta^2)[3+\cos(2\theta)-\left(\beta+\frac{1}{\beta}\right)\sin\theta\,]}{2\alpha(\theta)}$, and

$\alpha(\theta) = \frac{b^2(1+2\beta\, sin\,\theta+\,\beta^2)}{2}$.

$\beta = \frac{a}{b}$ denotes a constant parameter where a and b are dependent on the modulation size (Simon, M. K., & Alouini, M. S.,1998). The DBPSK modulation has $a = 10^{-3}$ and $b = \sqrt{2}$ and DQPSK modulation has $a = \sqrt{2 - \sqrt{2}}$ and $b = \sqrt{2 + \sqrt{2}}$.

The BER approximation of DiffAF relaying (Liu, K., Sadek, A., Su, W., & Kwasinski, A. 2008) is given by

$$P_b \approx \frac{(P_s \sigma_{sr}^2 + 1) Z_{min} + P_r \sigma_{rd}^2}{P_s^2 P_r \sigma_{sd}^2 \sigma_{sr}^2 \sigma_{rd}^2} N_0^2 C(\beta, \theta), \tag{3.35a}$$

where $C(\beta, \theta)$ is a constant that depends on the modulation size. The approximated BER expression for DiffAF relaying without threshold in equation (3.35a) considered as a benchmark for the BER simulation results with the proposed single threshold relay selection scheme.

Simulation Setup

In this subsection the simulation setup for testing the proposed single relay selection scheme for cooperative network with DiffAF relaying is presented. In the next section the BER performance of the single relay selection scheme with equal power allocation and unequal power allocation is presented. Simulation parameters consists of 10^5 random bits with DBPSK modulation that has $a = 10^{-3}$ and $b = \sqrt{2}$ and DQPSK modulation that has $a = \sqrt{2 - \sqrt{2}}$ and $b = \sqrt{2 + \sqrt{2}}$. The source to destination and relay to destination channel is modeled as Rayleigh fading channels with the noise variance assumed as $N_0 = 1$. In figure 3.8 the simulation parameters consist of the total power $P_t = 1$, and the source node power as $P_s = 0.8$ and the relay node power is fixed as $P_r = 0.2P_t$ and for case(ii) the relay is assumed to be at lesser distance from the destination and more distance from the source. In figure 3.9 the simulation and approximated BER in equation (3.35a) use the optimum power ratios $P_s =$

$0.7P_t$ and $P_r = 0.3P_t$ with the channel variance is chosen as $\sigma_{sd}^2 = \sigma_{sr}^2 = \sigma_{rd}^2 = 1$ for case (ii). The approximated BER in equation (3.35a) is used with power ratios $P_s = 0.5P_t$ and $P_r = 0.5P_t$ for equal power allocation curves.

Simulation Results and Discussion of Single Relay Cooperative DiffAF

Cooperative single relay AF protocol with DBPSK BER performance analyzed with equal power allocation and unequal power allocation. In this simulation, the case is assumed based on the distance between the S-R and R-D nodes. In figure 3.8, the unequal power allocation performance shows an improvement of more than 3dB at the BER of 10^{-3} for the power at the source and relay fixed as $P_s = 0.8P_t$ and $P_r = 0.2P_t$.

Figure 3.8 (a) presents the comparative BER Performance of Cooperative Single-relay DiffAF protocol with DQPSK for unequal power allocation and equal power allocation schemes. It is observed that unequal power allocation with DiffAF outperforms equal power allocation. Furthermore, performance improvement of 3 dB at the BER of 10^{-3} is evident from the results.

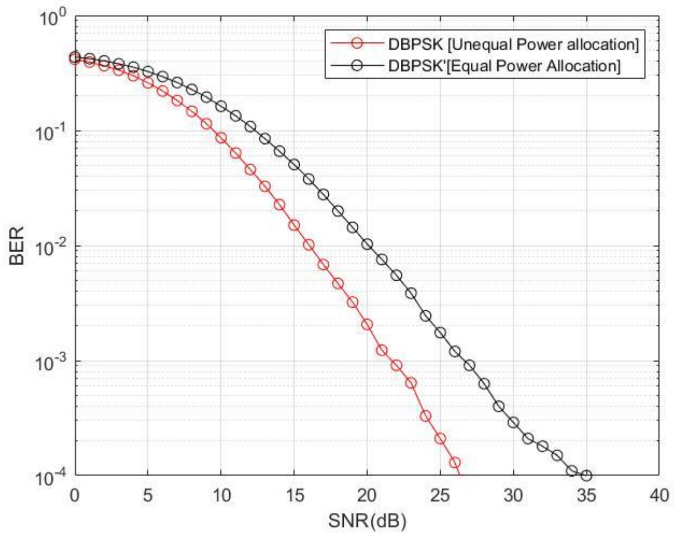

Figure 3.8. BER Performance of Cooperative Single-relay AF relaying with DBPSK

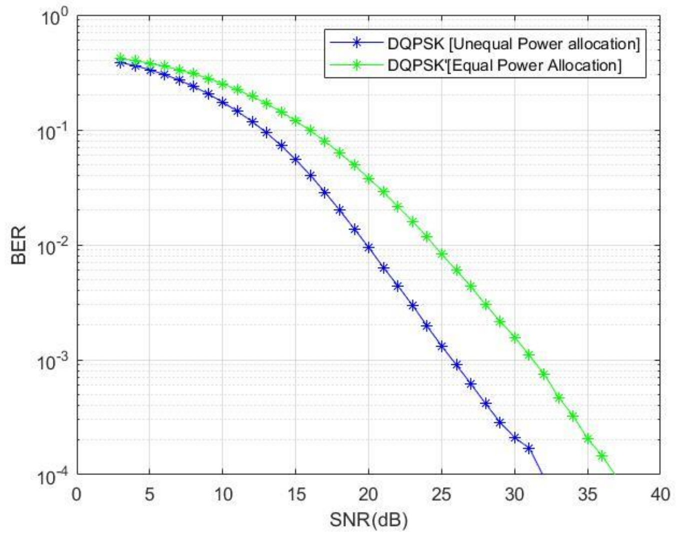

Figure 3.8 (a). BER Performance of Cooperative Single-relay DiffAF relaying with DQPSK

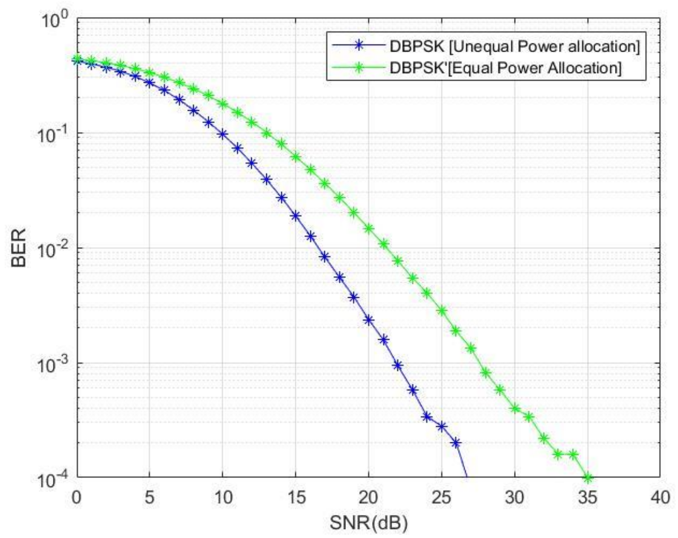

Figure 3.8 (b). BER Performance of Cooperative Single-relay DiffAF relaying with DBPSK

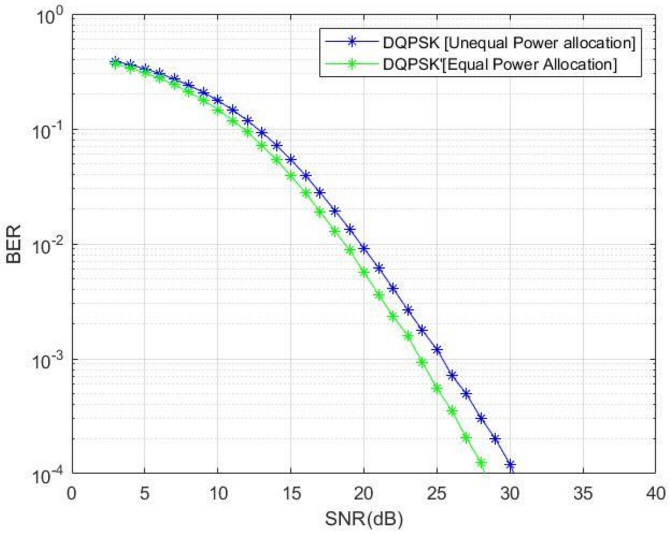

Figure 3.8 (c). BER Performance of Cooperative Single-relay DiffAF relaying with DQPSK for case(iii)

Figure 3.8 (c) shows the result of case(iii) with relay near to the source and away from the destination. Therefore, less power at the source and the power is high at the relay node. The unequal power allocation scheme shows performance degradation in this case. At an SNR of 33dB, the equal power allocation outperforms unequal power allocation by more than 2dB as expected.

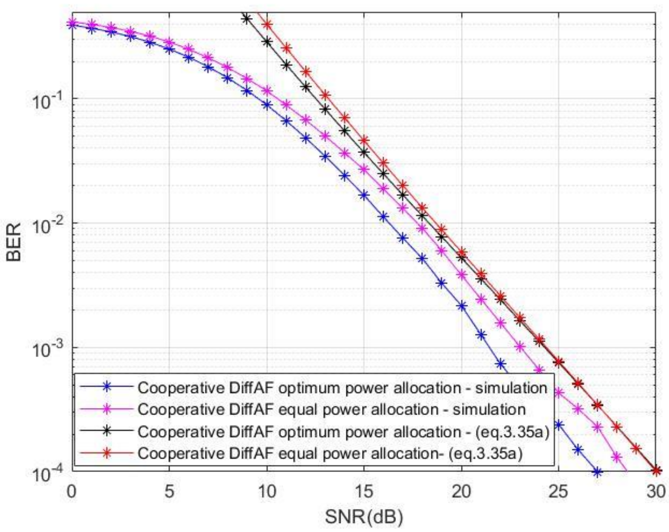

Figure 3.9. Comparison of BER Performance of Cooperative Single-relay DiffAF relaying using DBPSK with $P_s = 0.7P_t$ and $P_r = 0.3P_t$

Figure 3.9 presents the single relay cooperative DiffAF with DBPSK for the optimum power of $P_s = 0.7P_t$ and $P_r = 0.3P_t$. A performance gain of 2dB is observed in the DiffAF based optimum power allocation curve when compared to equal power allocation simulation curve. Furthermore, the performance difference of 1dB is observed between the analytical and simulation results for the SNR of 20dB at the BER of 10^{-3}. Figure 3.9 shows that increase in source power improves the BER performance. Moreover, the DiffAF with optimum power allocation scheme outperforms its counterpart.

3.3 Cooperative DiffAF with Single Threshold

In the proposed single threshold based DiffAF relay selection scheme, the significant difference is the relaying protocol employed at the relay.

Step 1: The relays receive the signal transmitted from the source to the destination node in the coverage area of the source.

Step 2: Relay node uses DiffAF relaying protocol. The input SNR threshold (γ_{iT}) is based on the distance between the source and destination.

Step 3: If the distance between source and destination is more then γ_{iT} will be less. Based on the distance the γ_{iT} will vary.

Step 4: If the squared amplitude of the received signal at the relay (y_{sr}^2) is above the input threshold (γ_{iT}) then the relay will be active mode and is ready to amplify and forward the source signal to the destination. If this condition is not satisfied, then the relay will be in sleep mode.

Step 5: If the threshold condition in Step 4 is not satisfied at the relay, then signal from the direct link S-D will be used at the destination for detection.

3.3.1 System Model

In the system model, the equation (3.1) to (3.6) is the same as mentioned in section 3.2.2. The channel is assumed to be constant within the two symbol periods. The channel between source and relay (S-R), relay to the destination (R-D) and the direct link source to destination (S-D) has Rayleigh fading conditions.

The signal from the relay amplified and forwarded to the destination node D with an amplification factor of A (Qiang Zhao et al. .2005)

$$A \cong \sqrt{\frac{P_r}{P_s \sigma_{sr}^2 + N_0}}. \tag{3.36}$$

The input threshold at the relay based on the following cases:

$$\begin{cases} Case(i): \gamma_{iT} \; will \; be \; less \; if \; d(S,R) \gg d(R,D) \\ Case(ii): \gamma_{iT} \; will \; be \; highif \; d(S,R) < d(R,D) \end{cases}. \tag{3.37}$$

The relay tests the received signal with the optimum threshold (Onat et al. 2007) before amplification with the conditions as shown below:

$$\begin{cases} if \; \frac{y_{sr}^2}{N_0^2} > \gamma_{iT} \; relay \; is \; active \; and \; amplify \; the \; received \; signal \; with \; the \; amplification \; factor \; A \\ \frac{y_{sr}^2}{N_0^2} < \gamma_{iT} \; relay \; will \; be \; in \; idle \; mode \end{cases}, \tag{3.38}$$

where y_{sr}^2 is the squared amplitude of the received signal at the relay and N_0^2 is the normalised noise variance.

The signal received at the destination D in Phase-II is given as

$$y_{rd} = A\sqrt{P_r}\, h_{rd} + n_{rd}, \tag{3.39}$$

where n_{rd} is the noise components in the relay to the destination channel and is given as

$$n_{rd} \sim CN(0,1). \tag{3.40}$$

Substituting equation (3.36) in equation (3.39) gives

$$y_{rd} = \sqrt{\frac{P_r}{P_s \sigma_{sr}^2 + N_0}} \sqrt{P_r}\, h_{rd} + n_{rd}. \tag{3.41}$$

The signal at the combiner is

$$\begin{cases} \varepsilon_d = y_{rd} + y_{sd} & if\ y_{rd} > \gamma_{iT}\ and\ y_{sd} > \gamma_{iT} \\ \varepsilon_d = y_{sd} & if\ y_{rd} < \gamma_{iT}\ and\ y_{sd} > \gamma_{iT} \end{cases}. \tag{3.42}$$

The instantaneous SNR at the S-D link is given as

$$\gamma_{sd} = \frac{P_s |h_{sd}|^2}{\sigma_{nsd}^2}, \tag{3.43}$$

with unit variance $\sigma_{nsd}^2 = 1$.

The instantaneous SNR at the R-D link is given as

$$\gamma_{rd} = \frac{P_s |h_{rd}|^2}{\sigma_{nrd}^2}, \tag{3.44}$$

with unit variance $\sigma_{nrd}^2 = 1$.

The average SNR of the S-R and S-D link is same as mentioned in equation (3.19) and (3.20).

The equivalent SNR of the S-R-D link is given as

$$\gamma_r = \frac{P_s P_r |h_{sd}|^2 |h_{rd}|^2}{N_0 (P_s \sigma_{sr}^2 + P_r |h_{rd}|^2 + N_0)}, \tag{3.45}$$

Simplifying equation (3.45) gives

$$\gamma_r = \frac{\gamma_{sr} \gamma_{rd}}{P_s + \gamma_{rd} + 1}. \tag{3.46}$$

The transmitted signal detected by applying the minimum Euclidean distance detection (J. G. Proakis et al.,2000) with the optimal detection rule is given as

$$\hat{x} = \arg\min|\varepsilon - x| \quad (x_1, x_2) \in x. \tag{3.47}$$

The instantaneous SNR at the output of the combiner is

$$\gamma_c = \gamma'_{sd} + \gamma'_r, \tag{3.48}$$

where

$$\gamma'_{sd} = \begin{cases} \gamma_{sd} & if\ \gamma_{sd} \geq \gamma_T \\ 0 & if\ \gamma_{sd} < \gamma_T \end{cases}, \tag{3.49}$$

and

$$\gamma'_r = \begin{cases} \gamma_r & if\ \gamma_r \geq \gamma_T \\ 0 & if\ \gamma_r < \gamma_T \end{cases}. \tag{3.50}$$

The channel coefficient h_{sd} follows the exponential distribution, so the instantaneous SNR of the S-D link is also exponentially distributed.

$$p(\gamma_{sd}) = \frac{1}{\overline{\gamma_{sd}}} exp\left(-\frac{\gamma_{s,d}}{\overline{\gamma_{s,d}}}\right). \tag{3.51}$$

3.3.2 BER Analysis of Single-Threshold based DiffAF Relay Selection Scheme

The conditional BER using (Simon, M. K., & Alouini, M. S. (1998), equation (3.25)) given as

$$P_b(E|\gamma_c) = \frac{1}{4\pi}\int_{-\pi}^{\pi} z(\theta)\exp[-\gamma_c\, l(\theta)]\, d\theta, \tag{3.52}$$

γ_c is the instantaneous SNR at the combiner output.

$z(\theta) = \frac{1-\beta^2}{1+2\beta sin\theta+\beta^2}$,

where $\beta = \frac{a}{b}$ and $l(\theta) = \frac{b^2}{2log_2 M}(1 + 2\beta sin\theta + \beta^2)$,

and

'M' refers to the constellation size. The parameter $\beta = \frac{a}{b}$ is constant and it depends on the type of modulation.

For DBPSK: $a = 0 \ and \ b = \sqrt{2}$.

Substituting $a = 0 \ and \ b = \sqrt{2}$

$z(\theta) = 1$ and $l(\theta) = 1$.

Substituting these values in equation (3.52) gives

$$P_b(E|\gamma_c) = \frac{1}{4\pi}\int_{-\pi}^{\pi} \exp[-\gamma_c] \, d\theta, \tag{3.53}$$

$$P_b(E|\gamma_c) = \frac{1}{2}\exp[-\gamma_c]. \tag{3.54}$$

Substituting equation (3.48) in equation (3.54) gives

$$P_b(E|\gamma_c) = \frac{1}{2}\exp[-(\gamma'_{sd} + \gamma'_{r})]. \tag{3.55}$$

Simulation Setup

The simulation setup for testing the proposed single threshold based relay selection scheme with DiffAF relaying is presented in this section. The BER performance of the single threshold based single relay selection scheme with equal power allocation and optimum power allocation is discussed in the next section. Simulation parameters of figure 3.10(a) and figure 3.10(b) consists of 10^5 random bits with DQPSK modulation that has $a = \sqrt{2-\sqrt{2}}$ and $b = \sqrt{2+\sqrt{2}}$.

The channels are modeled as Rayleigh fading channels and the noise variance is assumed as $N_0 = 1$. In figure 3.10(a) the simulation parameters consist of the power ratios $P_s = 0.8P_t$ and $P_r = 0.2P_t$ for case(ii). In figure 3.10(b) the single threshold single relay selection simulation and approximated BER in equation (3.35a) use the optimum power ratios $P_s = 0.8P_t$ and $P_r = 0.2P_t$ with the channel variance is chosen as $\sigma_{sd}^2 = \sigma_{sr}^2 = \sigma_{rd}^2 = 1$ for case (ii) with input threshold γ_{iT}=10. The approximated BER in equation (3.35a) is used with power ratios $P_s = 0.5P_t$ and $P_r = 0.5P_t$ for equal power allocation curves in figure 3.10(b).

Simulation Results and discussion of DiffAF with Single Threshold at the Relay

The performance of single threshold based DiffAF scheme is compared with DiffAF without threshold in figure 3.10(a). For a fair comparison, both the schemes use the DQPSK modulation scheme. The power ratios at the source and relay node fixed as $P_s = 0.8P_t$ and $P_r = 0.2P_t$ where the total power is $P_t = P_s + P_r$. The performance curves of single threshold based DiffAF and without threshold shows the difference of 1dB at the BER of 10^{-3}.

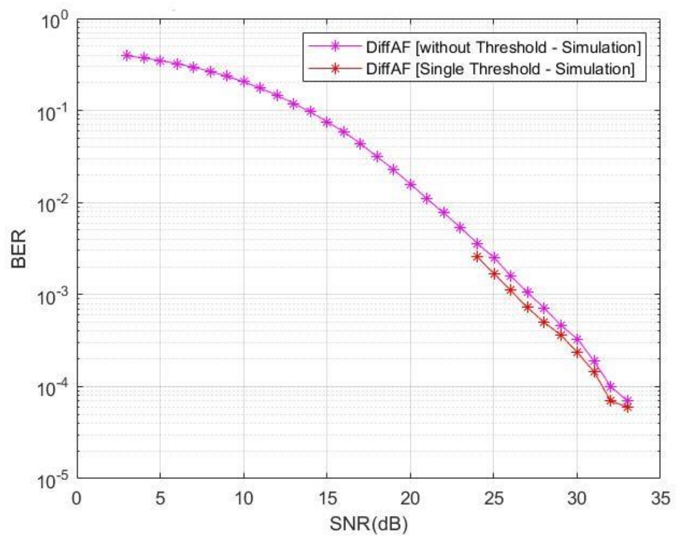

Figure 3.10(a). BER Performance comparison of Single-Threshold based DiffAF relaying

The threshold at the relay depends on the distance between the source and the relay. In figure 3.10 (a) and (b), the distance between the source and the relay assumed to be more than relay to the destination node distance as mentioned in equation (3.36), so less threshold fixed at the relay.

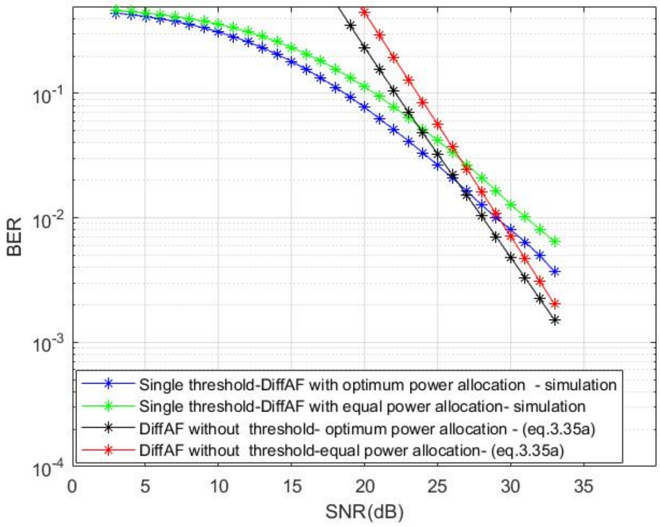

Figure 3.10(b). BER Performance comparison of Single-Threshold based DiffAF relaying with $P_s = 0.8P_t$ and $P_r = 0.2P_t$

Simulation Results and discussion of DiffAF with Single Threshold at the relay and destination

The threshold at the destination studied in this section, and the simulation performed by applying single threshold at the destination with DiffAF relaying. The comparative analysis of fixing threshold at the destination and the relay is investigated in this section. Figure 3.11 presents the comparison for case(ii) with $P_s = 0.8P_t$ and $P_r = 0.2P_t$ and the threshold of 10dB. Fixing threshold at the relay selects relays that satisfy the threshold condition, and it impacts at the low SNR region with the performance degradation compared to fixing threshold at the destination. Fixing threshold at the destination selects the relays that satisfy the threshold condition at the destination. The performance degradation observed at the high SNR region due to selection of more relays with deeply faded S-R link and less faded R-D links. Similar performance observed between the two single threshold based relay selection schemes at the

SNR of 22dB. From the comparison, the performance gain of more than 2dB achieved at the BER of 10^{-3} in the proposed scheme compared to applying threshold at the destination.

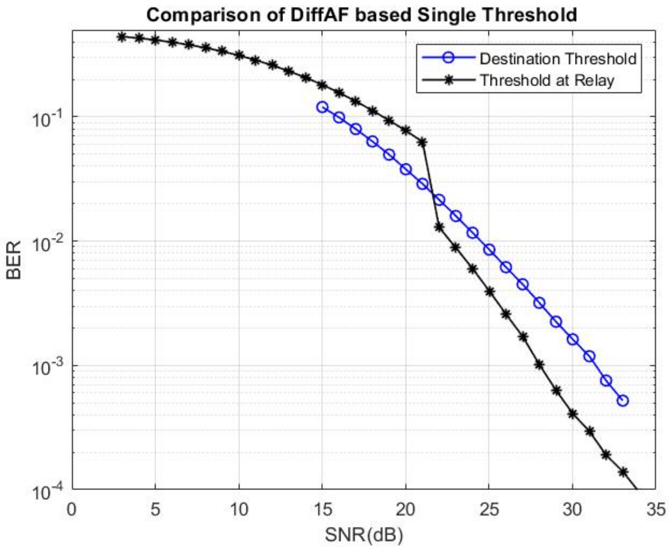

Figure 3.11. Comparison of DiffAF based Single-Threshold at the destination and relay for case(ii)

3.4 Conclusion

This chapter considers the single threshold-based relay selection with AF and DiffAF relaying protocols. The considered system model consists of a single relay between the source and the destination. Most of the existing literature assumed the relay is located at the center of the source and destination node and considered as an ideal scenario. This study considers the varied distance between the source to the relay. The assumptions are more distance between source and relay and less distance is between the source and relay. The distance variation between the source and relay impacts the threshold which is fixed at the relays. The threshold is varied based on the distance between the two nodes. If more distance between the source and relay nodes, then the threshold at the relay should be less and on the other hand if less distance, then threshold at the relay will be high. The effect of unequal power allocation is analyzed and compared with the equal power allocation scheme. From the results, the optimum power allocation with AF and DiffAF scheme without a threshold and with the threshold at the relay shows performance improvement compared to the equal power allocation scheme. Furthermore, this chapter analyses the effect of fixing the threshold at the relay and destination. The results show that the deploying threshold at the relay improves the performance compared to the threshold fixed at the destination.

Chapter 4

Double-Threshold and Multi-Threshold based Multi-Relay selection

4.1 Introduction

The multi-relay selection has the potential of exploiting the diversity gain in Cooperative wireless networks due to the increase in the number of relays (Hwang & Ko, 2007), (Himsoon et al., 2007). However, selecting multiple arbitrary relays degrades the performance of the cooperative network. Furthermore, the single threshold at the relay discussed in Chapter 3 guarantees only the best relay selection based on the received SNR at the relay, but if the relay to destination link has deep fade, then it degrades the overall performance of the network. Threshold-based schemes in the literature classified broadly as the threshold at the input to the combiner such as AT-GSC and NT-GSC (Lioumpas et al., 2008) and the threshold at the output of the combiner OT-MRC (Yang & Alouini, 2005), MS-GSC and OT-MRS (Amarasuriya et al., 2010). The primary issue in the input threshold-based schemes is a greater number of relays are selected, and it adds more complexity to the network. Furthermore, output threshold schemes have the chance of selecting relays with low-SNR branches.

Single relay selection schemes suffer from performance loss due to the error rate and outage probability. However, the complexity of the optimal Multi-relay selection (MRS) schemes increases exponentially with an increase in the number of relays. The MRS schemes based on Generalized section combining (GSC) achieves performance gains at the expense of channel estimation of all the relayed paths, which adds substantial complexity to the system. The GSC based MRS schemes select more relays as required. This problem is overcome by using the double threshold-based GSC scheme (DT-GSC) (Xie et al., 2014). In the above-mentioned existing schemes, the full channel state information (CSI) is required, obtaining CSI in the fast-fading environment is not suitable in a practical environment. In differential modulation, for example, DPSK relies only on the constant phase response of the channel and perfect CSI is not required. The DiffAF scheme requires only a long term average of the received signals, and no instantaneous CSI is required (Avendi & Nguyen, 2014).

The above-mentioned problem is overcome by extending the idea of OT-MRC (Yang & Alouini, 2005) and multi-hop threshold relay selection scheme (Amarasuriya et al., 2010). The differential modulation is a promising candidate since it reduces the receiver complexity and signalling overheads. The proposed double-threshold scheme is formulated by fixing the threshold at the relay node as input threshold and the destination node as an output threshold with differential modulation. In this proposed double threshold-based relay selection scheme, the input threshold is set based on the received signal at the relay, and the output threshold is based on the signal quality at the combiner input.

Multi-threshold based relay selection is presented in this chapter which is different from the combining scheme developed by Xie et al., (2014).

Significant differences between the proposed scheme and the DT-GSC scheme are as follows:

i. The DT-GSC scheme has a double threshold at the combiner, but the proposed scheme has a threshold at the combiner and the relay.

ii. DT-GSC scheme designed for multi-channel communication, and the proposed scheme is designed for the cooperative wireless network.

iii. The double threshold-based proposed scheme is analyzed with coherent and differential modulation schemes, but the DT-GSC scheme considers only coherent detection.

In this chapter, the double threshold-based relay selection scheme is proposed to overcome the issues mentioned in the input and output threshold schemes. Double-threshold has threshold placed at the relay and combiner output. This chapter presents the mathematical model of the proposed double threshold-based relay selection scheme with AF and DiffAF relaying using Coherent and Differential Modulation schemes and its performance analysis.

The power savings of the proposed scheme is compared to the existing schemes by determining the number of active branches. Complexity analysis of the double-threshold-based multi-relay selection scheme is presented in this chapter. Part of the work presented in this chapter is published in “Journal of Wireless Networking and Communications” (Shamganth.K. et al., 2018), and in “International Journal of Electronics and Communication Engineering & Technology” (Shamganth.K. et al., 2016).

4.2 Double Threshold-based Multi-Relay Selection with AF relaying

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Proposed Double-Threshold based Multi-Relay Selection Algorithm

Algorithm 1

Step1: The signal from the source is received by the destination and the relays that are in the coverage area.

Step2: Relay use either AF or DiffAF relaying. The input threshold (γ_{iT}) is placed at the relay. The threshold depends on the distance between the source and the relay node.

Step3: The relays with the received SNR more than input threshold (γ_{iT}) is selected, and it will be on active mode to forward the source signal to the destination node.

Step4: The relays that do not satisfy the condition in Step 3 will be in sleep mode.

Step5: The signal received is combined at the destination. The output threshold (γ_{OT}) is fixed at the combiner output to test received signal quality.

4.2.1 System Model

The multi-relay cooperative wireless network consists of '*N'* relays when a single source and destination is considered. For the multi-relay AF scheme, relay amplifies the received signal from the source and forward the amplified signal to the destination. Half-duplex transmission mode is considered in this model with the single antenna fixed at all the nodes. The signal transmissions in the system model comprise '*N + 1*' phases. The orthogonal channel is assumed between S-R and R-D links to avoid interference. The mode of operation of the proposed double-threshold scheme (Shamganth.K. et al., 2018) is shown in figure 4.1.

The information bits are converted in the format of Quadrature phase-shift keying (QPSK) symbol and each symbol consists of 4 bits. The transmitted signal from the source is given by

$$x_n(t) = \sqrt{\frac{2E_s}{T}}\cos\left[2\pi f_c t + \frac{2\pi}{M}(n-1)\right] \; where \; n = 1,2,3 \ldots M. \qquad (4.1)$$

The symbol energy is denoted as E_s and the carrier frequency as f_c. The term M denotes the constellation size and $M = 4$ is the case of QPSK. Moreover, n is the phase of the carrier in equation (4.1) (Proakis, J. G et al.,2008).

In Phase-I source node transmits the signal and is received by N relays and by the destination in the direct link from the source. The amplified signal forwarded by the set of N relays to the destination in Phase-II.

The signal received at the relay in Phase-I is given as:

$$y_{SR_i} = \sqrt{P_s} h_{SR_i} x + n_{SR_i} \qquad i = 1,2,3 \dots N, \tag{4.2}$$

where 'N' denotes the number of active relays.

The signal received at the destination node in the direct link S-D in Phase-I is given as:

$$y_{SD} = \sqrt{P_s} h_{SD} x + n_{SD}, \tag{4.3}$$

where P_s denotes the average source power of the transmitted signal. In equation (4.2) and (4.3) the terms n_{SR_i} , n_{SD} is the complex additive white Gaussian noise with zero-mean and variance N_0 . The term x denotes the transmitted information symbol.

The channel between source and the multiple relay nodes (S- R_i), relays to the destination node (R_i -D) and the direct link from source to destination (S-D) follows Rayleigh fading.

The channel coefficient of the S-R_i link has zero-mean and variance given as

$$h_{SR_i} \sim CN(0, \sigma^2_{SR_i}) \qquad i = 1,2,3 \dots N. \tag{4.4}$$

The channel coefficient of the S-D link has zero-mean and variance given as

$$h_{SD} \sim CN(0, \sigma^2_{SD}). \tag{4.5}$$

The relays fixed with the input threshold (γ_{iT}) and the SNR at each relay is tested with the input threshold in Phase-II. The relay is selected and AF the source signal to the destination based on the input threshold testing (K.Shamganth et al., 2016).

Case (i): CSI assisted relays (Relays with Full CSI)

The amplification factor at the relay (Laneman et al.,2004) is given by

$$\alpha_r = \frac{\sqrt{P_r}}{\sqrt{P_s\,\varsigma_1^2 + N_0}} \qquad i = 1,2,3 \ldots N, \tag{4.6}$$

where $\varsigma_1^2 = |h_{SRi}|^2$ the channel coefficient of the first hop.

In this case, the assumption is that instantaneous CSI is available at the receiver. Also, the transmit power at the relay will be less if the fading effect in the first hop (ς_1) is low.

The instantaneous SNR of the source to multiple relay nodes (R_i) given as

$$\gamma_{SR_i} = \frac{P_s \varsigma_1^2}{N_0} \qquad i = 1,2,3 \ldots N, \tag{4.7}$$

Input threshold testing at the relay is given as

$$\begin{cases} if\ \gamma_{SR_i} > \gamma_{iT}\ then\ relay\ will\ be\ in\ active\ mode \\ if\ \gamma_{SR_i} < \gamma_{iT}\ then\ relay\ will\ be\ in\ sleep\ mode \end{cases} \qquad R_i = R_1, R_2, R_3 \ldots R_N. \tag{4.8}$$

The input threshold depends on the distance between the source to the relay node. The relay may not always be at the center of the source and the destination.

The location of the relays may vary, and the system model is shown in figure 4.2. The input threshold (γ_{iT}) at the relay depends on the distance between the source and the relay. Furthermore, channel attenuation mainly depends on the distance between two nodes.

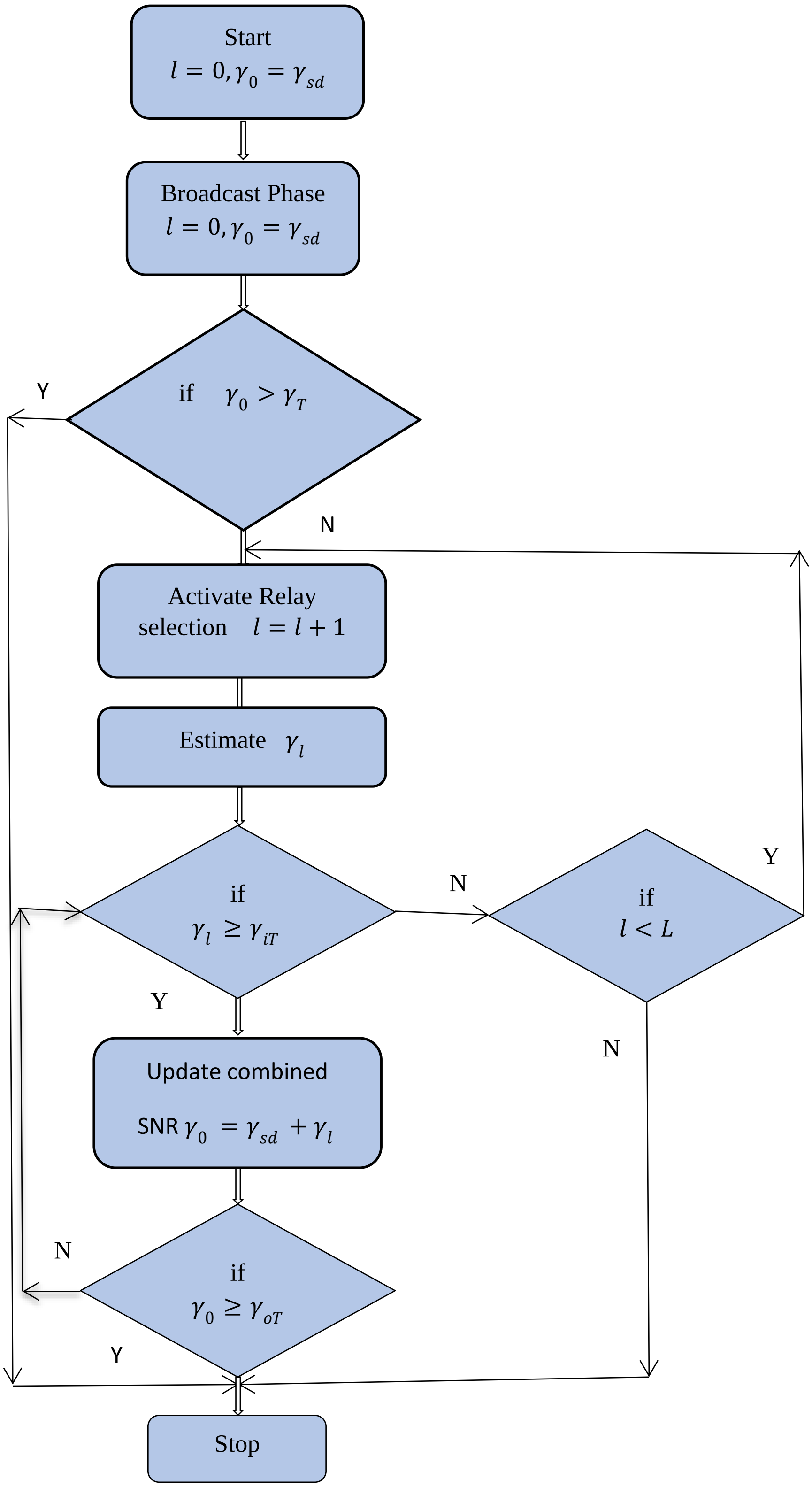

Figure 4.1. Mode of operation for Double Threshold-based MRS scheme

If the distance between the two nodes source and relay increases, then attenuation will increase as per the relation ${\sigma_{SR}}^2 \propto d^{-\alpha}$ the term α in this relation is the propagation constant. Based on this relation, the distance between the source, relay and destination nodes considered into three different cases as mentioned below:

Case(i): The distance between the source to the destination is

$$d(S,D) = d(S,R_i) + d(R_i,D). \tag{4.9}$$

Relays are at the center of the source and destination, then the distance between source to i^{th} relay is given as

$$d(S,R_i) = d(R_i,D). \tag{4.10}$$

The input threshold at the i^{th} relay is the fixed threshold for the case(i) in equation (4.10). The equal power allocation is applied, as mentioned below.

$$P_S = P_{Ri}. \tag{4.11}$$

Case(ii): If the distance between the source and i^{th} relay is more, then less input threshold (γ_{iT}) is fixed at the relay.

$$d(S,R_i) \gg d(R_i,D). \tag{4.12}$$

Case(iii): If less distance between the source and the i^{th} relay node, then a high input threshold (γ_{iT}) is fixed at the i^{th} relay.

$$d(S,R_i) < d(R_i,D). \tag{4.13}$$

The Equal power allocation scheme not suitable for the distance case mentioned in equation (4.12) and equation (4.13).

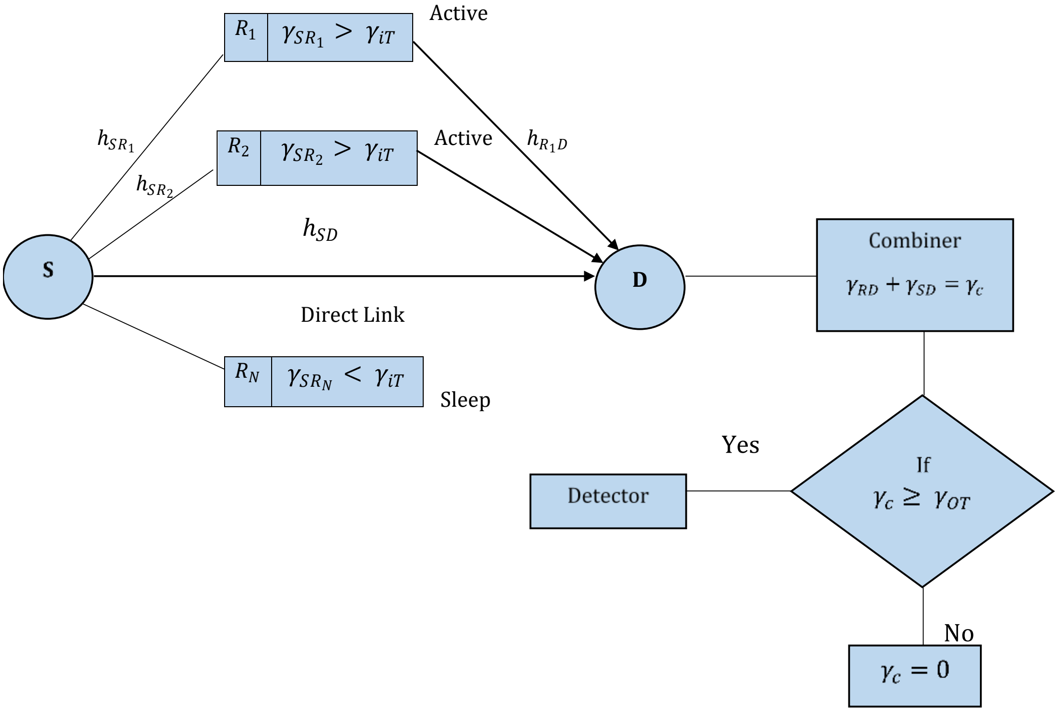

Figure 4.2. System Model Double Threshold-based MRS scheme

The optimum power allocation is stated in (Theorem 5.3.4, Liu et al.2008) for AF with M-PSK modulation for high SNR is given as

$$P_s = \frac{\sigma_{SR_i} + \sqrt{\sigma_{SR_i}^2 + 8\sigma_{R_iD}^2}}{3\sigma_{SR_i} + \sqrt{\sigma_{SR_i}^2 + 8\sigma_{R_iD}^2}} P \qquad i = 1,2,3 \dots N, \tag{4.14}$$

$$P_r = \frac{2\sigma_{SR_i}}{3\sigma_{SR_i} + \sqrt{\sigma_{SR_i}^2 + 8\sigma_{R_iD}^2}} P \qquad i = 1,2,3 \dots N. \tag{4.15}$$

The received signal at the destination D in Phase II is given as

$$y_{R_iD} = \alpha_r h_{R_iD} y_{SR_i} + n_{R_iD} \qquad i = 1,2,3 \dots N, \tag{4.16}$$

where n_{R_iD} is the noise components of the relay to destination link it is given as

$$n_{R_iD} \sim CN(0,1). \tag{4.17}$$

The channel coefficient between the R-D link has zero-mean and variance and is given by

$$h_{R_iD} \sim CN\left(0, \sigma_{R_iD}^2\right). \tag{4.18}$$

Substituting the amplification factor in equation (4.6) to equation (4.16) gives

$$y_{R_iD} = \frac{\sqrt{P_r}}{\sqrt{P_s\varsigma_1^2 + N_0}} h_{R_iD} y_{SR_i} + n_{R_iD} \quad i = 1,2,3 \ldots N. \tag{4.19}$$

Substituting equation (4.2) in equation (4.19) yields (Shamganth, K et al.,2014)

$$y_{R_iD} = \frac{\sqrt{P_r}}{\sqrt{P_s\varsigma_1^2 + N_0}} \ h_{R_iD}\left(\sqrt{P_s} h_{SR_i} x + n_{SR_i}\right) + n_{R_iD}, \tag{4.20}$$

$$y_{R_iD} = \frac{\sqrt{P_r P_s}}{\sqrt{P_s\varsigma_1^2 + N_0}} h_{R_iD} h_{SR_i} x + \frac{\sqrt{P_r}}{\sqrt{P_s\varsigma_1^2 + N_0}} h_{R_iD} n_{SR_i} + n_{R_iD}, \tag{4.21}$$

$$y_{R_iD} = \frac{\sqrt{P_r P_s}}{\sqrt{P_s\varsigma_1^2 + N_0}} h_{R_iD} h_{SR_i} x + \eta_{R_iD} \qquad i = 1,2,3 \ldots N, \tag{4.22}$$

$$\eta_{R_iD} = \frac{\sqrt{P_r}}{\sqrt{P_s\varsigma_1^2 + N_0}} h_{R_iD} n_{SRi} + n_{R_iD}, \tag{4.23}$$

where h_{R_iD} denotes the channel coefficient from the i^{th} relay to destination and n_{R_iD} is the complex additive white Gaussian noise between the i^{th} relay to destination channel.

The noise components n_{sr} and n_{rd}, are assumed to be independent and the equivalent noise η_{R_iD}, is zero-mean, complex Gaussian random variable with variance N_0.

$$N'_0 = N_0\left(\frac{P_r\varsigma_2^2}{P_s\varsigma_1^2 + N_0} + 1\right), \tag{4.24}$$

where N'_0 in (W/Hz) is the power spectral density of AWGN (Liu et al.,2008) and $\varsigma_2^2 = |h_{R_iD}|^2$ the channel coefficient of the second hop between the i^{th} relay to the destination node.

The instantaneous SNR of the direct link S-D is given by

$$\gamma_{SD} = \frac{P_s}{N_0} |h_{SD}|^2. \tag{4.25}$$

The instantaneous SNR of the i[th] relayed link R_i-D is given by

$$\gamma_{R_iD} = \frac{P_r\varsigma_2^2}{N_0}. \tag{4.26}$$

The threshold set at the output of the combiner test the combined i[th] relayed branch and the signal from the direct link. Combiner output threshold (γ_{oT}) follows the condition:

$$\begin{cases} if\ both\ \gamma_{SD} > \gamma_{oT}\ \ and\ \gamma_{SR_i} > \gamma_{iT}\ then\ \ \gamma_c = \gamma_{SD} + \gamma_{R_iD} \\ if\ \gamma_{SR_i} < \gamma_{iT}\ \ then\ \ \gamma_c = \gamma_{SD} \\ if\ \ \gamma_{SD} < \gamma_{oT}\ then\ \ \gamma_c = \gamma_{R_iD} \\ if\ both\ \gamma_{SD} < \gamma_{oT}\ \ and\ \gamma_{R_iD} < \gamma_{oT}\ then\ \ \gamma_c = 0 \end{cases}. \tag{4.27}$$

The total instantaneous SNR at the destination is the sum of the direct link SNR and the equivalent instantaneous SNR of the i[th] relay link S-R_i-D (Qiang Zhao et al. 2005) required for the calculation of mutual information between the source to the destination node.

The overall SNR for the relayed link S-R_i-D at the destination node for the relay with full CSI (Hasna & Alouini, 2004) is given by

$$\gamma_{R_i} = \frac{\frac{P_S\varsigma_1^2\varsigma_2^2}{N_0^2}}{\frac{\varsigma_2^2}{N_0}+\frac{1}{\alpha_r^2 N_0}}, \tag{4.28}$$

Substituting equation (4.6) into equation (4.28) gives

$$\gamma_{R_i} = \frac{\frac{P_S\varsigma_1^2\varsigma_2^2}{N_0^2}}{\frac{\varsigma_2^2}{N_0}+\frac{1}{\left(\frac{\sqrt{P_r}}{\sqrt{P_S\,\varsigma_1^2+N_0}}\right)^2 N_0}}, \tag{4.29}$$

Rewriting the equation (4.29) gives

$$\gamma_{R_i} = \frac{P_sP_r|h_{sd}|^2\varsigma_2^2}{N_0(P_s\varsigma_1^2+P_r\varsigma_2^2+N_0)}. \tag{4.30}$$

Substituting equation (4.7) and (4.25) in equation (4.30) gives

$$\gamma_{R_i} = \frac{\gamma_{SR_i}\,\gamma_{R_iD}}{\gamma_{SR_i}+\gamma_{R_iD}+1}. \tag{4.31}$$

The average SNR of the source to the ith relay link is

$$\overline{\gamma_{SR_\iota}} = \frac{\sigma^2_{SR_i}}{N_0}, \tag{4.32}$$

and the average SNR of the direct link between source to the destination node is given by

$$\overline{\gamma_{SD}} = \frac{\sigma^2_{SD}}{N_0}. \tag{4.33}$$

The total instantaneous SNR at the destination given as

$$\gamma_C = \gamma_{SD} + \sum_{i=1}^{N} \gamma_{R_i}. \tag{4.34}$$

At the output of the MRC combiner the signal detected by applying the minimum Euclidean distance detection technique (Proakis, J. G et al.,2008) using the optimal detection rule given as

$$\hat{x} = \arg\min|y - x| \quad (x_1, x_2, x_3, x_4) \in x, \tag{4.35}$$

The source to destination channel modelled as a Rayleigh fading channel, and the probability density function is given by

$$p(\gamma_{SD}) = \frac{1}{\overline{\gamma_{SD}}} exp\left(-\frac{\gamma_{SD}}{\overline{\gamma_{SD}}}\right), \tag{4.36}$$

The ith relay to destination channel modelled as a Rayleigh fading channel, and the probability density function is given by

$$p(\gamma_{R_iD}) = \frac{1}{\overline{\gamma_{R_\iota D}}} exp\left(-\frac{\gamma_{R_iD}}{\overline{\gamma_{R_\iota D}}}\right). \tag{4.37}$$

4.2.2 SER Analysis

The closed-form SER expression derived for M-PSK (K.J Ray et al.,2008, pp 219, pp123) is used as a benchmark for the simulation results.

The SER expression is given as

$$P_{SER} \approx \frac{1}{\pi}\int_0^{\frac{(M-1)\pi}{M}} M_{\gamma s}\left(\frac{sin^2\left(\frac{\pi}{M}\right)}{sin^2\theta}\right)\prod_{i=1}^{N} M_{\tilde{\gamma} i}\left(\frac{sin^2\left(\frac{\pi}{M}\right)}{sin^2\theta}\right)d\theta. \quad (4.38)$$

At high SNR, the SER expression for Multi-relay AF without threshold stated in (K.J Ray et al.,2008, pp 220, Theorem 6.2.1, equation (6.86)) given as

$$P_{SER} \approx \frac{1}{\pi}\int_0^{\frac{(M-1)\pi}{M}} sin^{2(R_N+1)}\theta(N_0)^{R_N+1}\frac{1}{P_s\sigma_{SD}{}^2}\prod_{i=1}^{N}\frac{P_s\sigma_{SR_i}{}^2+P_r\sigma_{R_iD}{}^2}{P_s\sigma_{SR_i}{}^2P_r\sigma_{R_iD}{}^2}d\theta. \quad (4.39)$$

Simulation Setup

In this section the simulation setup for testing the double threshold based multi-relay selection using coherent AF scheme is presented. The simulation results of the double threshold scheme with different distance cases are presented in the next section. Simulation parameters consists of 10^5 input random bits with QPSK modulation and AF relaying. The noise variance is assumed as $N_0 = 1$. The multi-relay scenario considers single antenna nodes and half-duplex communication. The source to destination and relay to destination channel is modeled as Rayleigh fading channels. The relay comparison for the double threshold based coherent AF model use 5, 10, 15, and 20-relay scenarios. The SER curves for different relay scenarios are plotted as a function of SNR.

Simulation Results and Discussion

The simulation results are categorized into three cases as discussed in section 4.2.1. The effect of increasing the number of relays in double threshold multi-relay coherent AF model is shown in figure 4.3 for case(ii). The optimum power ratios considered in this case is $P_s = 0.7P_t$ and $P_r = 0.3P_t$ with an input threshold of 3dB, less threshold is fixed as the relays are at a longer distance from the source. Increasing the number of relays to 20-relay from 5-relay show substantial performance improvement for the double threshold-based Coherent AF scheme. From the results, the difference between 15-relay and 20-relay scenario is less and 2dB difference is noticed between 5-relay and 10-relay scenario.

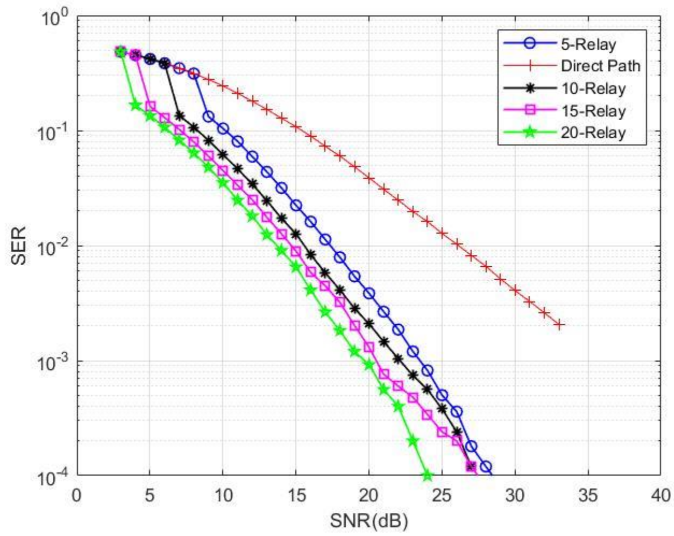

Figure 4.3. Relay Comparison of Double-Threshold based Coherent AF for case(ii)

Figure 4.4 presents the comparative results for case (iii) with relays near to the source is simulated with the input threshold of 10 dB and the combiner output threshold of 5 dB the power ratios used in the simulation is $P_s = 0.3P_t$ and $P_r = 0.7P_t$. Figure 4.3 shows a similar performance for more relay scenarios. However, an increase in the number of relays from 5 to 20 relays shows significant performance improvement. In figure 4.4, the performance difference of more than 4 dB observed between 5-relay and 20-relay scenario.

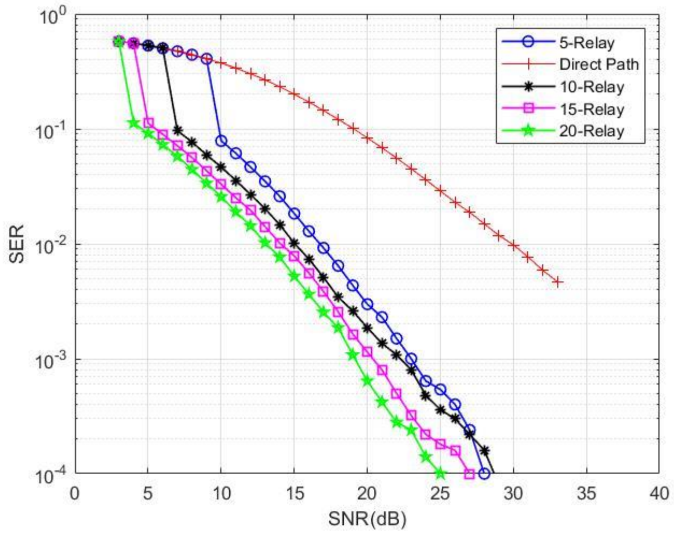

Figure 4.4. Relay Comparison of Double-Threshold based Coherent AF for case(iii)

4.3 Multi-Relay based Multi-Threshold DiffAF with Differential Modulation using the Proposed Combiner

Consider Multi-node multi-threshold cooperative system model with a source S and N relays shown in the figure. 4.5. The source signal is differentially modulated and the DiffAF relaying is applied at the relays. The input threshold (γ_{iT}) is tested at the relay, the relay will be in active mode or sleep mode depending upon the threshold value. In the multi-threshold model, the combiner at the destination has two thresholds: combiner input threshold (γ_{ciT}) and the combiner output threshold (γ_{coT}).

Algorithm 2

Step1 to Step 4 is the same as Algorithm 1.

Step5: The signal from the multiple relays and the direct link tested with the input threshold at the combiner (γ_{iT}).

Step 6: The signal from i[th] relayed link satisfying the condition $\left(\gamma_{R_iD} > \gamma_{iT}\right)$ is selected as the input to the combiner.

Step 7: The signal from direct link S-D satisfying the condition $(\gamma_{SD} > \gamma_{iT})$ is selected as the input to the combiner.

Step 8: The combined signal $\gamma_C = \gamma_{SD} + \sum_{i=1}^{N} \gamma_{R_i}$ is tested with the combiner output threshold (γ_{coT}). Output threshold is fixed at the combiner output to test received signal quality.

4.3.1 System Model

In differential Phase Shift Keying (DPSK) the information is modulated between the phases of the two consecutive symbols.

In Phase-I, the *M*-ary differential phase-shift keying (MDPSK) modulation is used (Proakis, J. G et al.,2008). The information symbol at the source node is given by

$$x_m = \sqrt{2E_s}\ e^{j\emptyset m} \qquad\qquad 1 \leq m \leq M, \tag{4.40}$$

where Es the symbol energy and $\emptyset_m = \frac{2\pi(m-1)}{M}$ the change in phase. Source transmission is the block-by-block transmission (Avendi & Nguyen, 2013).

The source differentially encodes (Proakis, J. G et al.,2008) the symbol x_m by

$$s^t = x_m s^{t-1}, \tag{4.41}$$

where 't' is the time index and s^t is the differentially encoded symbol to be transmitted at time t. The source transmits s^t with transmitted power P_S to the destination. Due to the broadcasting nature of the wireless network, the information also received by *N* relays.

The signal received at the relay in Phase-I is given as

$$y_{SR_i}{}^t = \sqrt{P_s} h_{SR_i}{}^t s^t + n_{SR_i}{}^t \qquad\qquad i = 1,2,3 \dots N, \tag{4.42}$$

where 'N' denotes the number of active relays.

The signal received at the destination node in the direct link S-D in Phase-I given as

$$y_{SD}{}^t = \sqrt{P_s} h_{SD}{}^t s^t + n_{SD}{}^t, \tag{4.43}$$

where P_s denotes the average source power of the transmitted signal. In equation (4.42) and (4.43) the terms $n_{SR_i}{}^t$ and $n_{SD}{}^t$ is the complex additive white Gaussian noise with zero-mean and variance N_0 .

The channel coefficient of the S-R_i link has zero-mean and variance given as

$$h_{SR_i}{}^t \sim CN(0, \sigma_{SR_i}^2) \qquad\qquad i = 1,2,3 \dots N. \tag{4.44}$$

The channel coefficient of the S-D link has zero-mean and variance given as

$$h_{SD}{}^t \sim CN(0, \sigma_{SD}^2). \tag{4.45}$$

For simplicity, the time index 't' is removed in the remaining equations in this system model. The relay tests the received signal with the threshold before amplification with the conditions as shown below:

$$\begin{cases} if \begin{array}{l} \dfrac{\left(\sigma_{SR_i}{}^t\right)^2}{N_0^2} > \gamma_{iT}\ relay\ is\ in\ active\ mode \\ \dfrac{\left(\sigma_{SR_i}{}^t\right)^2}{N_0^2} < \gamma_{iT}\ relay\ is\ in\ idle\ mode \end{array} \end{cases}, \tag{4.46}$$

where $\left(\sigma_{SR_i}{}^t\right)^2$ is the variance of the received SNR at the relay and N_0^2 is the normalized noise variance.

The signal from the i[th]-relay amplified and forwarded to the destination node D and the amplification factor (Qiang Zhao et al. 2005) is given by

$$A \cong \sqrt{\frac{P_r}{P_s\sigma_{SR_i}^2 + N_0}}. \tag{4.47}$$

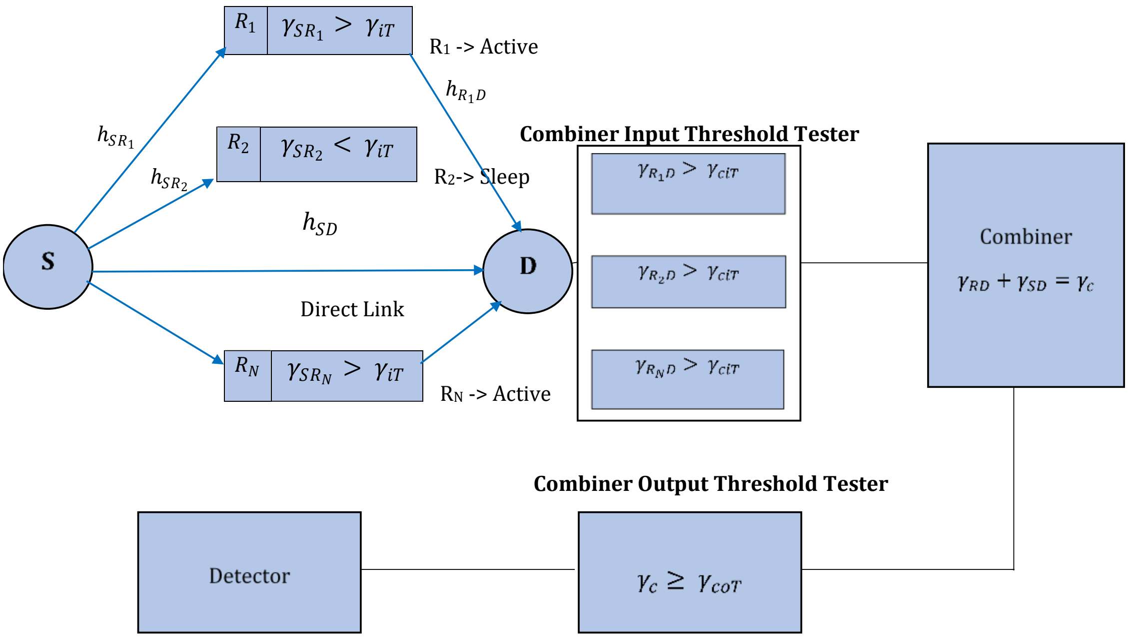

Figure 4.5. System Model Multi-Threshold based MRS scheme

The signal received at the destination D in Phase II in the relayed link is given by

$$y_{R_iD}{}^t = A\sqrt{P_r}\, h_{R_iD}{}^t + n_{R_iD}{}^t, \tag{4.48}$$

where $n_{R_iD}{}^t$ is the noise components in the i^{th} relay to destination channel and is given by

$$n_{R_iD}{}^t \sim CN(0,1). \tag{4.49}$$

Substituting equation (4.47) in equation (4.48) gives

$$y_{R_iD}{}^t = \sqrt{\frac{P_r}{P_s\sigma_{SR_i}^2 + N_0}}\sqrt{P_r}\, h_{R_iD}{}^t + n_{R_iD}{}^t. \tag{4.50}$$

The equivalent SNR of the S-R_i-D i^{th} relay link is given by

$$\gamma_r = \frac{P_s P_r |h_{SD}|^2 \left|h_{R_iD}\right|^2}{N_0(P_s \sigma_{SR_i}^2 + P_r \left|h_{R_iD}\right|^2 + N_0)}. \tag{4.51}$$

Simplifying equation (4.51) gives

$$\gamma_r = \frac{\gamma_{SR_i}\gamma_{R_iD}}{P_s + \gamma_{R_iD} + 1}, \tag{4.52}$$

with unit variance $\sigma_{SR_i}^2 = 1 \; and \; N_0 = 1$.

At the combiner input, the signal received in the direct link S-D is given by

$$\kappa_{SD} = y_{SD}^{*(t-1)} y_{SD}^{t}. \tag{4.53}$$

The signal at the input to the combiner from the i[th] relayed link is given by

$$\kappa_{R_iD} = y_{R_iD}^{*(t-1)} y_{R_iD}^{t}. \tag{4.54}$$

Threshold testing at the input to the combiner selects only the strongest branch and is given by

$$\begin{gathered} if\ \gamma_{SD} > \gamma_{ciT}\ \ then\ combiner\ will\ accept\ the\ input\ from\ the\ direct\ link\ and\ is\ given\ as\ \kappa = \kappa_{sd} \\ and\ if\ \gamma_{R_iD} > \gamma_{ciT}\ \ then\ combiner\ will\ accept\ the\ input\ from\ the\ relay\ link\ and\ is\ given\ as\ \kappa = \kappa_{R_iD}. \\ else\ \kappa = 0 \end{gathered} \tag{4.55}$$

The average SNR at the combiner is given by

$$\overline{\gamma_c} = \overline{\gamma_{SD}} + \overline{\gamma_{R_iD}}. \tag{4.56}$$

Substituting (4.40) in (4.42) and (4.43) and assuming the slow-fading assumption $h_{SD}^{t} = h_{SD}^{t-1}$ and $h_{R_iD}^{t} = h_{R_iD}^{t-1}$ in equation (4.48) gives

$$y_{SD}^{t} = s^t y_{SD}^{t-1} + w_{SD}^{t}, \tag{4.57}$$

$$w_{SD}^{t} = n_{SD}^{t} - s^t n_{SD}^{t-1}, \tag{4.58}$$

$$y_{R_iD}^{t} = s^t y_{R_iD}^{t-1} + w_{R_iD}^{t}, \tag{4.59}$$

$$w_{R_iD}^{t} = {n_{R_iD}}^{t} - s^t {n_{R_iD}}^{t-1}. \tag{4.60}$$

Threshold testing at the output of the combiner for the different cases are as follows:

$$\bar{\gamma}_c = \begin{cases} \gamma_{SD} \quad , & if\ \gamma_{SD} > \gamma_{coT}\ and\ \gamma_{SR_i} < \gamma_{iT} \quad or \quad \gamma_{R_iD} < \gamma_{ciT} \quad Case\ (i) \\ \gamma_{SD} + \gamma_{R_1D} \quad , & if\ \gamma_{SD} + \gamma_{R_1D} > \gamma_{coT}\ and\ \gamma_{SR_1} > \gamma_{iT}\ and\ \gamma_{SR_i} < \gamma_{iT}\ for\ (i = 2 \ldots\ldots N)\ \ Case\ (ii) \\ \gamma_{SD} + \sum_{i=1}^{N} \gamma_{R_iD} & if \gamma_{R_iD} \geq \gamma_{ciT}\ and\ \gamma_{SD} + \sum_{i=1}^{N} \gamma_{R_iD} > \gamma_{coT}\ \ for\ (i = 1,2 \ldots\ldots N)\ \ Case\ (iii) \\ \sum_{i=1}^{N} \gamma_{R_iD} & if\ \gamma_{SD} < \gamma_{ciT}\ \ and\ \gamma_{R_iD} \geq \gamma_{ciT}\ \ for\ (i = 1,2 \ldots\ldots N) \quad Case\ (iv) \\ 0 & if\ \gamma_{R_iD} < \gamma_{ciT}\ and\ \gamma_{SD} < \gamma_{ciT} \quad Case\ (v) \end{cases} .$$

(4.61)

The threshold at the output of the combiner is γ_{coT} is fixed. The relation between γ_{ciT} and γ_{coT} used in the proposed scheme is as follows:

$$\gamma_{coT} = \frac{\gamma_{ciT}}{4}, \tag{4.62}$$

$$\begin{cases} if \quad \gamma_c \geq \gamma_{coT}\ then\ combined\ signal\ will\ be\ send\ to\ the\ detector \\ else\ \gamma_c = 0 \end{cases} . \tag{4.63a}$$

In differential detection, the Rayleigh fading channels are constant over a two-bit interval. Non-coherent detection of the transmitted symbols obtained from the consecutive received symbols is given by

$$\kappa_{SD} = Re\{y_{SD}^{*t-1}\ y_{SD}^{t}\}, \tag{4.64}$$

$$\kappa_{R_iD} = Re\{y_{R_iD}^{*t-1}\ y_{R_iD}^{t}\}, \tag{4.65}$$

where κ_{SD} and κ_{R_iD} are the decision variables.

The output of the detector is given by

$$\kappa = \kappa_{SD} + \kappa_{R_iD}. \tag{4.62}$$

The transmitted signal decoded at the destination as

$$\hat{s^t} = \begin{cases} -1 & if\ \kappa < 0 \\ +1 & if\ \ \kappa > 0 \end{cases}. \tag{4.63}$$

4.3.2 BER Analysis

The conditional BER using (Simon & Alouini, 1998 (Equation.25)) is given as

$$P_b(E|\gamma_c) = \frac{1}{4\pi}\int_{-\pi}^{\pi} z(\theta)\exp[-\gamma_c\ l(\theta)]\, d\theta, \tag{4.64}$$

where γ_c is the instantaneous SNR at the combiner output. The

$$z(\theta) = \frac{1-\beta^2}{1+2\beta sin\theta+\beta^2}, \tag{4.65}$$

where $\beta = \frac{a}{b}$ and

$$l(\theta) = \frac{b^2}{2log_2 M}(1 + 2\beta sin\theta + \beta^2). \tag{4.66}$$

In equation (4.66) ‘M’ refers to the constellation size. The parameter $\beta = \frac{a}{b}$ is constant and it depends on the type of modulation (Simon & Alouini, 1998).

For DPSK: $a = 0\ \ and\ b = \sqrt{2}$.

Substituting $a = 0\ \ and\ b = \sqrt{2}$ in equation (4.65) and (4.66) gives

$$z(\theta) = 1 \text{ and } l(\theta) = 1, \tag{4.67}$$

Substituting equation (4.67) in equation (4.64) gives

$$P_b(E|\gamma_c) = \frac{1}{4\pi}\int_{-\pi}^{\pi} \exp[-\gamma_c]\, d\theta, \tag{4.68}$$

$$= \frac{1}{2}\exp[-\gamma_c], \tag{4.69}$$

Substituting equation (4.56) in equation (4.69) gives

$$P_b(E|\gamma_c) = \frac{1}{2}\exp[-(\gamma_{SD} + \gamma_r)]. \tag{4.70}$$

The performance of the proposed threshold-based relay selection with double threshold combining scheme is analyzed with two cases as mentioned below:

Case (i): $if\ \gamma_{SD} < \gamma_{ciT}\ \ and\ \gamma_{R_iD} \geq \gamma_{ciT}$

Only the relay link SNR is above the threshold at the input to the combiner γ_{ciT}. The equivalent SNR of the relay link S-R_i-D given in equation (4.52) as

$$\gamma_r = \frac{\gamma_{SR_i}\gamma_{R_iD}}{P_s+\gamma_{R_iD}+1}.$$

The PDF of equation (4.52) is derived using (Papoulis, A. et al., 2001) as follows:

Let $C_1 = \gamma_{SR_i}\gamma_{R_iD}$ and $C_2 = P_s + \gamma_{R_iD} + 1$.

$$p(\gamma_r) = \int_0^{\infty} |C_2| p_{C1,C2}(\gamma_r C_2, C_2) dC_2. \tag{4.71}$$

$p_{C1,C2}$ is the joint PDF of C_1 and C_2

$$p_{C1,C2}(C_1, C_2) = p_{C1|C2}\left(\frac{C_1}{C_2}\right) p_{C2}(C_2). \tag{4.72}$$

Marginal PDF of C_2 is given by

$$p_{C2}(C_2) = \frac{1}{\overline{\gamma_{R_iD}}}\exp\left(\frac{-(C_2-P_s-1}{\overline{\gamma_{R_iD}}}\right). \tag{4.73}$$

The conditional PDF of $p_{C1|C2}\left(\frac{C_1}{C_2}\right)$ is as follows:

$$p_{C1|C2}\left(\frac{C_1}{C_2}\right) = \frac{1}{P_s|C_2-P_s-1|} exp\left(-\left(\frac{C_1}{P_s(C_2-P_s-1)}\right)\right). \tag{4.74}$$

Substituting equation (4.72) and (4.73) into equation (4.71) gives

$$p(\gamma_r) = \int_0^\infty \left|P_s + \gamma_{R_iD} + 1\right| \left(\frac{1}{P_s|C_2-P_s-1|} exp\left(-\left(\frac{C_1}{P_s(C_2-P_s-1)}\right)\right) \frac{1}{\overline{\gamma_{R_iD}}} \exp\left(\frac{-(C_2-P_s-1}{\overline{\gamma_{R_iD}}}\right)\right) d\gamma_{R_iD},$$

(4.75)

Simplifying equation (4.75) gives

$$p(\gamma_r) = \int_0^\infty \left|P_s + \gamma_{R_iD} + 1\right| \gamma_r \left[\frac{1}{P_s\left|\gamma_{R_iD}\right|} exp\left(-\frac{\gamma_{SR_i}}{P_s}\right) \frac{1}{\gamma_{R_iD}} \exp\left(\frac{-\gamma_{R_iD}}{\overline{\gamma_{R_iD}}}\right)\right] d\gamma_{R_iD}. \quad (4.76)$$

Let $m = \frac{1}{\overline{\gamma_{R_iD}}}$ and $n = \frac{\gamma_r(1+P_s)}{P_s}$ in equation (4.85) using [Ryzhik, I. M. (2007), Eqn.3.478.4], the PDF $p(\gamma_r)$ can be written as

$$p(\gamma_r) = 2\frac{(P_s+1)}{P_s\overline{\gamma_{R_iD}}} exp\left(-\frac{\gamma_r\gamma_{SR_i}}{P_s}\right) K_0(\beta\sqrt{\gamma_r}) + \frac{2}{P_s\overline{\gamma_{R_iD}}}\sqrt{\frac{\gamma_r(P_s+1)\gamma_{R_iD}}{P_s}}\, exp\left(-\gamma_r\gamma_{SR_i}\right) K_1(\beta\sqrt{\gamma_r}).$$

(4.77)

where $\beta = 2\sqrt{\frac{P_s+1}{P_s\overline{\gamma_{R_iD}}}}$ and $K_0(\cdot)$ denotes the zeroth-order modified Bessel function of the second kind.

$K_1(\cdot)$ denotes the first-order modified Bessel function of the second kind.

The BER expression of single channel binary DPSK (Proakis, J. G et al.,2008) is

$$P_{er} = \int_0^\infty \frac{1}{2} exp(-\gamma_r)\, p(\gamma_r) d\gamma_r. \quad (4.78)$$

In equation (4.78), Let $r = \sqrt{\gamma_r}$ gives

$$P_{er} = 2\frac{(P_s+1)}{P_s\overline{\gamma_{R_iD}}} \int_0^\infty exp\left(-\frac{r^2\gamma_{SR_i}}{P_s}\right) K_0(\beta r) dr +$$

$$\frac{2}{P_s\overline{\gamma_{R_iD}}} \sqrt{\frac{\gamma_r(P_s+1)\overline{\gamma_{R_iD}}}{P_s}} \int_0^\infty r^2 exp\left(-\frac{r^2\gamma_{SR_i}}{P_s}\right) K_1(\beta r) dr. \quad (4.79)$$

Case (ii): if $\gamma_{SD} > \gamma_{ciT}$ *and* $\gamma_{R_iD} \geq \gamma_{ciT}$

If both the relay and direct link SNR is above the input threshold at the combiner γ_{ciT}.

Binary differential PSK with multiple independent channels the BER conditioned on γ_c [Proakis, J. G et al.,2008 equation (11.1-11.3)] is given by

$$P_e(\gamma_c) = \frac{1}{8}(4 + \gamma_c)\exp(-\gamma_c). \tag{4.80}$$

Averaging the conditional BER with respect to the joint PDF of γ_r and γ_{SD} and substituting equation (4.52) in equation (4.80) gives

$$P_e = \iint_0^\infty \frac{1}{8}(4 + \gamma_{SD} + \gamma_r)\exp\left(-(\gamma_{SD} - \gamma_r)\right)p(\gamma_r)p(\gamma_{SD})d\gamma_r\,\gamma_{SD}. \tag{4.81}$$

Substituting equation (4.77) and (4.36) in equation (4.81) gives

$$P_e = \iint_0^\infty \frac{1}{8}\left(4 + \gamma_{SD} + \gamma_r\right)\exp\left(-\left(\gamma_{SD} - \gamma_r\right)\right)2\frac{(P_s+1)}{P_s\overline{\gamma_{R_iD}}}\,exp\left(-\frac{\gamma_r\gamma_{SR_i}}{P_s}\right)K_0\left(\beta\sqrt{\gamma_r}\right) +$$

$$\frac{2}{P_s\gamma_{R_iD}}\sqrt{\frac{\gamma_r(P_s+1)\overline{\gamma_{R_iD}}}{P_s}}\,exp\left(-\gamma_r\gamma_{SR_i}\right)K_1\left(\beta\sqrt{\gamma_r}\right)\frac{1}{\overline{\gamma_{SD}}}exp\left(-\frac{\gamma_{SD}}{\overline{\gamma_{SD}}}\right)d\gamma_r\,d\gamma_{SD}\,. \tag{4.82}$$

Simulation Setup

In this section the simulation setup for testing the multi-threshold based multi-relay selection using DiffAF relaying is presented. The simulation results of the multi- threshold scheme with different distance cases is discussed in the next section. Simulation parameters consists of 10^5 random input bits with DPSK modulation and DiffAF relaying. The channel between source to destination and relay to destination is modeled as Rayleigh fading channels and the noise variance is assumed as $N_0 = 1$. The relay node is with single antenna and half-duplex communication is considered.

Simulation Results and Discussion of Multi-Threshold DiffAF and AF

Simulation results presented in this section consider the multi-threshold scenario with input SNR threshold at the relay. Destination threshold testing at the combiner input performed by comparing the SNR of the received signal from the relay to destination link with the combiner input threshold and the strong relay to destination branches are selected. The threshold at the combiner output tests the signal quality for detection.

The comparative analysis of multi-threshold based DiffAF for case(ii) is presented in figure 4.6. The analysis considers 10, 15 and 20-relay scenario with the optimum power ratios of $P_s = 0.7P_t$ and $P_r = 0.3P_t$. Increase in the number of relays, in this case, shows lesser performance improvement and difference of 3dB observed for 10-relay and 20-relay scenario for the threshold values considered for the simulation.

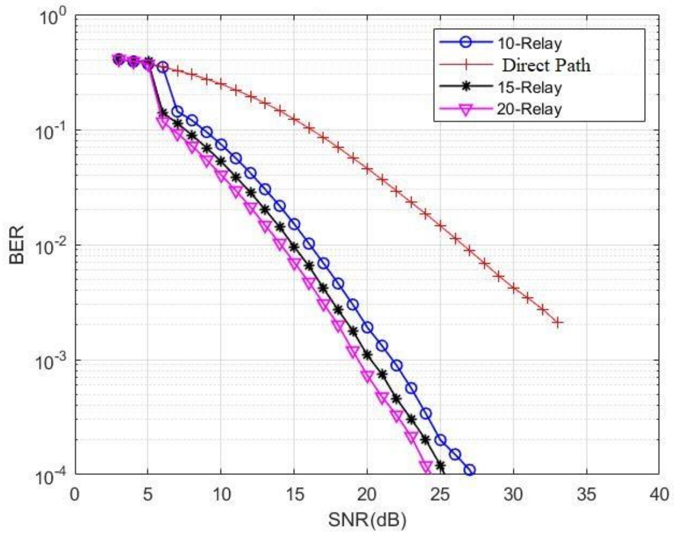

Figure 4.6. Relay Comparison of Multi-Threshold DiffAF for case(ii)

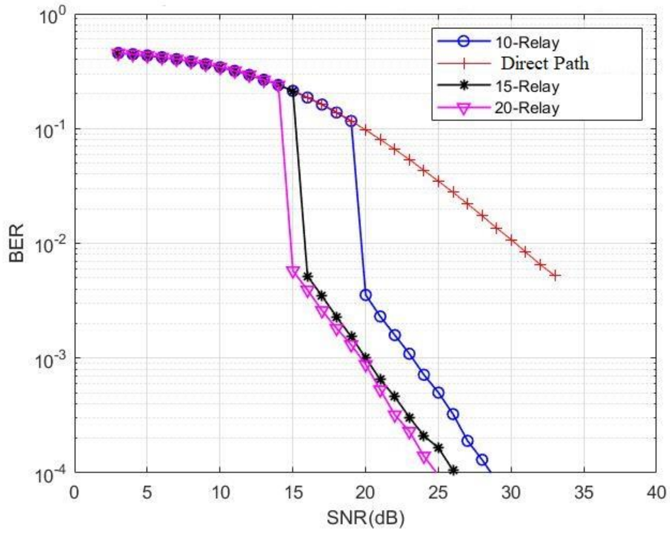

Figure 4.7. Relay Comparison of Multi-Threshold DiffAF for case(iii)

Figure 4.7 presents the comparative results of Multi-threshold DiffAF for case (iii) with the input threshold of 20dB and combiner input threshold of 9dB and combiner output threshold of 25dB. Furthermore, the results show a lesser performance difference between 15-relay and 20-relay scenario. However, the significant performance difference of 3dB observed between 10-relay and 15-relay scenario. Increasing the number of relays shows performance improvement in this case.

Simulation Setup for Multi-Threshold AF

In this section the simulation setup for testing the multi-threshold based multi-relay selection using AF relaying is presented. In the next section the simulation results of the multi- threshold AF scheme with different distance cases are presented. Simulation parameters consists of 10^5 random input bits with DPSK modulation and AF relaying. The channels source to destination, source to relay and relay to destination is modeled as Rayleigh fading channels and the noise variance is assumed as $N_0 = 1$.

Simulation Results and Discussion of Multi-Threshold AF

The comparative analysis of Multi-threshold AF with the varied number of relays for case(ii) presented in figure 4.8. The analysis considers 5,10, 15 and 20-relay scenarios with the power ratios $P_s = 0.7P_t$ and $P_r = 0.3P_t$. Increasing the number of relays, in this case, show significant performance improvement. Furthermore, the difference of 4dB observed between 5-relay and 20-relay scenario for the input threshold of 20dB and combiner input threshold of 15dB and output threshold of 25dB. However, results show less performance difference between 15-relay and 20-relay scenario. Figure 4.9 presents the relay comparison of Multi-threshold AF for case (iii). Furthermore, the results show the performance of 10-relay outperform 15-relay and 20-relay scenario. However, the performance difference is very less above 17dB for the 15-relay and 20-relay scenarios.

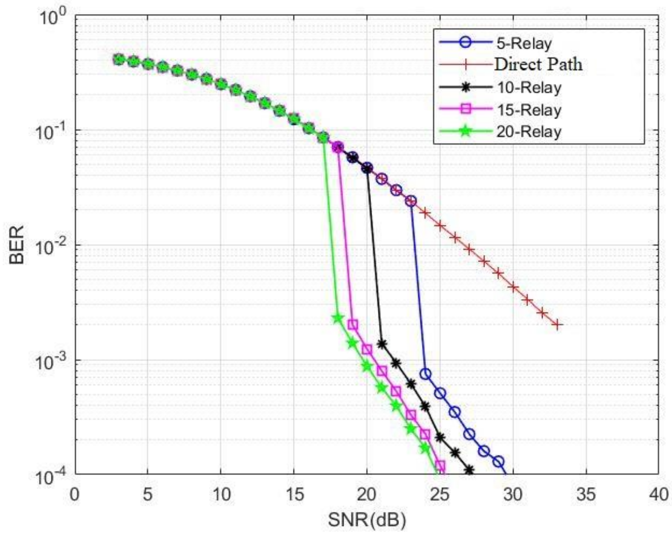

Figure 4.8. Relay Comparison of Multi-Threshold AF for case(ii)

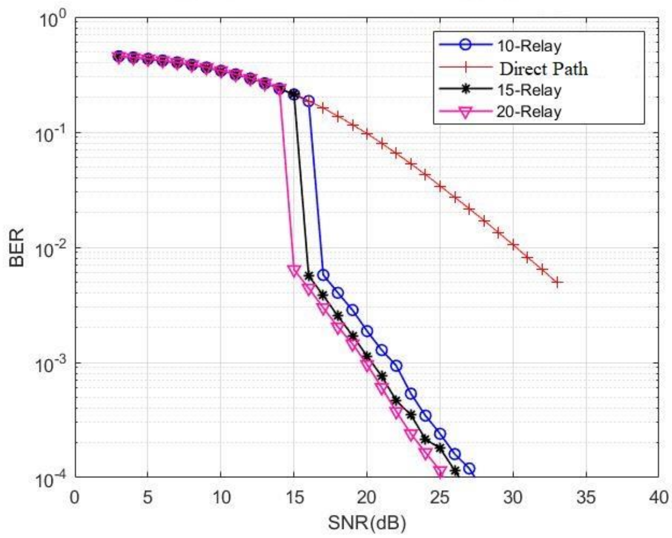

Figure 4.9. Relay Comparison of Multi-Threshold AF for case(iii)

4.4 Multi-Relay based Multi-Threshold AF with Coherent Modulation

In a multi-relay based cooperative D2D network with a source S and N relays, the source signal is amplified and forward to the destination using AF relaying. In the system model equation (4.1) to (4.37) is same as mentioned above. The difference in this scheme is the additional threshold at the input to the combiner. Threshold testing at the output of the combiner can improve the overall quality of the e2e communication.

The SNR at the output of the combiner is given as

$$\gamma_c = \gamma'_{SD} + \gamma'_{R_i} \qquad i = 1,2, \dots N, \tag{4.83}$$

where $\gamma'_{SD} = \begin{cases} \gamma_{SD} & if\ \gamma_{SD} \geq \gamma_{ciT} \\ 0 & if\ \gamma_{SD} < \gamma_{ciT} \end{cases},$ (4.84)

and

$$\gamma_{R_i}{}' = \begin{cases} \gamma_{R_i} & if\ \gamma_{R_i} \geq \gamma_{ciT} \\ 0 & if\ \gamma_{R_i} < \gamma_{ciT} \end{cases}. \tag{4.85}$$

Combiner output threshold condition is given by

$$\gamma_c = \begin{cases} \gamma'_{SD} + \gamma'_{R_i} & if\ \gamma'_{SD} + \gamma'_{R_i} > \gamma_{coT} \\ 0 & if\ \gamma'_{SD} + \gamma'_{R_i} < \gamma_{coT} \end{cases}. \tag{4.86}$$

Relation between γ_{ciT} and γ_{coT} is same as mentioned in equation (4.62). Furthermore, signal detection follows equation (4.35).

Simulation Setup

In this section the simulation setup for testing the multi-threshold based multi-relay selection using AF relaying is presented. The simulation results of the multi- threshold AF scheme with coherent modulation are presented. Simulation parameters consists of 10^5 random input bits with QPSK modulation and AF relaying. The channels are modeled as Rayleigh fading channels and the noise variance is assumed to be $N_0 = 1$. The SER curves for different relay scenarios are plotted as a function of SNR.

Simulation Results and Discussion of Multi-threshold AF with Coherent Modulation

The comparative analysis of 3,5,10 and 15-relay scenarios for Multi-threshold coherent AF is presented in figure 4.10. Results show that 15-relay scenario shows substantial performance improvement compared to other relays considered. Moreover, the difference in the performance is less for high relay scenarios 10-relay and 15-relay scenario considered for case(ii).

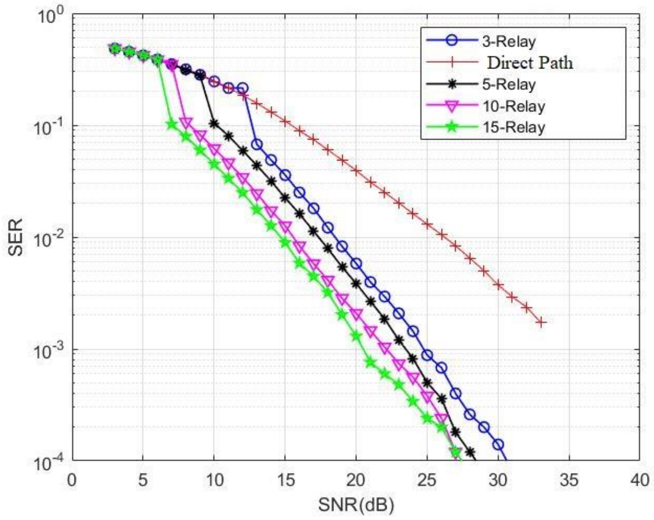

Figure 4.10. Relay Comparison of Multi-Threshold Coherent AF for case(ii)

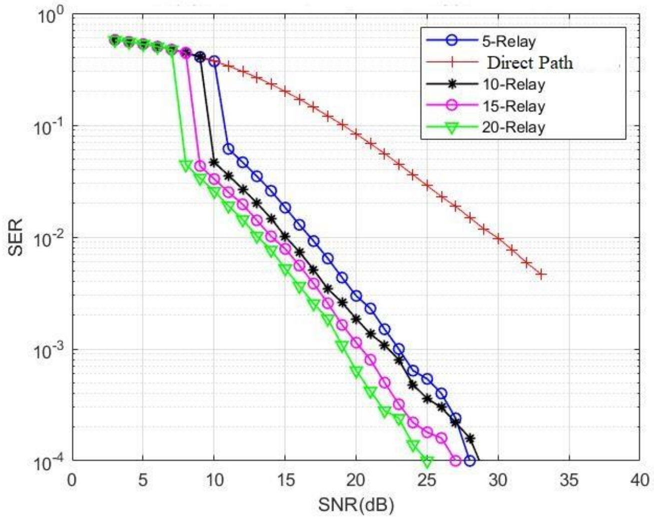

Figure 4.11. Relay Comparison of Multi-Threshold Coherent AF for case(iii)

The relay comparison of Multi-threshold AF for case (iii) with the input threshold of 10dB and combiner input threshold of 5dB and combiner output threshold of 10dB is presented in figure 4.11. Furthermore, the results show the performance of 20-relay outperform 15-relay,10-relay, and 5-relay scenarios. However, the performance difference is very less above 8dB between 15-relay and 20-relay scenarios.

Comparative analysis of different threshold values in Multi-threshold AF for 5-relay scenario shown in figure 4.12. Three threshold sets considered for the comparison, and the combiner input threshold varied from 5 to 9dB. The input threshold of 10dB and combiner input and output of 5dB and 10dB outperform the higher threshold values considered, and it is due to a greater number of relays selected for assisting the source transmission. Furthermore, the combiner will receive more relay to destination link and choose the link with high SNR compared to the combiner input threshold.

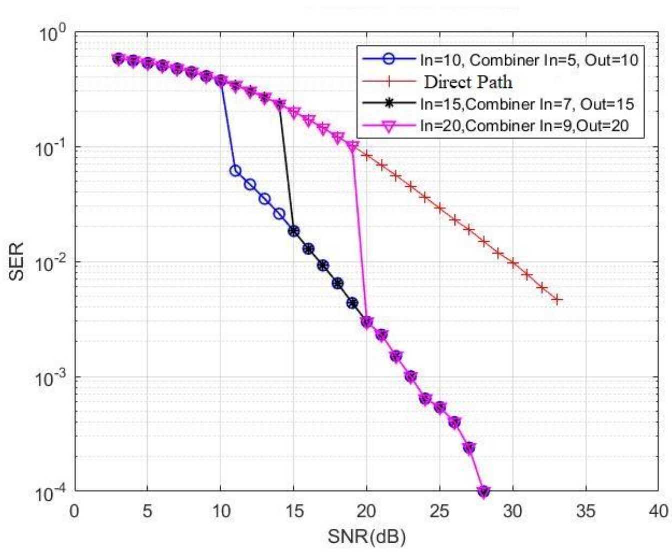

Figure 4.12. Threshold Comparison of Multi-Threshold Coherent AF for case(iii)

4.5 Double Threshold-based Multi-Relay DiffAF with Differential Modulation

4.5.1 System Model

Multi-relay cooperative network with a single source (S) and destination (D) with N-relays and DQPSK modulation considered in this model. Double threshold is applied in this scheme, as discussed in Algorithm 1. Input threshold γ_{iT} at the relays and combiner output threshold γ_{oT} at the output to the combiner at the destination is used.

Information bits converted to the format of differential M-ary phase-shift keying (DMPSK), the symbol at the source is given as

$x_m = e^{j\emptyset_m}$,

where $\emptyset_m = \frac{2\pi(m-1)}{M}$, for $m = 0,1,\ldots,M-1$,

and $M = 4$ is the constellation size considered in the system model.

In the BER analysis, the conditional BER expression reported by (Simon & Alouini, (Equation.25) 1998) is applied. So, the BER analysis of the proposed scheme is

$$P_b(e|\gamma_C) = \frac{1}{4\pi}\int_{-\pi}^{\pi} z(\theta)\exp[-\gamma_C\, l(\theta)]\, d\theta, \tag{4.87}$$

$$z(\theta) = \frac{1-\beta^2}{1+2\beta sin\theta+\beta^2}, \tag{4.88}$$

and $\beta = \frac{a}{b}$ and $l(\theta) = \frac{b^2}{2log_2 M}(1+2\beta sin\theta+\beta^2)$.

For $M = 4$, the parameter $\beta = \frac{a}{b}$ is constant and depends on the type of modulation reported in (Simon & Alouini, 1998) for DQPSK

$a = \sqrt{2-\sqrt{2}}$ and $b = \sqrt{2+\sqrt{2}}$.

Substituting $a = 0.7653$, $b = 1.847$, $M = 4$

$\beta = 0.414$, gives

$z(\theta) = \frac{0.828}{1+0.828(sin\theta)+0.1713}$, and

$l(\theta) = 0.852(1 + 0.828sin\theta + 0.171)$.

Substituting $z(\theta)$ and $l(\theta)$ in equation (4.87) gives

$$P_b(e|\gamma_C) = \frac{1}{4\pi}\int_{-\pi}^{\pi}\frac{0.828}{1+0.828(sin\theta)+0.1713}\exp[-\gamma_C\ (0.8521 + 0.828sin\theta + 0.171)]\, d\theta, \quad (4.98)$$

$$P_b(e|\gamma_C) = \frac{1}{4\pi}\int_{-\pi}^{\pi}\frac{0.828}{1+0.828(sin\theta)+0.1713}\exp\left[-(\gamma_{SD} + \gamma_{R_iD})\ (0.8521 + 0.828sin\theta + 0.171)\right] d\theta \quad (4.89)$$

The multi-node DiffAF BER expressions without threshold mentioned below serve as a benchmark for the simulated results of the proposed double threshold based DiffAF scheme.

The average BER formulation derived in (Liu et al.,2008, equation 9.147) is given as

$$P_e = \frac{1}{2^{2(N+1)}\pi}\int_{-\pi}^{\pi}\frac{f(\theta,\beta,N+1)}{1+k_{SD}(\theta)} \times \prod_{i=1}^{N}\frac{1}{1+k_{SR_i}(\theta)}\left(1 + \frac{k_{SR_i}(\theta)Z_i(\theta)}{1+k_{SR_i}(\theta)}\ \frac{P_s\sigma_{SR_i}^2+N_o}{P_r\sigma_{R_iD}^2}\right) d\theta. \quad (4.90)$$

The BER upper bound (Himsoon et al., 2008) given as

$$P_e \leq \frac{C(\beta,N+1)N_0^{N+1}}{P_s\sigma_{SD}^2}\ \prod_{i=1}^{N}\frac{P_i\sigma_{R_iD}^2+\left(P_s\sigma_{SR_i}^2+N_0\right)Z_{i,max}}{P_sP_r\sigma_{SR_i}^2\sigma_{R_iD}^2}, \quad (4.91)$$

where

$$C(\beta, N + 1) = \frac{1}{2^{2(N+1)}\pi}\int_{-\pi}^{\pi}\frac{f(\theta,\beta,N+1)}{\alpha^{N+1}(\theta)}\, d\theta, \quad (4.92)$$

is a constant that depends on modulation size and number of relays, $\alpha(\theta)$, and $f(\theta, \beta, N + 1)$.

The approximated BER expression (Himsoon et al., 2008) is given as

$$P_e \approx \frac{C(\beta,N+1)N_0^{N+1}}{P_s\sigma_{SD}^2}\prod_{i=1}^{N}\frac{P_i\sigma_{R_iD}^2+\left(P_s\sigma_{SR_i}^2+N_0\right)Z_{i,min}}{P_sP_r\sigma_{SR_i}^2\sigma_{R_iD}^2}. \tag{4.93}$$

Simulation Setup

In this section the simulation setup for testing the double threshold based multi-relay selection using AF and DiffAF relaying scheme is presented. The simulation results of the double threshold scheme with different distance cases are presented in the next section. Simulation parameters consists of 10^5 input random bits with DQPSK modulation. The source to destination and relay to destination channel is modeled as Rayleigh fading channels with the noise variance of $N_0 = 1.$ The multi-relay scenario considers single antenna nodes and half-duplex communication.

Simulation Results of Double Threshold AF and DiffAF

The simulation results of the proposed double threshold-based relay selection scheme for cooperative wireless network is presented in this section. Figure 4.13 presents the Multi-relay AF comparative simulation results for QPSK with DQPSK scheme with equal power allocation, and the 5-relay scenario considered. It is evident from the results that the coherent modulation scheme shows an improved performance as compared to the differential modulation without threshold.

Figure 4.14 shows the Multi-relay AF comparative simulation results for QPSK with DQPSK scheme with $P_s = 0.8P_t$ and $P_r = 0.2P_t$ and 5-relays. In this case, the relays are nearer to the destination. The result is as expected with a 3dB difference between the coherent and differential modulation schemes without threshold at BER of 10^{-3}.

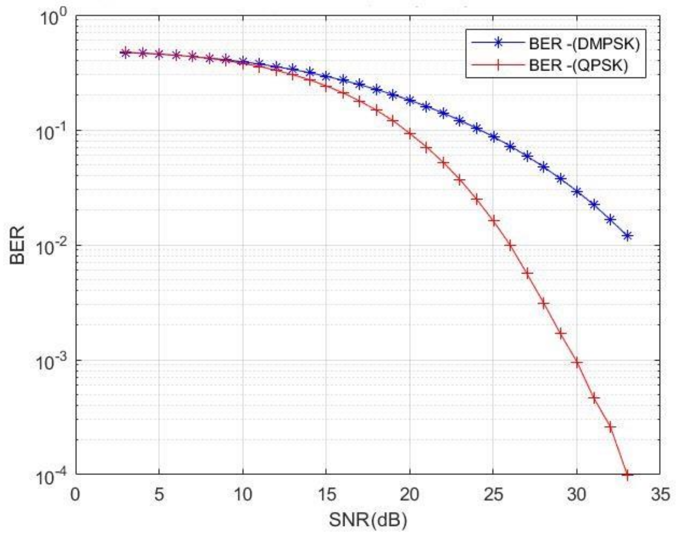

Figure 4.13. Comparison of Coherent Vs Differential Modulation scheme for Multi-relay AF with Equal Power allocation

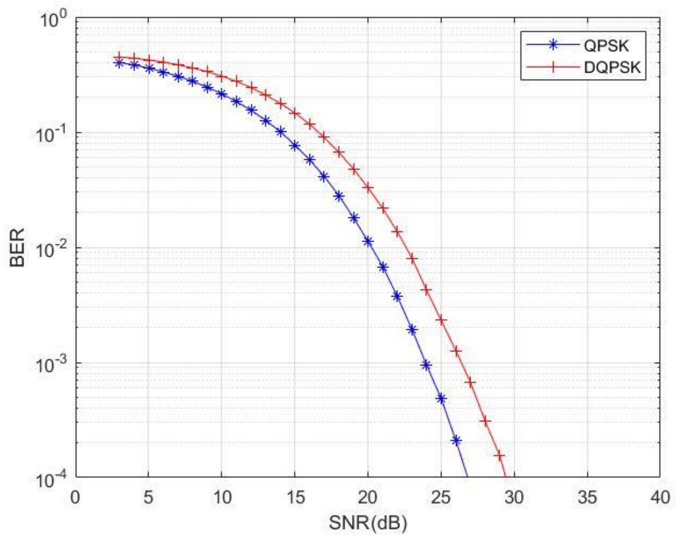

Figure 4.14. Comparison of Coherent Vs Differential Modulation scheme for Multi-relay AF with $P_s = 0.8P_t$ and $P_r = 0.2P_t$

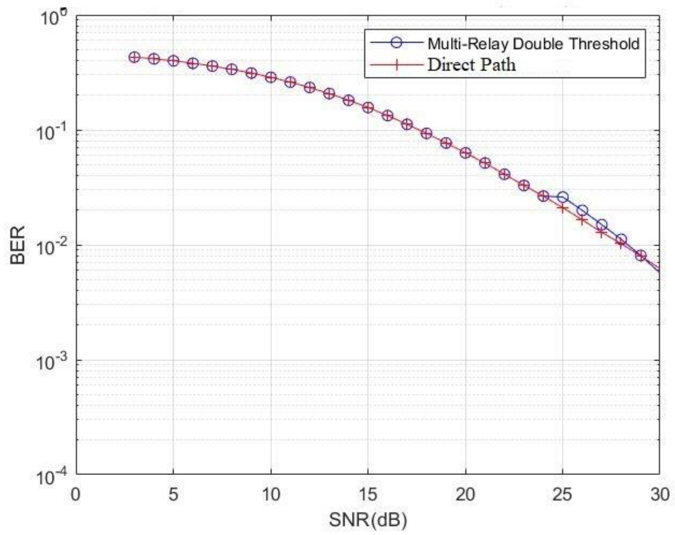

Figure 4.15. Multi-relay AF with Double-Threshold

Figure 4.15 shows the Multi-relay cooperative AF with an input threshold of 10dB at the relay the combiner output threshold of 5dB with equal power allocation. Also, five relays considered in this simulation with equal distance between the source and destination to the relays. The simulation considers the DQPSK modulation of the source signal. Similar performance with the direct path without relay is observed in the simulation results with equal power allocation at the source and the relays.

In figure 4.16, the proposed double threshold scheme with 5-relay and an input threshold of 3dB and combiner output threshold of 5dB outperforms the direct path. In the simulation, the source power and relay power fixed as $P_s = 0.7P_t$ and $P_r = 0.3P_t$. The distance between the source and relay based on case (ii). The simulation results show more than 5dB performance improvement at the BER of 10^{-3}.

The simulation results in figure 4.17 based on case(iii) with the relays nearer to the source. Moreover, similar performance is observed for the direct path without relay and double threshold up to an SNR of 20dB. Furthermore, at high SNR above 20dB performance improvement is observed, at an SNR of 22dB, the proposed scheme achieves the BER of 10^{-3}.

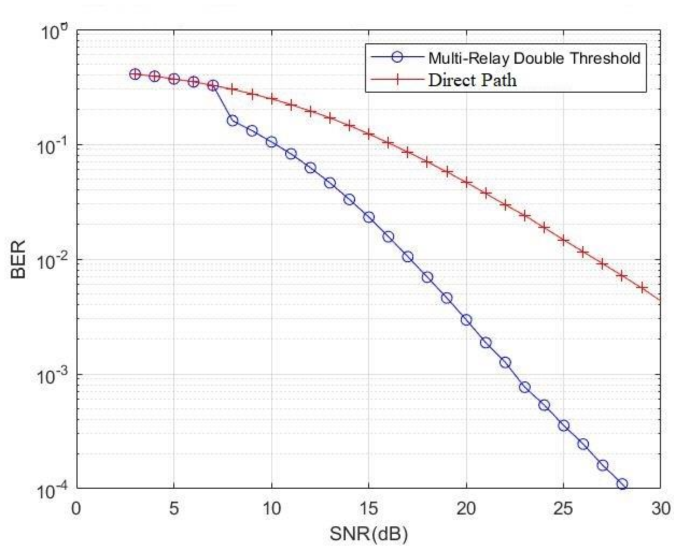

Figure 4.16. Multi-relay AF with Double-Threshold for case(ii)

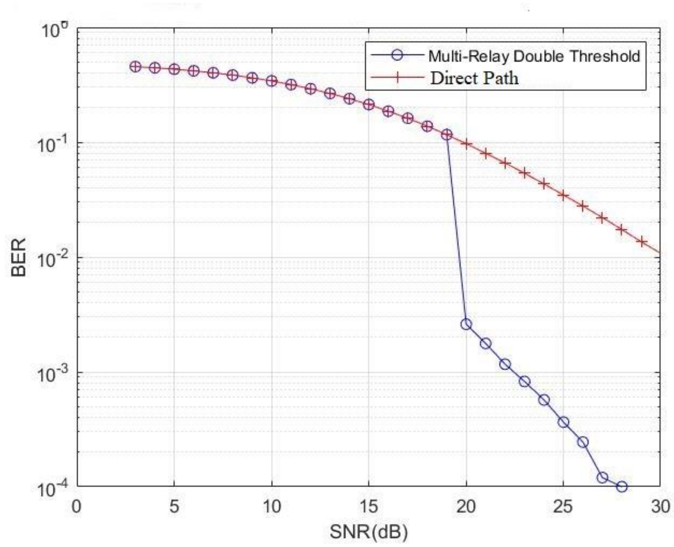

Figure 4.17. Multi-relay AF with Double-Threshold for case(iii)

Simulation Results and Discussion of DiffAF based Double Threshold Scheme

The double threshold based DiffAF simulation results for case (ii) is presented in figure 4.18. Double threshold curve achieves more than 5 dB performance improvement as compared to the direct path for a BER of 10^{-3}. In figure 4.19, the double threshold curve shows the performance improvement from an SNR of 7dB as compared to the direct path. The BER of

10^{-3} is achieved at an SNR of 23dB. Increase in the number of relays in the simulation of figure 4.20 results in improved performance as compared to the double threshold curve in figure 4.19. It is observed that the double threshold curve is steep at an SNR of 6 dB and the BER of 10^{-3} is achieved at an SNR of 21dB, so an increase in the number of relays shows an improvement of 2dB in figure 4.20 as compared to the double threshold curve in figure 4.20.

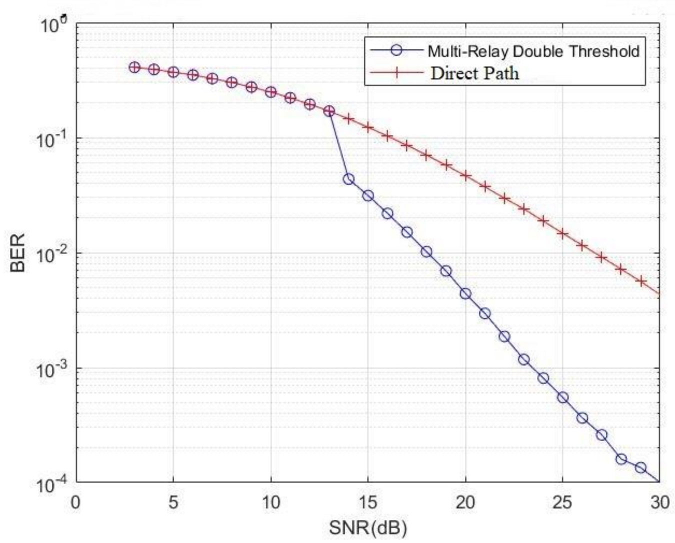

Figure 4.18. Double-Threshold based DiffAF for case(ii)

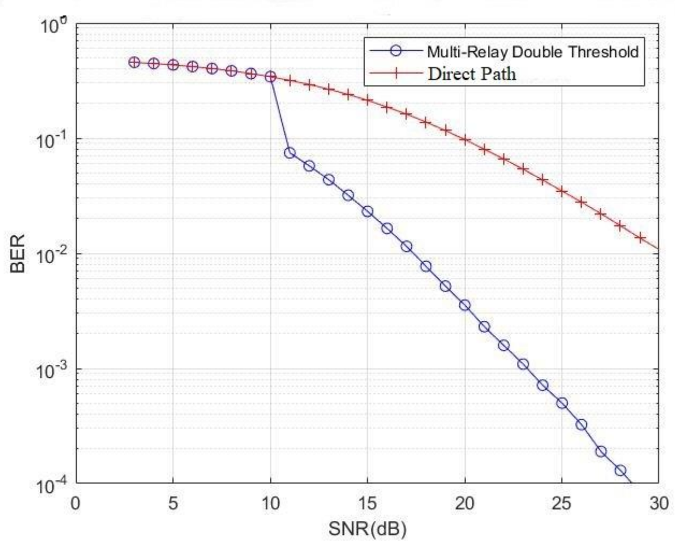

Figure 4.19. Multi-relay DiffAF with Double-Threshold using 5-relay for case(iii)

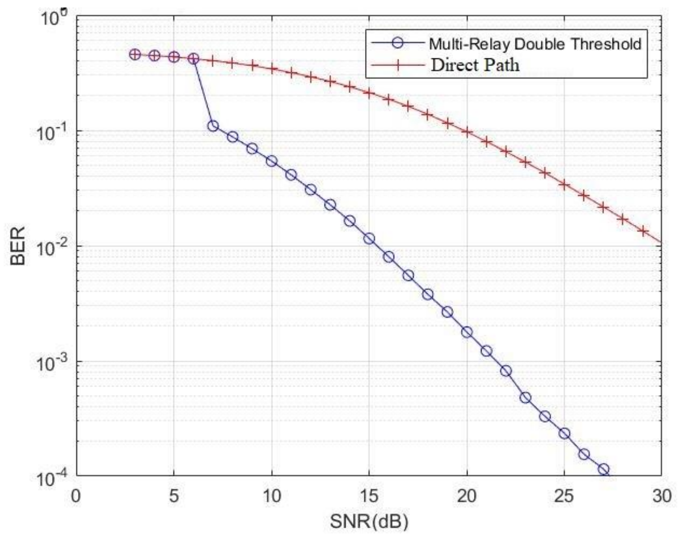

Figure 4.20. Multi-relay DiffAF with Double-Threshold using 10-relay for case(iii)

Comparative Analysis based on the Number of Relays for Double Threshold based DiffAF

The comparative results presented in figure 4.21 based on case (ii) with the relays located at a distance from the source node. The optimum power ratios used in this simulation with $P_s = 0.7P_t$ and $P_r = 0.3P_t$ and the input threshold is less in this case due to the relays located at a far distance from the relays the path loss will be more due to that signal power at the relay will be less and hence threshold at the relay is less in this case. Increasing the number of relays shows the performance improvement for the double threshold-based scheme. The difference of 2dB observed between 5-relay and 10-relay curve at the BER of 10^{-3}. Moreover, the same difference observed between 10-relay curve and 15-relay curve. Furthermore, 1dB difference noticed between 15-relay and 20-relay curve. Increasing the number of relays above 20-relay results in a similar performance. The difference of 5dB at the BER of 10^{-3} is noticed in figure 4.21 between 20-relay and 5-relay.

Figure 4.22 presents the comparative results for case (iii) with relays near to the source is simulated with the input threshold of 10dB and the combiner output threshold of 5dB the power ratios used in the simulation is $P_s = 0.3P_t$ and $P_r = 0.7P_t$. Increase in the number of relays from 5 to 20 relays shows improved performance. The difference of 2dB is observed between 5-relay and 10-relay results; however, this difference reduces as the number of relay increases. It is noticed that difference between 15-relay curve to 10-relay curve is 1dB at 10^{-3}. Furthermore, the difference of 4 dB at the BER of 10^{-3} is observed between 20-relay and 5-relay scenario.

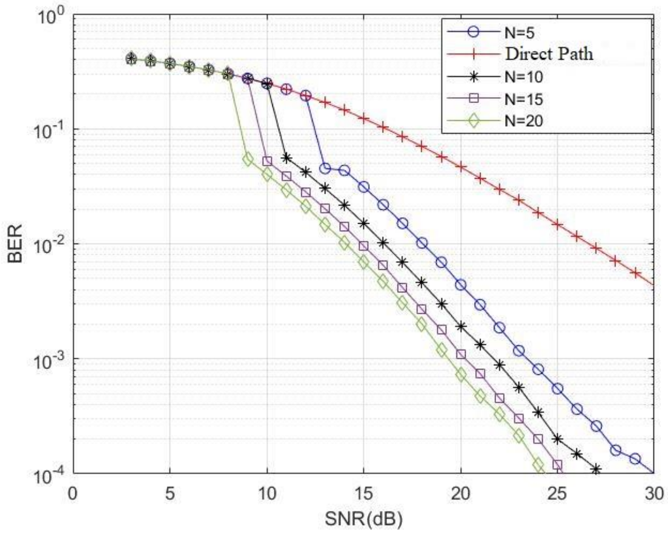

Figure 4.21. Multi-relay DiffAF with Double-Threshold with $P_s = 0.7P_t$ and $P_r = 0.3P_t$ and Th_In=5 and Th_Out=10 for case(ii)

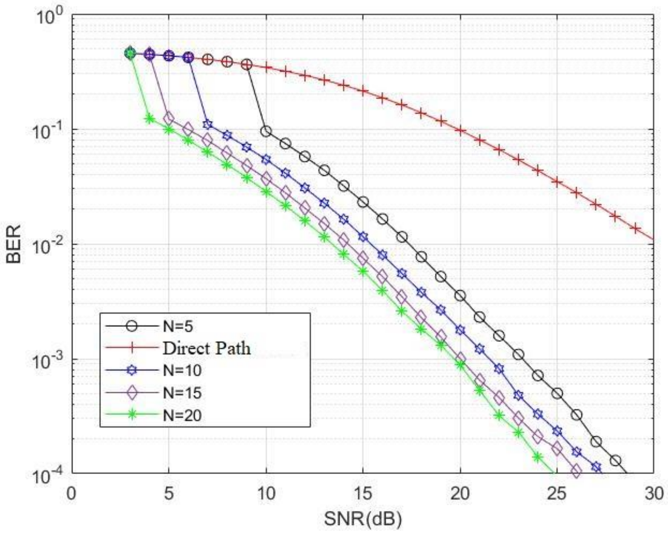

Figure 4.22. Multi-relay DiffAF with Double-Threshold with $P_s = 0.3P_t$ and $P_r = 0.7P_t$ and Th_In=10 and Th_Out=5 for case(iii)

Comparative Analysis based on the Number of Relays for Double Threshold based AF

The comparative results for case (ii) with relays away from the source is shown in figure 4.23 and the difference of 4dB at the BER of 10^{-3} is observed between 20-relay and 5-relay scenarios. Moreover, the BER of 10^{-3} is achieved at an SNR of 22dB for the 5-relay scenario and 21dB for the 10-relay and 20dB for the 15-relay and 20-relay scenario. Furthermore, similar performance is observed for the BER of 10^{-3} for 15-relay and 20-relay scenarios.

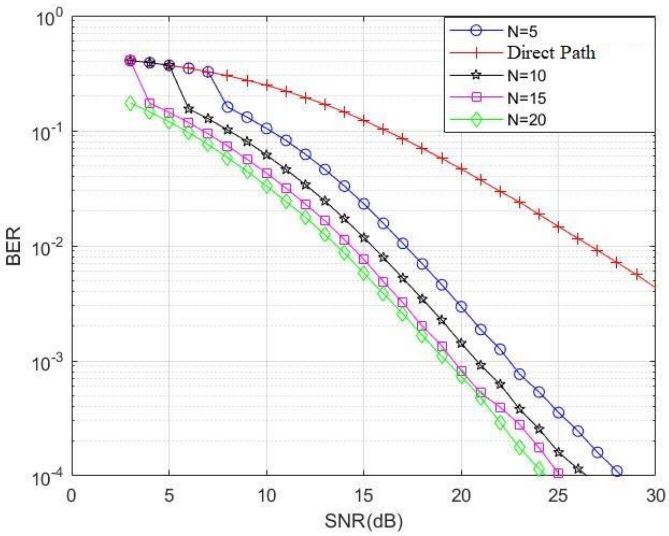

Figure 4.23. Multi-relay AF with Double-Threshold with $P_s = 0.7P_t$ and $P_r = 0.3P_t$ and Th_In=3 and Th_Out=5 for case(ii)

The comparative results for case (iii) with relays nearer to the source shown in figure 4.24, 5-relay scenario achieve the BER of 10^{-3} at the SNR of 22dB and there is a difference of 2dB between 5-relay and 10-relay scenario. Furthermore, the performance of 20-relay scenario is excellent compared to 15, 10 and 5-relay scenarios. There is a difference of 4dB is noticed at the BER of 10^{-3} between 20-relay and 5-relay scenarios. The simulation considers the input threshold of 10dB and the output threshold of 5dB.

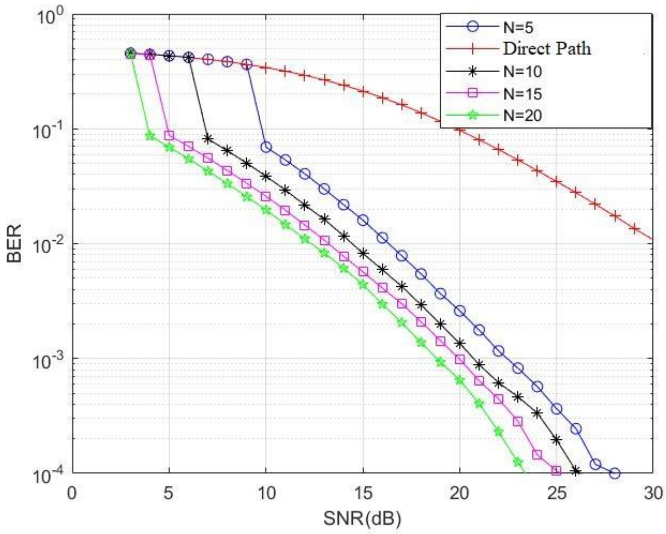

Figure 4.24. Multi-relay AF with Double-Threshold with $P_s = 0.3P_t$ and $P_r = 0.7P_t$ for case(iii)

4.6 Complexity Analysis of the Proposed Double-Threshold based Relay Selection Scheme

Published as

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In the double threshold scheme the input threshold (γ_{iT}) fixed at the relay and the combiner threshold (γ_{OT}) is at the output of the combiner as mentioned in Algorithm 1.The combiner output SNR (γ_c) of the proposed double threshold scheme based on different cases given as

$$\gamma_c = \begin{cases} \gamma_{SD} \quad , \quad if\ \gamma_{SD} \geq \gamma_{OT}\ and\ \gamma_{SR_i} < \gamma_{iT} & Case\ (i) \\ \gamma_{SD} + \gamma_{R_1D} \quad , \quad if\ \gamma_{SD} + \gamma_{R_1D} \geq \gamma_{OT}\ and\ \gamma_{SR_1} > \gamma_{iT}\ and\ \gamma_{SR_i} < \gamma_{iT}\ for\ (i = 2 \ldots\ldots N) & Case\ (ii) \\ if\ \gamma_{SD} + \sum_{i=1}^{N} \gamma_{R_iD} \quad if\ \gamma_{SD} \geq \gamma_{OT}\ and\ \gamma_{R_iD} \geq \gamma_{OT} \quad for\ (i = 1,2 \ldots\ldots N) & Case\ (iii) \\ \sum_{i=1}^{N} \gamma_{R_iD}\ \ if\ \gamma_{SD} < \gamma_{OT}\ \ and\ \gamma_{R_iD} \geq \gamma_{OT} \quad for\ (i = 1,2 \ldots\ldots N) & Case\ (iv) \end{cases} \tag{4.94}$$

The expression for the CDF of the combiner output (Shamganth.K et al.,2018) given as

$$F_{\gamma_c}(x) = \sum_{i=1}^{M} Pr\left(\left[\gamma_c = \gamma_{SD} + \sum_{i=1}^{N} \gamma_{R_iD}\right] \; for \; [\gamma_c \leq x\right], \tag{4.95}$$

$$F_{\gamma_c}(x) = P_r(\gamma_{OT} \leq \delta_1 \leq x) + \sum_{i=2}^{M} P_r\,(\gamma_{OT} \leq \delta_i \leq x) \;\&\; [0 \leq \delta_{i-1} < \delta_{OT}]$$

$$+ P_r([0 \leq \delta_M \leq x] \;\&\; [0 \leq \delta_{M-1} < \delta_{OT}]\,). \tag{4.96}$$

In equation (4.96), δ_i is the combined SNR of the i^{th} -relayed paths and direct path and is given by

$$\delta_i = \gamma_{SD} + \sum_{i=1}^{N} \frac{\gamma_{SR_i}\gamma_{R_iD}}{P_s + \gamma_{R_iD} + 1}. \tag{4.97}$$

In equation (4.96) the first term refers to the combined SNR of the direct path and the first relayed path is above the combiner threshold $i.e., \delta_1 > \gamma_{OT}$.

The second term in equation (4.96) based on ‘i’ relays combined with the direct path to form an output SNR above the threshold (γ_{OT})

$$\delta_i > \gamma_{OT} \; if \; \gamma_{Ri} > \gamma_{iT} \; for \; (i = 1,2 \ldots .N). \tag{4.98}$$

The third term in equation (4.96) is the worst case where the sum of N-1 relayed paths and the direct path does not exceed the combiner threshold (γ_{OT}).

From the mode of operation of the proposed double threshold scheme, an observation listed below:

a. A single relay forwards the source information, and the relayed signal is combined with the direct path if the SNR at the relay is above the input threshold (γ_{iT}) and the combined SNR is above the combiner output threshold (γ_{OT}).
b. The i^{th} relayed link $(2 \leq i \leq N-1)$ is used when the combined SNR of an N-1 branch and the direct link is above the combiner output threshold (γ_{OT}). $\gamma_{SD} + \sum_{i=1}^{N} \gamma_{Ri} \geq \gamma_{OT} \; and \; \sum_{i=1}^{N} \gamma_{Ri} > \gamma_{iT}$

c. No relay is selected, and feedback is sent to the source to retransmit the data. i.e., $\gamma_{SD} + \sum_{i=1}^{N} \gamma_{Ri} < \gamma_{OT}$

Mathematically:

$$P_r[\gamma_c = \gamma_{SD} + \sum_{i=1}^{N} \gamma_{Ri}] = \begin{cases} P_r[\gamma_{R1} \geq \gamma_{iT}]\ for\ i = 1\ and \\ \gamma_{SD} + \gamma_{R1} \geq \gamma_{OT} \\ P_r \begin{bmatrix} \sum_{i=2}^{N-1} \gamma_{Ri} > \gamma_{iT} \\ and \end{bmatrix} \\ \gamma_{SD} + \sum_{i=2}^{N-1} \gamma_{Ri} > \gamma_{OT} \\ P_r \begin{bmatrix} \sum_{i=1}^{N} \gamma_{Ri} < \gamma_{iT} \\ and \end{bmatrix} \\ if\ P_r[\gamma_c < \gamma_{OT}]\ No\ output \end{cases} . \tag{4.99}$$

Applying total probability theorem, the CDF of the output SNR $P_o(x)$ is given as

$P_o(x) = P_r[\gamma_c < x]$,

$$P_o(x) = P_r\left[\left(\sum_{i=1}^{N} \gamma_{Ri} + \gamma_{SD}\right) < x\right]. \tag{4.100}$$

Let

$C_1 = P_r[\gamma_c < \gamma_{OT}] = F(\gamma_{iT}) - F(\gamma_{oT})$,

$C_2 = P_r[\gamma_c < \gamma_{OT}] = F(\gamma_{OT})$,

$$C_3 = P_r[\gamma_c \geq \gamma_{OT}] = 1 - F(\gamma_{OT}). \tag{4.101}$$

Average Channel Estimation

If the number of channel estimation (N_e) increases, then it will lead to an increase in the complexity of the relay selection scheme in a multi-relay cooperative D2D network (Shamganth.K et al.,2018).

Case (i): $N_e = 1$; in this case, the first relayed link SNR $\gamma_{R_1} > \gamma_{iT}$ and the combiner output $\left(\gamma_c = \gamma_{SD} + \gamma_{R_1}\right)$ is above the combiner threshold (γ_{OT}),

It is given as $\gamma_c \geq \gamma_{OT}$.

So, the probability for *Case (i)* given as

$$C_3 = P_r[\gamma_c \geq \gamma_{OT}] = 1 - F(\gamma_{OT}). \tag{4.102}$$

Case (ii): If $2 \leq N_e \leq N-1$, there are two cases that exist:

i. The first $N-1$ relayed link SNR is below the input threshold (γ_{iT}), but the remaining ith relayed link SNR, and the direct path is above the combiner output threshold (γ_{OT}). Given as

$\gamma_c = \gamma_{SD} + \gamma_{Ri}$ and $\gamma_c > \gamma_{OT}$.

The probability is given by

$$C_2^{N-1}C_3 = F^{N-1}(\gamma_{OT})[1 - F(\gamma_{OT})]. \tag{4.103}$$

ii. In the relayed path, if the first N-1 relayed link SNR at the relay is above the input threshold (γ_{iT}), and the combined SNR of the relayed link SNR and the direct link SNR (γ_{SD}) is below the combiner threshold (γ_{OT}),

i.e, $\gamma_c = \gamma_{SD} + \gamma_{R_{i-1}}$ for $i = \{1,2,..N\}$,

and $\gamma_c < \gamma_{OT}$ but the combined SNR of the Nth relayed link and the direct link (γ_{SD}) is above the combiner threshold (γ_{OT}).

Given as

$\gamma_c = \gamma_{SD} + \gamma_{R_i}$ and $\gamma_c \geq \gamma_{OT}$.

The probability is given by

$$\sum_{i=1}^{M-1} \binom{M-1}{i} C_1^{M-1-i}\left[F^{(i)}(\gamma_{OT}).C_3 - F^{(i+1)}(\gamma_{OT})\right]. \tag{4.104}$$

For $N_e = M$; the probability is $1 - \sum_{i=1}^{M-1} P_r[N_e = i]$.

After arranging, the number of path estimation calculated as follows:

$$P_r[N_e = i] = \begin{cases} \sum_{i=1}^{M-1} \binom{M-1}{i} C_1^{M-1-i} B_{i+1} & 1 \leq i \leq M-1 \\ 1 - \sum_{i=1}^{M-1} P_r\,[N_e = i] & i = M \end{cases}, \tag{4.105}$$

where $B_1 = C_3$

$B_2 = C_1C_3 - F^{(2)}\gamma_{OT},$

$B_3 = [F^{(2)}\gamma_{OT}C_3 - F^{(3)}\gamma_{OT}],$

$B_i = [F^{(i-1)}\gamma_{OT}C_3 - F^{(i)}\gamma_{OT}].$

Mathematical expression for the average number of path estimation N_e (Ning Xie,2014) is given by

$$N_e = \sum_{i=1}^{M} i.P_r\,[N_e = i]. \tag{4.106}$$

Average Number of Combined branches

Based on the mode of operation of the proposed double threshold scheme, the average number of combined branches (Shamganth.K et al.,2018) calculated as follows:

a. $N_c = 0;$ if all the relayed link SNR is less than the input threshold (γ_{iT}) and the combined SNR (γ_c) is less than the output threshold $(\gamma_c < \gamma_{OT})$. The probability is C_2^M in this case, first M-1 relayed links SNR is below input threshold (γ_{iT}), so the relays in the sleep mode and the M$^{\text{th}}$ relayed link SNR is above γ_{iT} and the combined branch SNR (γ_c) is above the combiner threshold (γ_{OT}) .

b. $N_c = 1;$ The two cases are as follows:

Case (i): only one relay link SNR is above input threshold (γ_{iT}), and the combined SNR $\gamma_c \geq \gamma_{OT}$ the probability is given as $MC_2^{M-1}C_1$.

Case (ii): In this case first $M-1$ relay link SNR is below input threshold (γ_{iT}), so the relay is in sleep mode and the M$^{\text{th}}$ relay link SNR is above γ_{iT} and the combined SNR (γ_c) is above γ_{OT} .

The probability is given as $C_3 \sum_{i=0}^{M-1} C_2^i$.

Probability of combining one branch is

$MC_2^{M-1}C_1 + C_3 \sum_{i=0}^{M-1} C_2^i$.

c. $N_C = M$; all the relayed link SNR is above input threshold (γ_{iT}), and the combined SNR (γ_c) is above output threshold (γ_{OT}).

The probability is given as $F^M(\gamma_{\mathrm{OT}})C_3$.

Numerical Results and Discussion

Numerical results for an average number of channel estimation presented in this section. Furthermore, average channel estimation is analyzed in the following cases as discussed above:

Case(i): For $N_e = 1$; only the first relay link channel estimation is required since the first relay link SNR is above the input threshold (γ_{iT}). And the combined SNR (γ_c) is above combiner threshold (γ_{OT}).

The probability for the Rayleigh fading channel calculated using equation (4.102) for the normalized SNR ranges from 0dB to 15dB. It is evident from table 4.1, for high values of normalized SNR the number of channel estimation reduced.

Table 4.1: Channel estimation for Case (i) (Shamganth.K et al.,2018)

S.No	Normalized SNR	Average Channel estimation
1.	0dB	0.3679
2.	5dB	0.1690
3.	10dB	0.0423
4.	15dB	0.0036

Case (ii): For $2 \leq N_e \leq N-1$, the probability is calculated using (4.103) as shown in table 4.2.

Table 4.2: Channel estimation for Case (ii) (Shamganth.K et al.,2018)

S.No	Normalized SNR	Average Channel estimation
1.	-5dB	0.0010
2.	0dB	0.0097
3.	5dB	0.0585
4.	10dB	0.1689

4.7 Complexity Analysis of the Proposed Multi-Threshold based Relay Selection Scheme

In the Multi-Threshold scheme the input threshold (γ_{iT}) is at the relay, and the combiner has two thresholds as combiner input threshold (γ_{ciT}) and combiner input threshold (γ_{OT}) as discussed in Algorithm 2. The combiner output SNR ($\overline{\gamma_c}$) of the proposed multi-threshold scheme mentioned in equation (4.61) based on different cases is given as

$$\overline{\gamma_c} = \begin{cases} \gamma_{SD} \quad , & if\ \gamma_{SD} > \gamma_{coT}\ and\ \gamma_{SR_i} < \gamma_{iT} \quad or \quad \gamma_{R_iD} < \gamma_{ciT} \qquad Case\ (i) \\ \gamma_{SD} + \gamma_{R_1D} \quad , & if\ \gamma_{SD} + \gamma_{R_1D} > \gamma_{coT}\ and\ \gamma_{SR_1} > \gamma_{iT}\ and\ \gamma_{SR_i} < \gamma_{iT}\ for\ (i = 2 \ldots\ldots N) \quad Case\ (ii) \\ \gamma_{SD} + \sum_{i=1}^{N} \gamma_{R_iD} & if \gamma_{R_iD} \geq \gamma_{ciT}\ and\ \gamma_{SD} + \sum_{i=1}^{N} \gamma_{R_iD} > \gamma_{coT} \quad for\ (i = 1,2 \ldots\ldots N)\ Case\ (iii) \\ \sum_{i=1}^{N} \gamma_{R_iD} & if\ \gamma_{SD} < \gamma_{ciT}\ and\ \gamma_{R_iD} \geq \gamma_{ciT} \quad for\ (i = 1,2 \ldots\ldots N) \qquad Case\ (iv) \\ 0 & if\ \gamma_{R_iD} < \gamma_{ciT}\ and\ \gamma_{SD} < \gamma_{ciT} \qquad Case\ (v) \end{cases} .$$

The CDF of the combiner output given as

$$F_{\gamma_c}(x) = \sum_{i=1}^{M} Pr\left(\left[\gamma_c = \gamma_{SD} + \sum_{i=1}^{N} \gamma_{R_i}\right] \ for \ [\gamma_c \le x\right], \quad (4.107)$$

$$F_{\gamma_c}(x) = \ P_r(\gamma_{coT} \le \delta_1 \le x) + \sum_{i=2}^{M} P_r\,(\gamma_{coT} \le \delta_i \le x)\ \& \ [0 \le \delta_{i-1} < \delta_{coT}]$$

$$+ P_r([0 \le \delta_M \le x]\ \&\ [0 \le \delta_{M-1} < \delta_{coT}]\,). \quad (4.108)$$

In equation (4.119), δ_i is the combined SNR of the first ith relayed paths and direct path and is given as

$$\delta_i = \gamma_{SD} + \sum_{i=1}^{N} \gamma_{R_i}, \quad (4.109)$$

where $\gamma_{R_i} = \sum_{i=1}^{N} \frac{\gamma_{SR_i}\gamma_{R_iD}}{\gamma_{SR_i} + \gamma_{R_iD} + 1}$,

and

$\delta_i > \gamma_{coT}\ if\ \gamma_{Ri} > \ \gamma_{ciT}\ for\ (i = 1,2 \ldots .N)$.

Based on Algorithm 2 of the proposed multi-threshold scheme, an observation is listed below:

a. A single relay forwards the source information, and the relayed signal is combined with the direct link if the SNR at the relay is above the input threshold (γ_{iT}) and the relayed link is above the combiner input threshold (γ_{ciT}) and the direct link (γ_{SD}) is above γ_{ciT} (the combined output is above the combiner output threshold (γ_{coT}).

b. The ith relayed link $(2 \le i \le N - 1)$ is used when the input to the combiner of an $N - 1$ relayed branch is above the input threshold (γ_{ciT}) and the direct link is above γ_{ciT}. Furthermore, the combiner output is above the combiner output threshold (γ_{coT}) $\gamma_{\mathrm{SD}} + \sum_{\mathrm{i}=1}^{\mathrm{N}} \gamma_{\mathrm{Ri}} \ge \gamma_{\mathrm{coT}}$.

c. No output and the feedback sent to the source for retransmission $\gamma_{\mathrm{SD}} + \sum_{\mathrm{i}=1}^{\mathrm{N}} \gamma_{\mathrm{Ri}} < \gamma_{\mathrm{coT}}$,

Mathematically:

$$P_r[\gamma_c = \gamma_{SD} + \sum_{i=1}^{N} \gamma_{Ri}] = \begin{cases} P_r[\gamma_{R1} \geq \gamma_{iT}]\, for\ i = 1\ and \\ \gamma_{SD} + \gamma_{R1} \geq \gamma_{coT} \\ P_r \begin{bmatrix} \sum_{i=2}^{N-1} \gamma_{Ri} > \gamma_{iT} \\ and \end{bmatrix} \\ \gamma_{SD} + \sum_{i=2}^{N-1} \gamma_{Ri} > \gamma_{coT} \\ P_r \begin{bmatrix} \sum_{i=1}^{N} \gamma_{Ri} < \gamma_{iT} \\ and \end{bmatrix} \\ if\ P_r[\gamma_c < \gamma_{coT}]\ No\ output \end{cases} . \tag{4.110}$$

Applying total probability theorem, the CDF of the combiner output SNR $P_o(x)$ is given as,

$P_o(x) = P_r[\gamma_c < x]$,

$$= \mathrm{P_r}\left[\left(\sum_{i=1}^{N} \gamma_{Ri} + \gamma_{SD}\right) < x\right]. \tag{4.111}$$

Let

$C_1 = P_r[\gamma_{ciT} \leq \gamma_c < \gamma_{coT}] = F(\gamma_{coT}) - F(\gamma_{ciT})$,

$C_2 = P_r[\gamma_c < \gamma_{coT}] = F(\gamma_{coT})$,

$$C_3 = P_r[\gamma_c \geq \gamma_{coT}] = 1 - F(\gamma_{coT}). \tag{4.112}$$

Average Channel Estimation

The increase in the number of channel estimation (N_e) will increase in the complexity of the relay selection scheme in a multi-relay cooperative D2D network.

Case (i): $N_e = 1$; in this case, the first relayed link SNR $\gamma_{R_1} > \gamma_{iT}$ and the direct link $\gamma_{SD} > \gamma_{ciT}$. Also, the combiner output $\left(\gamma_c = \gamma_{SD} + \gamma_{R_1}\right)$ is above γ_{coT}, and is given as

$\gamma_c \geq \gamma_{coT}$.

The probability for this case is given as

$$C_3 = P_r[\gamma_c \geq \gamma_{coT}] = 1 - F(\gamma_{coT}). \tag{4.113}$$

Case (ii): If $2 \leq N_e \leq N - 1$, there will be two cases as follows:

i. The first relayed link SNR is below the input threshold (γ_{ciT}), but the remaining ith

relayed link SNR and the direct link SNR (γ_{SD}) is above the combiner output threshold (γ_{coT}), and is given as

$$\gamma_{SD} + \sum_{i=2}^{N} \gamma_{R_i} > \gamma_{coT}. \quad (4.114)$$

The probability for this case is given as

$$C_2^{N-1} C_3 = F^{N-1}(\gamma_{coT})[1 - F(\gamma_{coT})]. \quad (4.115)$$

ii. The first N-1 relayed link SNR is above the input threshold (γ_{ciT}), and the combined SNR of the first N-1 branch SNR and the direct link SNR (γ_{SD}) is below the combiner output threshold (γ_{coT}), and is given as

$$\gamma_c = \gamma_{SD} + \gamma_{R_{N-1}}, \quad (4.116)$$

and $\gamma_c < \gamma_{coT}$ but the combined SNR of the N^{th} relayed link SNR, and the direct link is above the combiner output threshold (γ_{coT}), and is given as

$\gamma_c = \gamma_{SD} + \gamma_{R_N}$ and $\gamma_c \geq \gamma_{coT}$.

The probability for this case is given as

$$\sum_{i=1}^{M-1} \binom{M-1}{i} C_1^{M-1-i} \left[F^{(i)}(\gamma_{coT}).C_3 - F^{(i+1)}(\gamma_{coT})\right]. \quad (4.117)$$

For $N_e = M$; the probability is given as $1 - \sum_{i=1}^{M-1} P_r[N_e = i]$.

The number of path estimation calculated as follows:

$$P_r[N_e = i] = \begin{cases} \sum_{i=1}^{M-1} \binom{M-1}{i} C_1^{M-1-i} B_{i+1} & 1 \leq i \leq M-1 \\ 1 - \sum_{i=1}^{M-1} P_r\,[N_e = i] & i = M \end{cases}, \quad (4.118)$$

where $B_1 = C_3$,

$$B_2 = C_1 C_3 - F^{(2)} \gamma_{coT},$$

$$B_3 = [F^{(2)} \gamma_{coT} C_3 - F^{(3)} \gamma_{coT}],$$

$$B_i = [F^{(i-1)}\gamma_{coT}C_3 - F^{(i)}\gamma_{coT}].$$

Mathematical expression for the average number of path estimation (N_e) (Xie et al., 2014) is given as

$$N_e = \sum_{i=1}^{M} i.P_r\,[N_e = i]. \quad (4.119)$$

Average Number of Combined branches

The average number of combined branches calculated as follows:

a. $N_c = 0$; if the first M-1 relayed link SNR is less than input threshold (γ_{iT}) and the combined SNR (γ_c) is less than combiner output threshold ($\gamma_c < \gamma_{OT}$) . The probability is C_2^M in this case first M-1 relayed links SNR is below input threshold (γ_{ciT}), and the M^th relayed link SNR is above γ_{ciT} and the combined SNR γ_c is above the combiner output threshold (γ_{coT}) .

b. $N_c = 1$; The two cases are as follows:

Case (i): only one relay link SNR is above input threshold (γ_{iT}), and the combined SNR $\gamma_c \geq \gamma_{coT}$ the probability is given as $MC_2^{M-1}C_1$.

Case (ii): If the first $M-1$ relayed link SNR is below the combiner input threshold (γ_{ciT}), and the M^th relay link SNR is above γ_{iT} and the combined SNR (γ_c) is above γ_{coT} .

The probability for this case is given as

$$C_3 \sum_{i=0}^{M-1} C_2^i \,.$$

Probability for combining one branch is given as

$$MC_2^{M-1}C_1 + C_3 \sum_{i=0}^{M-1} C_2^i \,. \quad (4.120)$$

c. $N_C = M$; all the relayed link SNR is above input threshold (γ_{iT}), and the combiner input threshold (γ_{ciT}) and the combined SNR (γ_c) is above combiner output threshold (γ_{coT}).

The probability is given as

$$F^M(\gamma_{coT})C_3\ . \tag{4.121}$$

Complexity Analysis with the Special Case

The multi-relay cooperative scheme discussed in this chapter considers the transmission from the source received by multiple relays and by the destination. Moreover, all the relays not located at the center between source to destination. The relays located randomly, and it is at different distances from the source. In the literature, mostly the relays are assumed to be at the center between the source to the destination. The retransmission from the relays assumed to reach the destination directly, and not received by the relays in the path between the source and destination. For multi-node cooperative decode and forward (DF) relaying the cooperative diversity protocols discussed as cooperation scheme $C(m)$ for Virtual MIMO proposed in (Sadek et al., 2005). Furthermore, the cooperation $C(m)$ has two categories as $C(1)$ and $C(R-1)$ and R denotes the number of relays in the cooperative network. And this cooperation scheme proposed for DF in (Sadek et al., 2005) is adapted as a special case for Multi-relay double threshold AF with coherent modulation.

Cooperation scheme $\boldsymbol{C(1)}$

As a special case, the relay is active in the multi-relay double threshold-based AF scheme, if the SNR of the S-R link is above the input threshold. The active relays located nearer to the destination receives the signal in Phase-I from the source and assist in forwarding the source information to the destination in Phase-II. During this phase the signal from the previous relay also received by the active relay for the same source information then, an active relay also considers the received signal from the previous relay before its transmission to the destination in Phase-II and the cooperation scheme adapted from (Sadek et al., 2005) is $C(1)$. In general the $(k+1)^{th}$ relay combines the signals received from the source and the k^{th} relay.

The number of channel estimation for the cooperation scheme $C(1)$ mentioned in (Liu et al.,2008, equation 6.44) is given by

$$nc_{h,1} = 3R. \tag{4.122}$$

The number of channels estimated at the destination is $R + 1$ and $2R - 1$ channel estimated by the R relays; in the case of $C(1)$, the k^{th} relay estimates only one channel from its previous relay.

Cooperation scheme $\boldsymbol{C(\mathrm{R}-1)}$

In this scheme, the active relay located very near to the destination receives the signal from $R - 1$ relays in addition to the signal from the source node. In $C(\mathrm{R} - 1)$ cooperation scheme the $(k + 1)^{\text{th}}$ relay combines the signals received from the source and all of the previous relays. Furthermore, this cooperation scheme has high complexity as more channel estimation is required. Since the cooperation scheme $C(1)$ does not require each relay to estimate the CSI of all the previous relays as in $C(R - 1)$ the complexity is less, and it has reduced channel estimation computations (Liu et al.,2008).

In the cooperation scheme $C(R - 1)$, the k^{th} relay estimates k channels, and thus the number of computations for this case (Liu et al.,2008, equation 6.45) is given as

$$nc_{h,R-1} = \frac{1}{2}[R^2 + 3R + 1]. \tag{4.123}$$

The ratio of savings in the number of channel estimation by using $C(1)$ compared to $C(R - 1)$ (Liu et al.,2008, equation 6.46) is given as

$$\frac{nc_{h,1}}{nc_{h,R-1}} = \frac{6R}{[R^2+3R+1]}. \tag{4.124}$$

In this chapter, the number of relays considered for the analysis is 5,10,15, and 20 for the multi-relay double threshold scheme scenarios and table 4.3 shows the number of channel estimation for the set of active relays assisting the source transmission to the destination node and its savings in channel estimation computations of the cooperative scheme $C(1)$ with respect to $C(R-1)$ scheme.

Table 4.3 Channel estimation for the special case

Number of Relays	Number of channel Estimation $\boldsymbol{C(1)}$	Number of channel Estimation $\boldsymbol{C(R-1)}$	Savings in Channel Estimation
5	15	20.5	0.7317
10	30	65.5	0.4580
15	45	135.5	0.3321
20	60	230.5	0.2603
25	75	350.5	0.2139

Simulation Results and Discussion

The number of channel estimations for the cooperation scheme $C(m)$ with $C(1)$ and $C(R-1)$ comparative results shown in figure 4.25. The results show that $C(1)$ scheme has less channel estimation since the k^{th} relay considers only one previous relay transmission in addition to the source transmission. However, the $C(R-1)$ scheme has very high complexity due to the increased number of channel estimation, as shown in the comparative results.

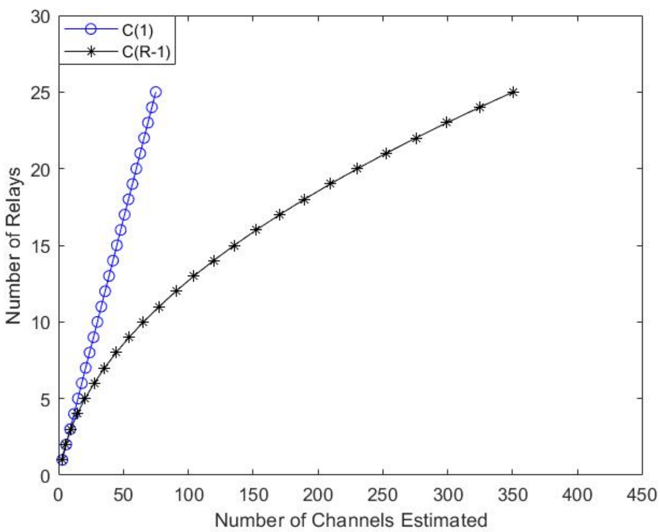

Figure 4.25. Comparative Channel estimation for the cooperation scheme

Figure 4.26 presents the savings in the channel computation concerning the number of relays. Furthermore, as the number of relays increases the savings in the channel computation reduces and it is as expected as the number of relays increases the number of channel estimation in $C(R-1)$ scenario increases significantly.

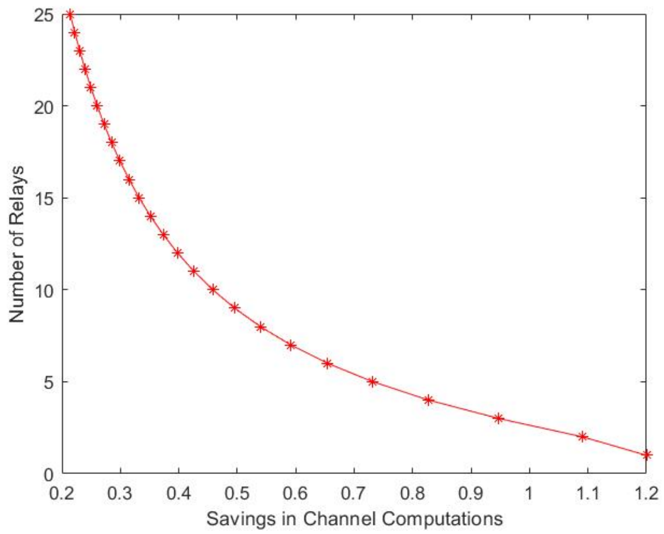

Figure 4.26. Savings of Channel computation

Comparative Analysis of Double-Threshold-based AF and DiffAF using Differential Modulation

The comparative results for Case(ii) with an input threshold of 3dB and combiner output threshold of 5dB shown in figure 4.27 For the 20-relay scenario, similar performance is observed between DiffAF and AF relaying. However, the difference of 1dB noticed between DiffAF and AF relying on 5-relay scenario. Furthermore, the AF outperforms DiffAF with the double threshold for the case with relays away from the source.

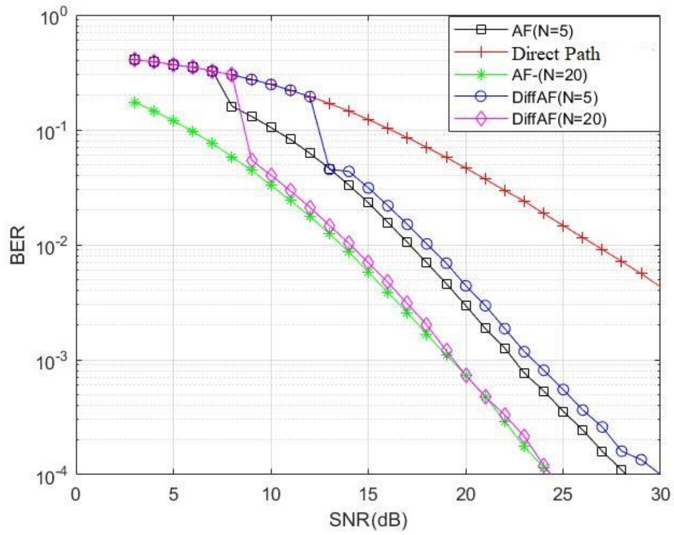

Figure 4.27. Comparative Multi-relay Double-Threshold with DQPSK with $P_s = 0.7P_t$ and $P_r = 0.3P_t$ and Th_In=3 and Th_Out=5 (AF Vs DiffAF)

Comparative Analysis of Multi-Threshold-based AF and DiffAF using Differential Modulation

Comparison of AF and DiffAF based on the number of relays for case (ii) shown in figure 4.28. The input threshold considered for the simulation is 20dB and the combiner input and output threshold of 15dB and 25dB. DiffAF scheme shows substantial performance improvement compared to the multi-threshold AF scheme. However, above 17dB similar performance observed between 20-relay AF and DiffAF relaying. For the comparison, 10-relay and 20-relay scenario considered. The 10-relay DiffAF show significant performance improvement compared to 10-relay AF scheme up to an SNR of 21dB.

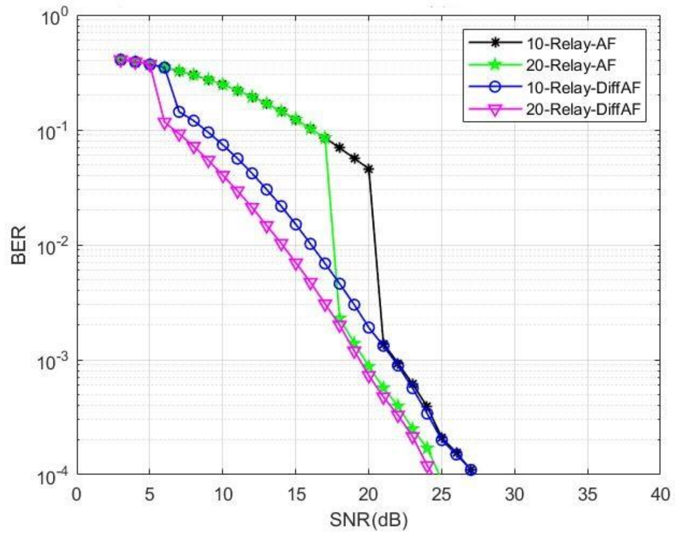

Figure 4.28. Comparative Analysis of Multi-Threshold AF Vs DiffAF Relay Comparison with for case(ii)

Comparative Analysis of Multi-Threshold Coherent AF and Differential AF Relaying Schemes

The comparative analysis of coherent AF and differential AF for the multi-threshold scheme is shown in figure 4.29. The comparison considers 5-relay and 15-relay scenario for case(ii). Coherent AF outperforms differential AF in both relay scenarios as expected. Moreover, the 15-relay scenario shows significant performance improvement compared to the 5-relay scenario.

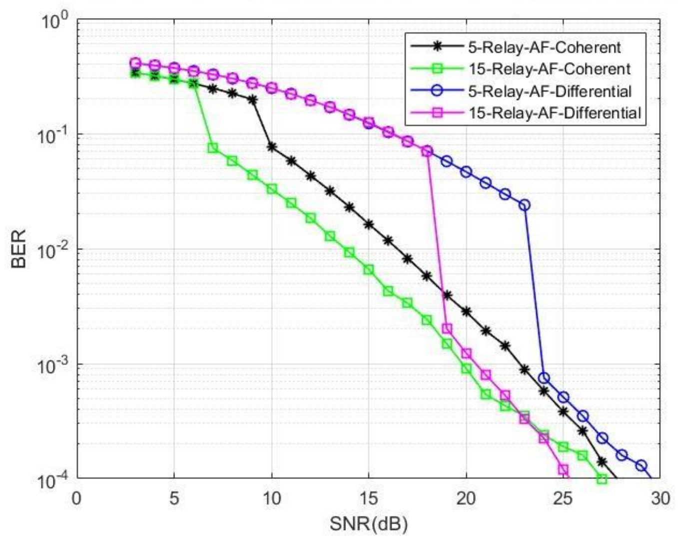

Figure 4.29. Relay Comparison of Coherent AF and Differential AF for case(ii)

4.8 Conclusion

This chapter considers the double threshold-based relay selection with AF and DiffAF relaying protocols. The considered system model consists of the input threshold at the relay and output threshold at the combiner. The performance analysis of the double threshold-based relay selection with AF and DiffAF relaying using differential and coherent modulation is analyzed. The results of double threshold-based relay selection raise a new concern that weak relayed paths were also selected at the combiner and to avoid this issue multi-threshold-based relay selection scheme proposed. The considered system model consists of combiner input and output threshold in addition to the input threshold at the relay. The complexity of double threshold-based relay selection and multi-threshold-based relay selection scheme is analyzed in this chapter. The comparative analysis of double threshold and multi-threshold-based AF and DiffAF relaying with differential modulation shows for a greater number of relays similar performance is observed however, the significant difference observed for lesser relays. The additional comparative analysis results of double threshold and multi-threshold-based relay selection are included in the Appendix-A.

Chapter 5

Double Threshold Relay Selection based Physical Layer Security Enhancement in Cooperative Wireless Network

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5.1 Introduction

Physical layer security is an essential technique for securing data transmission, and it can be achieved by modifying the capacity of the main link channel more than source to eavesdropper link (Zou, Y et al.,2013). The chances of security issues exist if the rate of secrecy capacity falls below zero. This issue is generally observed due to fading effect (Chen, X et al.,2015), (Li, Q et al.,2015). Part of the work presented in this chapter published in "Data Communication and Networks. Advances in Intelligent Systems and Computing, vol 1049. Springer, Singapore", (Shamganth.K et al.,2020).

The secrecy in the cooperative wireless network increased by applying efficient relay selection technique. In this chapter, the double threshold-based relay selection is applied to the existing AF based optimal relay selection scheme (AFbORS). The proposed scheme combines the optimal relay selection scheme developed by Zou et al. (2013), i.e., P-AFbORS with double threshold relay selection.

Zou et al. (2013) proposed the optimal relay selection technique (P-AFbORS) to improve the physical layer security in cooperative wireless network. Also, the optimal relay selection is applied with the simple relay selection (Bletsas et al., 2006) and presented the traditional AF based optimal relay selection scheme (T-AFbORS). The difference between P-AFbORS and the T-AFbORS is on the CSI considered for the relay selection. The P-AFbORS scheme consider relay to eavesdropper CSI in addition to the source to relay and relay to destination link CSI in the calculation of secrecy capacity and the relay with maximum secrecy capacity is selected as the optimal relay. In the traditional relay selection-based T-AFbORS only the source to relay and relay to destination link CSI considered and the relay with largest secrecy capacity of relay to destination is selected as the optimal relay.

The effect of applying the double threshold-based relay selection to improve the physical layer security is investigated in this chapter. Furthermore, the performance analysis of the proposed double-threshold based P-AFbORS and double-threshold based T-AFbORS based on the distance between the source and the relay nodes is studied.

5.2. System Model

The system model consists of a single source (S), and destination (D), and multiple relay nodes R_1, R_2,..,R_N. Relays are located between S and D to assist the source transmission as shown in figure 5.1. Eavesdropper node (E) is located near the relays, and it receives the signal from the source due to the broadcasting nature in Phase-I. Input threshold is fixed at the relays, and the relay compare the received signal SNR with the threshold. If the received signal SNR is above the input threshold, then the relay will be in active mode, and if the condition is not satisfied, then the relay goes into the sleep mode. The threshold combined with the optimal relay selection is compared against the existing literature P-AFbORS and T-AFbORS scheme (Zou et al., 2013). The output threshold is fixed at the combiner output to test the combined signal quality. The proposed scheme adapt the optimal-relay selection scheme P-AFbORS proposed by (Zou et al., 2013) for the evaluation purposes. The intercept probability analysis of the proposed double threshold scheme is compared with the existing P-AFbORS and T-AFbORS without threshold.

Secrecy Capacity

The direct transmission is considered for comparison with the proposed scheme. The secrecy capacity of direct transmission is calculated based on the capacity of the source to destination and the capacity of source to the eavesdropper node.

The capacity of direct transmission from source to destination (Shamganth.K et al.,2020) is given as

$$C_{\mathrm{sd}}^{\mathrm{direct}} = \log_2\left(1 + \frac{|h_{sd}|^2}{\sigma_n^2}\right). \tag{5.1}$$

The capacity of wiretap link from source to eavesdropper (Zou et al., 2013) is given as

$$C_{\mathrm{se}}^{\mathrm{direct}} = \log_2\left(1 + \frac{|h_{se}|^2}{\sigma_n^2} P\right). \tag{5.2}$$

From equation (5.1) and (5.2) the secrecy capacity of direct transmission (Shamganth.K et al.,2020) is given as

$$C_{\mathrm{sd}}^{\mathrm{direct}} = C_{\mathrm{sd}}^{\mathrm{direct}} - C_{\mathrm{se}}^{\mathrm{direct}}. \tag{5.3}$$

The observation from equation (5.3) is that secrecy capacity will be negative if the capacity of main link is less than the wiretap link capacity. So, the eavesdropper can intercept the source signal. Thus, the probability that the eavesdropper successfully intercepts source signal is called intercept probability. It is an important parameter in the performance evaluation of physical-layer security.

AF based Optimal Relay Selection

The P-AFbORS protocol is applied with double threshold based relay selection to select the optimal relay and to enhance the capacity of AF relaying $(C_i AF)$ based transmission from relay to destination node (Zou et al., 2013).

Optimal relay selection criteria with AF relaying is given as,

$$ORS = arg\ max\ i \in R_N\ C_i AF, \tag{5.4}$$

where, R_N denotes the set of 'N' relays.

Optimal relay selection criteria of P-AFbORS with main link and the wiretap link (Shamganth.K et al.,2020) is given as

$$ORS = arg\ max_{i \in R_N} \frac{1+\frac{|h_{si}|^2 |h_{id}|^2 P}{2(|h_{si}|^2+|h_{id}|^2)\sigma_n^2}}{1+\frac{|h_{si}|^2 |h_{id}|^2 P}{2(|h_{si}|^2+|h_{ie}|^2)\sigma_n^2}}, \tag{5.5}$$

where h_{si} and h_{id} denotes the main link CSI and h_{ie} is the wiretap link CSI.

DF based Optimal Relay Selection

The capacity of DF relaying based transmission from source to destination using the relay node R_i (Shamganth.K et al.,2020) is given as

$$C_{\mathrm{sid}}^{\mathrm{DF}} = \min(C_{si}, C_{id}), \tag{5.5}$$

where $C_{si}\ and\ C_{id}$ represent the channel capacity from source to relay R_i and that from R_i to destination.

The capacity of source to relay (Zou et al., 2013) is given as

$$C_{\mathrm{si}} = \log_2\left(1 + \frac{|h_{si}|^2}{2\sigma_n^2} P\right). \tag{5.6}$$

The capacity of relay to destination (Shamganth.K et al.,2020) is given as

$$C_{\mathrm{id}} = \log_2\left(1 + \frac{|h_{id}|^2}{2\sigma_n^2} P\right). \tag{5.7}$$

The channel capacity from R_i to eavesdropper (Zou et al., 2013) is given as

$$C_{\mathrm{ie}}^{\mathrm{DF}} = \log_2\left(1 + \frac{|h_{ie}|^2}{2\sigma_n^2} P\right). \tag{5.8}$$

The secrecy capacity of DF relaying based on equation (5.5) and (5.8) (Shamganth.K et al.,2020) is given as

$C_{\mathrm{i}}^{\mathrm{DF}} = C_{\mathrm{sid}}^{\mathrm{DF}} - C_{\mathrm{ie}}^{\mathrm{DF}},$ resulting in

$$C_{\mathrm{i}}^{\mathrm{DF}} = \log_2\left(1 + \frac{\min(|h_{si}|^2, |h_{se}|^2)}{2\sigma_n^2} P\right) - \log_2\left(1 + \frac{(|h_{se}|^2 P)}{2\sigma_n^2}\right). \tag{5.9}$$

The criteria for the selection of DF based optimal relay (Zou et al., 2013) is

$$ORS = arg\ max\ i \in R_N C_{\mathrm{i}}^{\mathrm{DF}}. \tag{5.10}$$

Intercept probability

The closed-form intercept probability of direct transmission ((Zou et al., 2013) is given as

$P_{\mathrm{intercept}}^{\mathrm{direct}} = \frac{\sigma_{se}^2}{\sigma_{se}^2 + \sigma_{sd}^2},$

where $\sigma_{se}^2 = E(|h_{se}|^2)$, and $\sigma_{sd}^2 = E(|h_{sd}|^2)$.

The the main-to-eavesdropper ratio (MER) is the ratio of average channel gain from source to destination to that from source to eavesdropper and is the ratio between S-D and S-E given as

$\lambda_{de} = \frac{\sigma_{sd}^2}{\sigma_{se}^2}.$

The intercept probability of the DF based relaying (Zou et al., 2013) is given as

$$P_{\text{intercept}}^{\text{DFbORS}} = Pr(max_{i \in \mathrm{R}} C_i^{DF} < 0). \quad (5.13)$$

The intercept probability of the AF based relaying (Zou et al., 2013) is given as

$$P_{\text{intercept}}^{\text{AFbORS}} = Pr\left(max_{i \in \mathrm{R}} C_i^{AF} < 0\right). \quad (5.14)$$

which computes the number of paths amongst source to destination and the selection of optimal path to transfer the data.

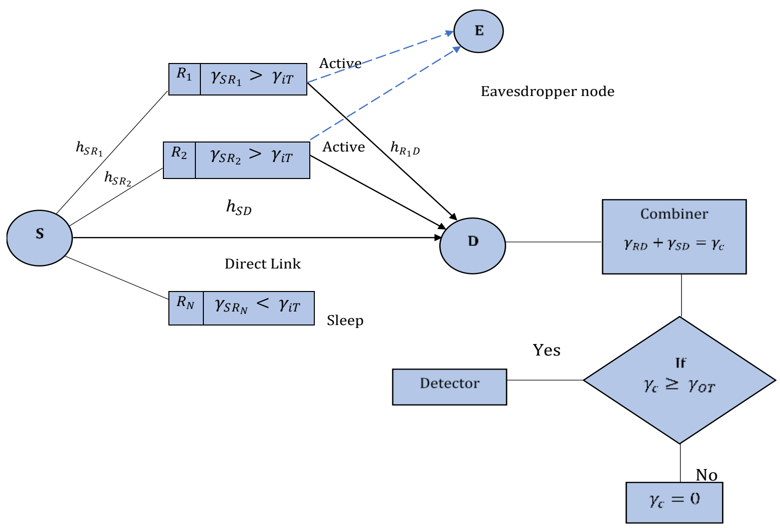

Figure 5.1. System Model of Double Threshold scheme with eavesdropper

5.2.1 Simulation Results and Discussion

The simulation results of combining the proposed double threshold-based relay selection scheme with P-AFbORS and T-AFbORS scheme to enhance the physical layer security in cooperative D2D out-band communication is presented in this section. The performance analysis of the proposed scheme is categorized and based on the distance between the source, relay, eavesdropper, and destination node, as shown below:

Case (i): Equal power allocation is assigned to the source and the relays. The relays are assumed to be at the center of the source and destination nodes. Furthermore, the eavesdropping node is assumed to be located at the center.

$$d(S, R) = d(R, D).$$

Case (ii): The relay is assumed to be located at more distance from the source and the power ratios used in the simulation are $P_s = 0.7P_t$ and $P_r = 0.3P_t$. Furthermore, the eavesdropping nodes are assumed to be away from the source node.

$$d(S, R) \gg d(R, D).$$

Case (iii): The relay is assumed to be located near to the source and the power ratios used in the simulation are $P_s = 0.3P_t$ and $P_r = 0.7P_t$. Moreover, the eavesdropping node is assumed to be near to the source node.

$$d(S, R) \ll d(R, D).$$

The comparative analysis of the proposed scheme with the existing scheme are as follows:

Intercept probability analysis of AFbORS and DFbORS schemes and P-DFbORS and T-DFbORS schemes are compared based on the number of relays, modulation schemes and threshold.

The Double-Threshold based P-AFbORS and T-AFbORS schemes compared based on different relay scenarios, modulation schemes, different input and output thresholds and MER values.

a. Simulation Results and Discussion for Case (i)

Figure 5.1a depicts the comparative intercept probability performance of P-AFbORS, T-AFbORS and direct transmission. The case of equal power at the source and the relay node with the input threshold of 5dB at the relay, output threshold of 10dB at the combiner for 5-relay scenario using QPSK modulation scheme is studied. From the simulations it can be observed that the P-AFbORS scheme outperforms T-AFbORS scheme and direct transmission. Furthermore, the results show that P-AFbORS scheme enhances the physical layer security as the intercept probability is less as compared to the other scheme.

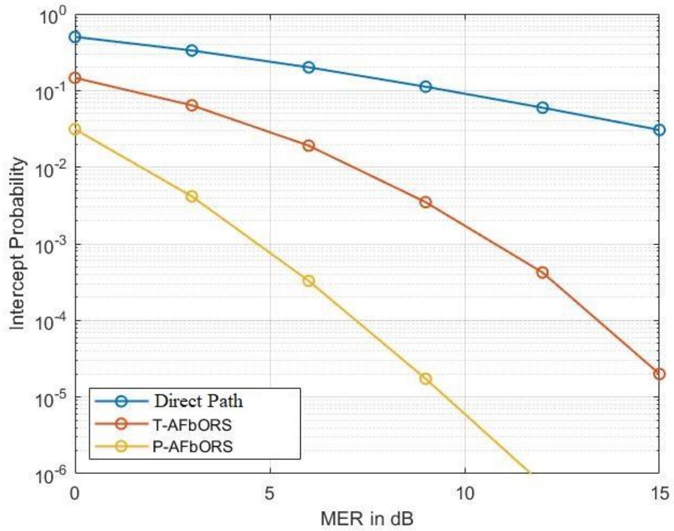

Figure 5.1a. Comparison of Intercept Probability performance for AFbORS schemes with Equal Power

Figure 5.2 presents the comparative intercept probability performance of P-DFbORS and T-DFbORS with direct transmission. This simulation result shows that P-DFbORS scheme outperforms the T-DFbORS and direct transmission. The result also shows that direct transmission performs worse than P-DFbORS and T-DFbORS schemes in terms of intercept probability.

Figure 5.3 shows the comparative BER performance of P-AFbORS without threshold when 5-relays are employed. From the results, it is observed that when employing P-AFbORS without threshold, the BER performance improves as the MER is increased. Moreover, from the simulation, it can be observed that the performance of P-AFbORS with

MER=15dB outperforms all the previous schemes and is able to reach a BER value of 10^{-3} at an SNR of 20dB.

In figure 5.4, the performance of P-AFbORS with the double-threshold scheme is shown with an input threshold of 5 dB and the output threshold of 10 dB for 5-relay scenario. The simulation results show that BER value of 10^{-3} at an SNR of 13dB. Furthermore, the comparative results show 5dB difference at the BER of 10^{-3} between MER=6dB and 3dB, respectively.

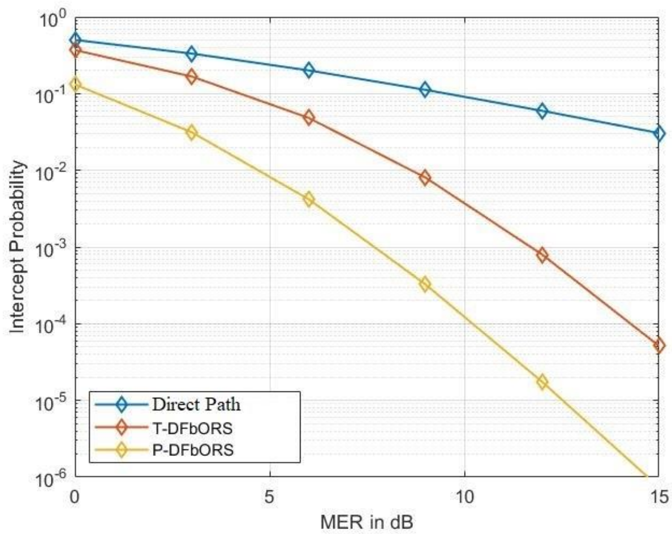

Figure 5.2. Comparison of Intercept Probability DFbORS schemes with Equal Power

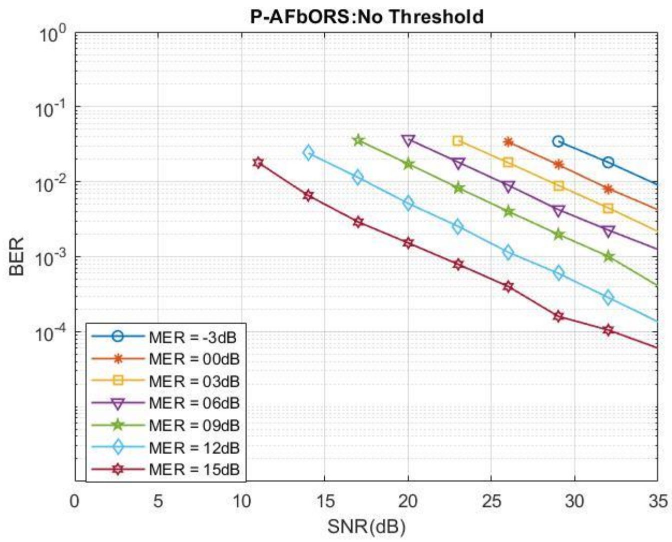

Figure 5.3. Comparison of MER for P-AFbORS without Threshold with Equal Power

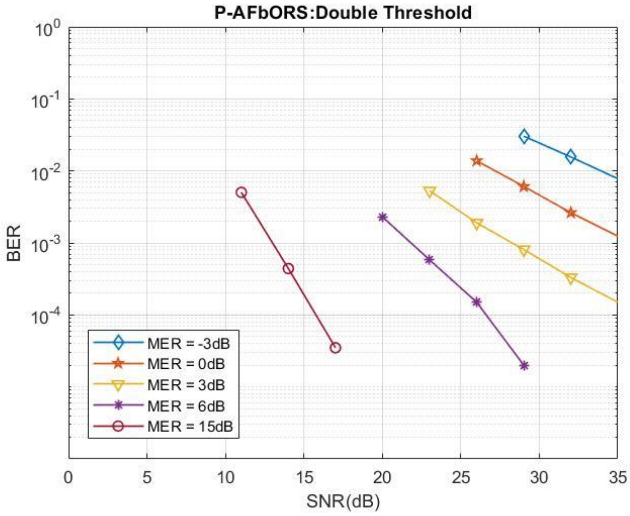

Figure 5.4. Comparison of MER for Double Threshold based P-AFbORS with Equal Power

Figure 5.5 depicts the comparative BER performance of P-AFbORS without threshold for 5-relay scenario. Moreover, the M-PSK scheme considered with M=4,8 and 16 in the simulation with an MER of -3dB and 15dB, respectively. From the results, it is observed that 16-PSK performs worse than 8-PSK and 4-PSK. The difference observed between 4-PSK and 8-PSK at the BER of 10^{-3} is 5dB for the MER of 15dB. Furthermore, the results show that performance is worse for an MER of -3dB where the eavesdropper channel gain is more as compared to the main channel.

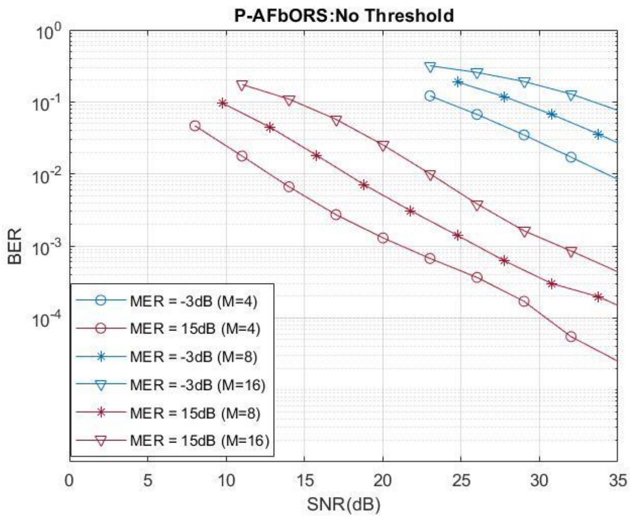

Figure 5.5. Comparison of P-AFbORS without Double Threshold for MER=-3dB and MER=15dB for different modulation schemes with Equal Power

Comparative Analysis based on different Relay Scenarios

The comparative intercept probability performance of the different number of relays is presented in figure 5.6. It is observed that as the number of relays increases the intercept probability reduces which is an indication that, the improvement in the physical layer security is observed. Furthermore, in figure 5.6, it is noticed that P-AFbORS scheme with 15-relay outperforms T-AFbORS scheme and direct transmission. Moreover, the difference of 6dB is observed between 5-relay and 10-relay scenario for P-AFbORS scheme and 3dB difference is observed between 15-relay and 10-relay intercept probability performance of P-AFbORS. The results of T-AFbORS shows 3dB difference between 5-relay and 10-relay scenario and the same difference is observed between 10-relay and 15-relay scenarios.

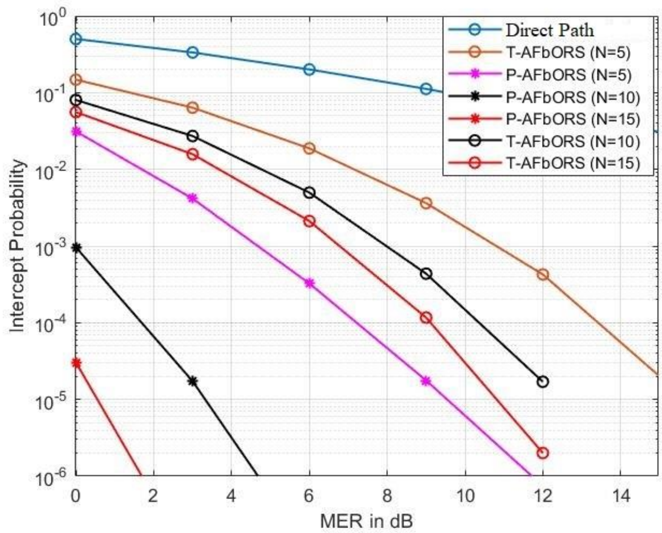

Figure 5.6. Comparison of Intercept Probability for AFbORS with different relay scenarios with Equal Power and Th_In=5 and Th_Out=10

Figure 5.7 and figure 5.8 shows the comparative intercept probability performance of the different number of relays for P-DFbORS and T-DFbORS, respectively. From both the figures, it is observed that as the number of relays increases the intercept probability decreases. As expected, the 15-relay P-DFbORS scheme outperforms 10-relay and 5-relay P-DFbORS schemes. Moreover, it is evident from the results that physical layer security improvement is obtained by increasing the number of cooperative relays. Furthermore, in figure 5.8, it is noticed that T-DFbORS scheme with 15-relay outperforms 10-relay, 5-relay T-DFbORS scheme and direct transmission. Moreover, the difference of 6dB is observed between 5-relay and 15-relay in T-DFbORS results.

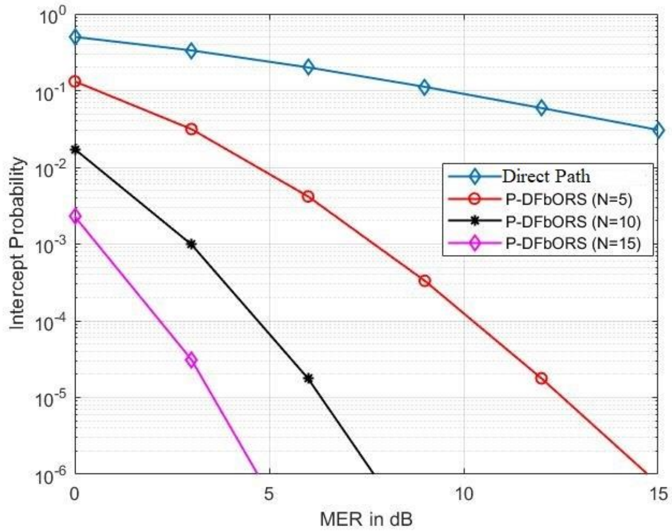

Figure 5.7. Comparison of P-DFbORS performance of different relay scenarios with Equal Power and Th_In=5 and Th_Out=10

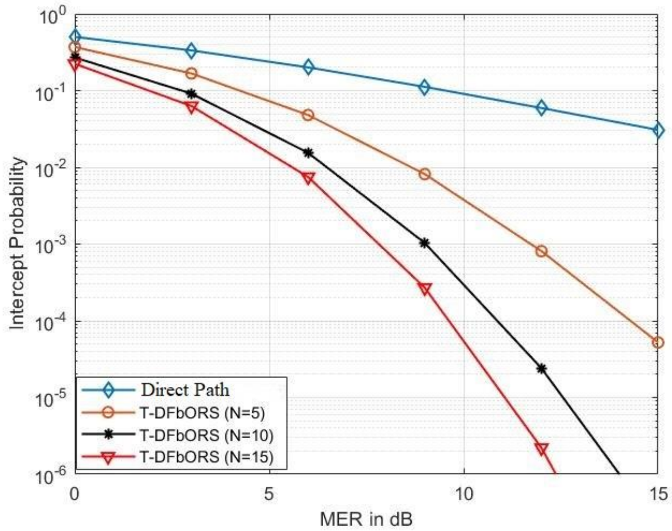

Figure 5.8. Comparison of T-DFbORS performance of different relay scenario with Equal Power and Th_In=5 and Th_Out=10

b. Simulation Results and Discussion for Case(ii)

Figure 5.9 depicts the comparative intercept probability performance of P-AFbORS and T-AFbORS with direct transmission for the case with relays located near to the destination with the power ratios $P_s = 0.7P_t$ and $P_r = 0.3P_t$. The simulation performed for 5-relay scenario with the input threshold of 5dB and the combiner output threshold of 10dB with the QPSK modulation scheme. It is observed that P-AFbORS scheme outperforms T-AFbORS scheme.

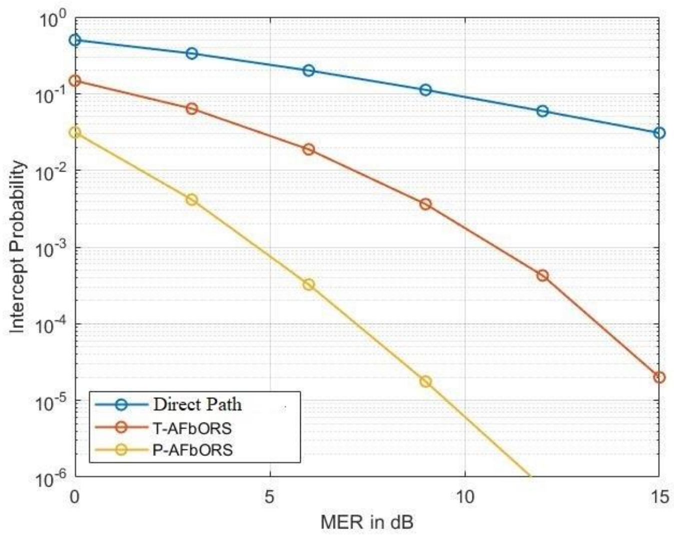

Figure 5.9. Comparison of Intercept Probability performance for AFbORS schemes with $P_s = 0.7P_t$ and $P_r = 0.3P_t$

Figure 5.10 presents the comparative intercept probability performance with the power ratios $P_s = 0.7P_t$ and $P_r = 0.3P_t$. It is noticed that intercept probability performance of P-DFbORS scheme outperforms the T-DFbORS and direct transmission. Figure 5.11 presents the comparative performance analysis of P-AFbORS with the double threshold for different MER values. It is observed from the result that 15dB and 12dB MER shows similar BER performance. The simulation performed with the input threshold of 5dB and combiner output threshold of 10dB.

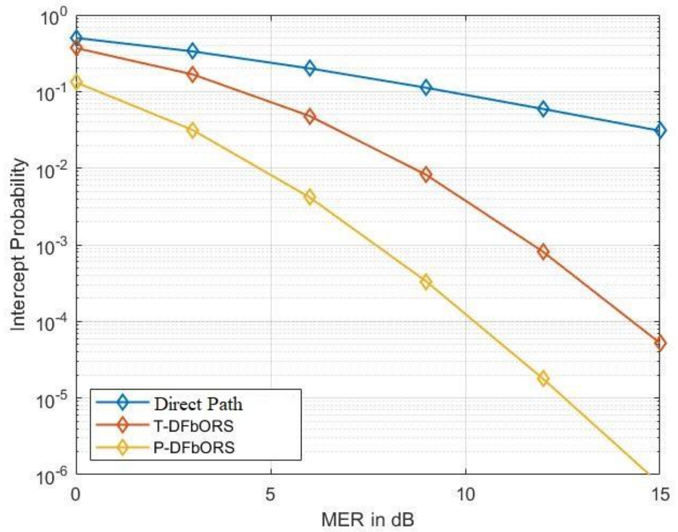

Figure 5.10. Comparison of Intercept Probability performance for DFbORS schemes with $P_s = 0.7P_t$ and $P_r = 0.3P_t$ and Th_In=5 and Th_Out=10

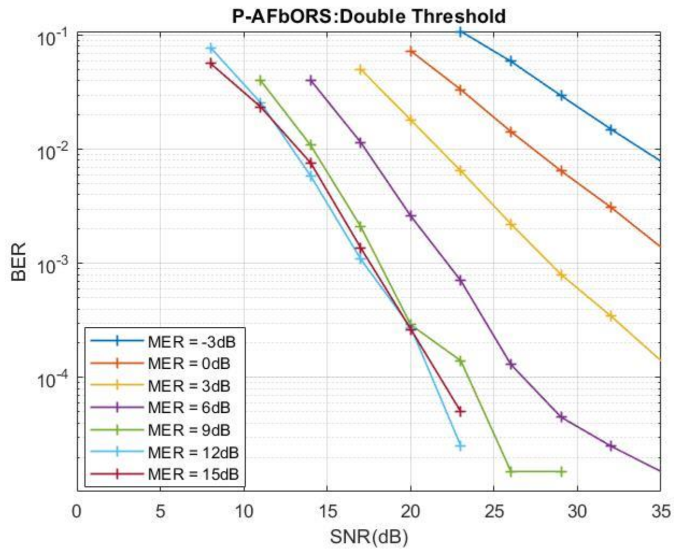

Figure 5.11. Comparison of P-AFbORS with Double Threshold for $P_s = 0.7P_t$ and $P_r = 0.3P_t$

Figure 5.12 depicts the performance of AFbORS for 5-relay scenario with -3dB MER. Moreover, the performance of P-AFbORS with and without threshold is similar to that of direct path. However, the T-AFbORS with double threshold outperforms the other AFbORS scheme. It is noticed that T-AFbORS achieves the BER of 10^{-3} at the SNR of 26dB.

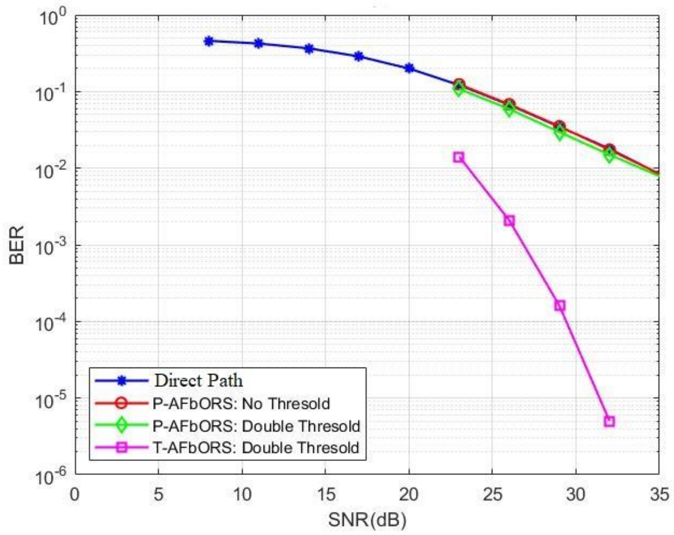

Figure 5.12. BER Performance of AFbORS scheme with and without Double Threshold for MER=-3 dB with $P_s = 0.7P_t$ and $P_r = 0.3P_t$

In figure 5.13, the performance of P-AFbORS with double threshold shows the considerable performance improvement as compared to results of -3dB MER in figure 5.12 for the 5-relay scenario with the input threshold of 5dB and the combiner output threshold of 10dB with QPSK modulation scheme. Increase in MER results in a similar performance between P-AFbORS and T-AFbORS, as shown in figure 5.14 for the 12dB MER simulation with the same input and output threshold considered for earlier simulations. In figure 5.15, similar performance is observed for T-AFbORS and P-AFbORS at 10^{-3} BER. Moreover, the significant performance improvement noticed with the application of the proposed double-threshold with P-AFbORS and T- AFbORS as compared to without threshold P-AFbORS schemes.

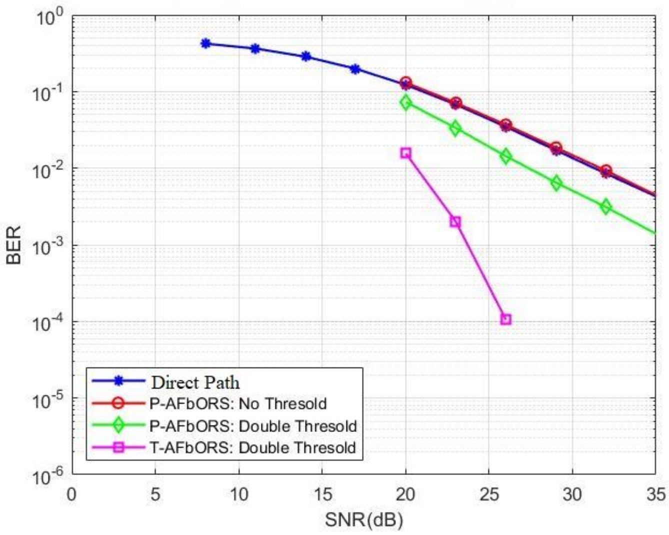

Figure 5.13. BER Performance of AFbORS scheme with and without Double Threshold for MER=0 dB with $P_s = 0.7P_t$ and $P_r = 0.3P_t$

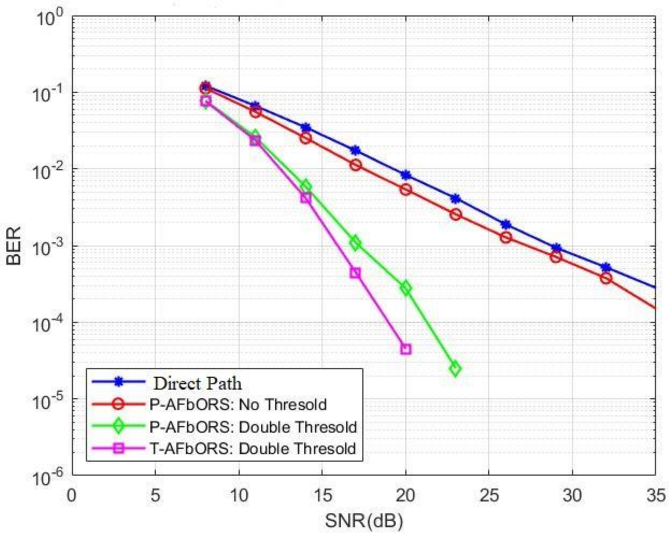

Figure 5.14. BER Performance of AFbORS scheme with and without Double Threshold for MER=12 dB with $P_s = 0.7P_t$ and $P_r = 0.3P_t$

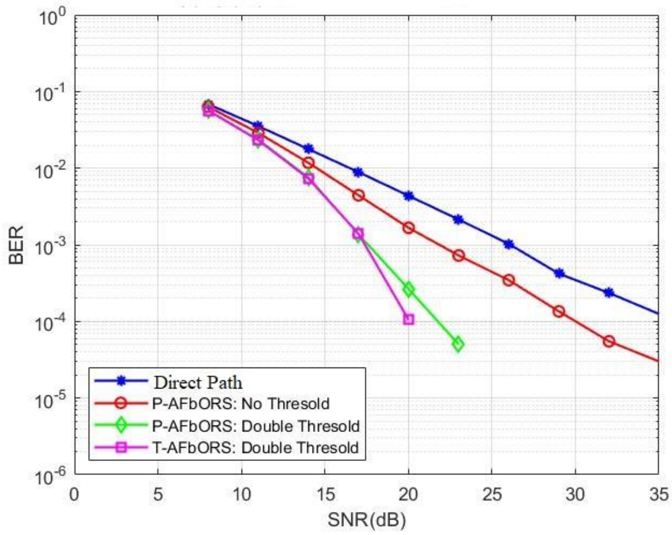

Figure 5.15. BER Performance of AFbORS scheme with and without Double Threshold for MER=15 dB with $P_s = 0.7P_t$ and $P_r = 0.3P_t$

Comparative Analysis based on different Modulation Schemes for Case(ii)

The comparative performance of different modulation schemes with P-AFbORS, and T-AFbORS for different MER discussed in this section. The following simulation considers the 5dB input threshold at the relays and 10dB combiner output threshold for the 5-relay scenario. Figure 5.16 shows the comparative performance of T-AFbORS with double threshold for -3dB and 15dB MER. The T-AFbORS show a substantial performance improvement of 4-PSK as compared to 8-PSK and 16-PSK. It is noticed that 5dB difference for 15dB MER between 4-PSK,8-PSK and 16-PSK modulation schemes.

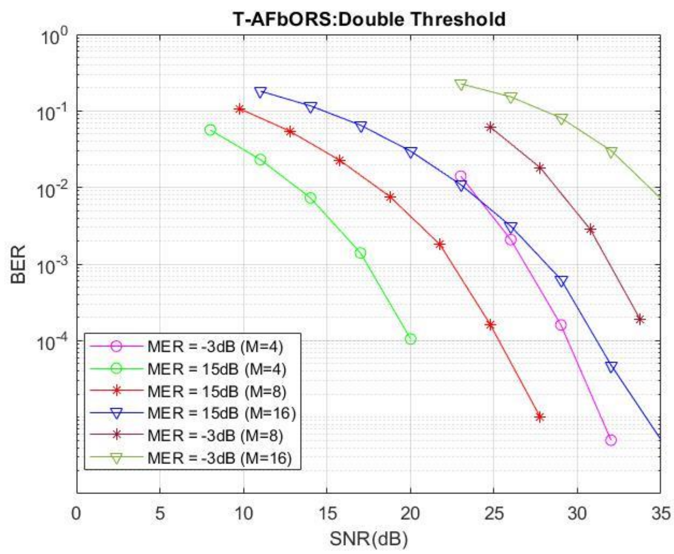

Figure 5.16. Comparison of T-AFbORS with Double Threshold for different constellation size with $P_s = 0.7P_t$ and $P_r = 0.3P_t$

Comparative Analysis based on the different Relay Scenarios for Case(ii)

Figure 5.17 depicts the intercept probability performance of AFbORS for different relay scenarios. It is observed that as the number of relays increases the intercept probability of P-AFbORS with double threshold significantly reduced as compared to other schemes. Moreover, the difference of 3dB is observed between 15-relay and 10-relay scenario for P-AFbORS scheme and 2dB difference is observed between 15-relay and 10-relay of T-AFbORS scheme.

In figure 5.18, the comparative intercept probability performance of P-DFbORS and T-DFbORS presented for the different number of relays. It is observed that P-DFbORS with 15-relay scenario outperforms all the other schemes considered in the analysis. Similarly, in figure 5.18, it is noticed that T-DFbORS scheme with 15-relay outperforms 10-relay and 5-relay T-DFbORS scheme.

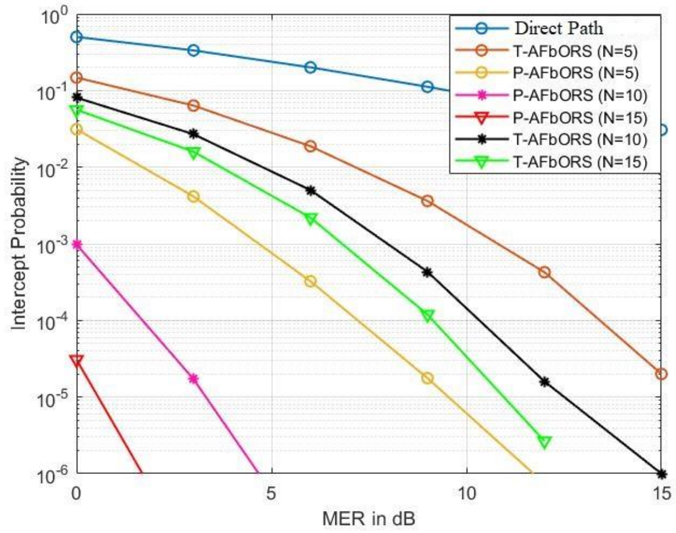

Figure 5.17. Comparison of Intercept Probability-AFbORS performance of different relay scenarios with $P_s = 0.7P_t$ and $P_r = 0.3P_t$

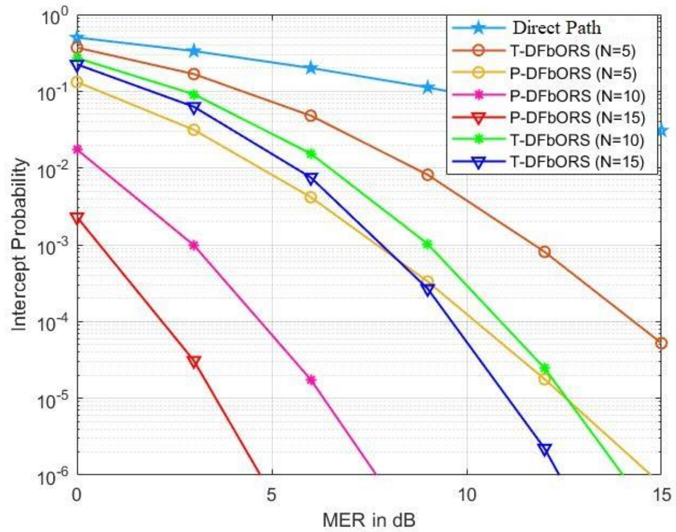

Figure 5.18. Comparison of Intercept Probability-DFbORS performance of different relay scenarios with $P_s = 0.7P_t$ and $P_r = 0.3P_t$

Figure 5.19 shows the comparative BER performance of P-AFbORS with double threshold for 5-relay, 10-relay, and 15-relay scenarios. Moreover, the comparative analysis is based on -3dB and 15dB MER. From the results of 15dB MER similar performance is observed for15-relay,10-relay, and 5-relay scenarios. At high MER increase in the number of relays has very less effect as opposed to very low MER of -3dB where an appreciable difference is observed between the number of relays under consideration.

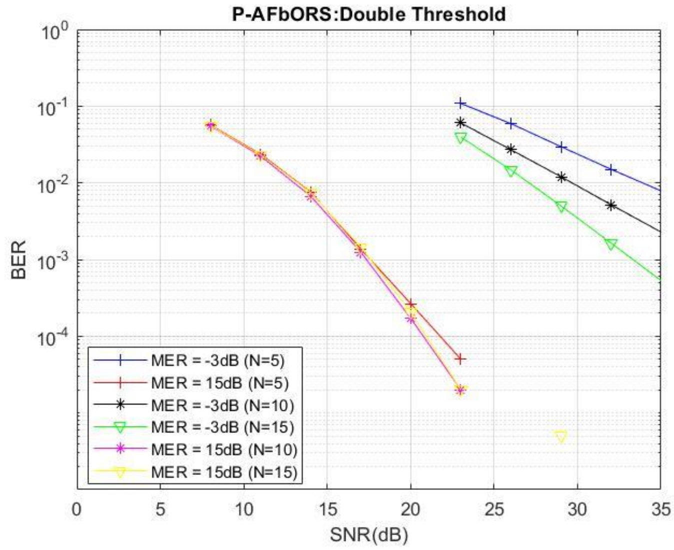

Figure 5.19. Comparison of P-AFbORS with Double Threshold performance for different number of relays with $P_s = 0.7P_t$ and $P_r = 0.3P_t$ for (MER=-3dB and 15dB)

c. Simulations Results and Discussion for Case(iii)

The simulation in this section considers the relays located near to the source node and the power ratios considered are $P_s = 0.3P_t$ and $P_r = 0.7P_t$.

Comparative Analysis based on different Modulation Schemes for Case(iii)

The P-AFbORS scheme with double threshold is compared for different M-PSK schemes for the MER under consideration is shown in figure 5.20. The results of P-AFbORS with double threshold for -3dB and 6dB MER is shown. From the results, 5dB difference is observed at the BER of 10^{-3} between 4-PSK and 8-PSK at 6dB MER.

Comparative Analysis based on different Relay Scenarios for Case(iii)

The comparative performance analysis of P-AFbORS based double threshold shown in figure 5.21 for 5-relay,10-relay, and 15-relay scenarios. The performance difference is less in P-AFbORS with double threshold for the same MER. Furthermore, this analysis the MER considers are 3dB, 6dB and 12dB. Moreover, the difference in the performance of 1dB is observed between 10-relay and 15-relay in all the MER considered.

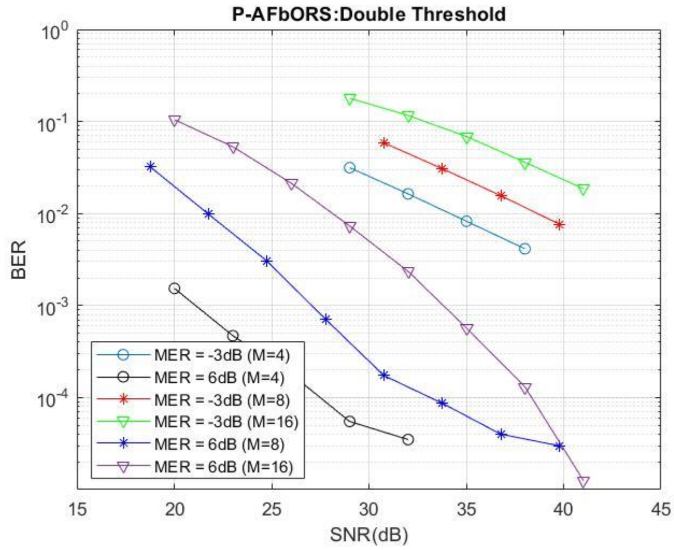

Figure 5.20. Comparison of P-AFbORS with Double Threshold for different modulation scheme for MER=-3dB and 6dB with $P_s = 0.3P_t$ and $P_r = 0.7P_t$

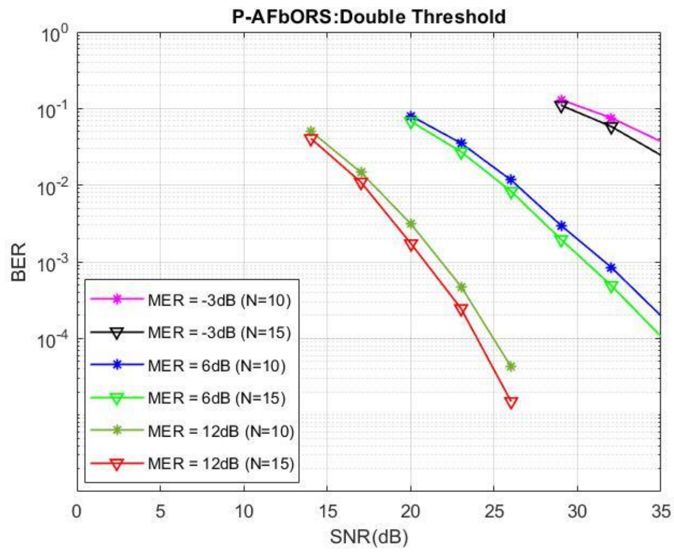

Figure 5.21. BER performance comparison of P-AFbORS with Double Threshold for different number of relays

5.3. Conclusion

This chapter considered the security issues in cooperative wireless network. In this chapter the physical layer security enhancement using relay selection is mainly focused. The proposed model combines the double threshold based relay selection with optimal relay selection schemes such as P-AFbORS and T-AFbORS. The intercept probability analysis of proposed scheme shows significant improvement in the performance. The proposed double threshold based AFbORS shows better performance compared to the existing optimal relay selection scheme without threshold. The performance of the proposed scheme is analyzed based on the number of relays and modulation schemes with different MER value. Increasing the number of relays with high MER shows substantial performance improvement compared to lesser relay scenarios. Simulation results showed that significant improvement in the secrecy performance against the eavesdropping attack is achieved by increase in the number of cooperative relays.

Chapter 6

Conclusions and Recommendations

6.1 Conclusions

Threshold-based relay selection schemes is proposed in this research for cooperative wireless network. This thesis addresses the critical issues such as power consumption, increase in complexity based on number of relay nodes and physical layer security issues. We try to bridge the existing research gap in the above-mentioned areas. The power consumption at the relay nodes in the cooperative wireless network is high due to large number of relay nodes in the coverage area of the source node. Therefore, the power consumption and complexity which are related to the number of relays involved in the communication operation are an integrated phenomenon. Increase in the number of relay nodes results in cooperative wireless network results in increased power consumption and complexity of the system. This research contributes to address the power consumption issue at the relay node by threshold-based relay selection scheme. Threshold-based relay selection assist in the selection of best relays and reduce the channel estimation requirement based on the number of relay nodes involved in the communication.

Existing threshold-based schemes in the literature are discussed in chapter 2 which focus on the cooperative wireless network applying DF relaying strategy due to its slightly improved performance compared to AF relaying at the cost of increased complexity. Moreover, the existing threshold-based relay selection techniques that consider DF strategy for the coherent relaying require full CSI.

The channel estimation requirement is high in coherent relaying due to its instantaneous CSI requirement, which is further reduced by our approach of applying differential modulation schemes. Differential modulation schemes help further reduce the requirement of instantaneous CSI, as a result it assists in reducing the channel estimation and complexity of the system. Threshold-based relay selection scheme with differential modulation proposed in this research selects the best relay nodes based on the threshold condition. Moreover, the cooperative network deals with both fast fading and slow fading scenarios. Furthermore, this scheme will be applicable to fast fading scenario, as full CSI will not be required at the relay and at the destination. This will make the proposed scheme more practical and easier to implement in real world.

Major research contributions of this thesis include:

- Threshold based single-relay selection with differential modulation is proposed in Chapter 3. The performance analysis of AF and DiffAF relaying with differential modulation is also studied in this chapter.
- This study also analyzed the performance of the proposed scheme in three different scenarios based on the distance between the source and the relay node. The power at the source and relay node is varied based on the distance. By adopting this approach, the simulation is closer to the practical scenario, and it shows the difference in performance for three different cases based on the distance.
- Double threshold relay selection scheme is proposed in Chapter 4 for Multi-relay selection addresses the problem of single threshold. The existing double-threshold scheme in the literature consider only coherent DF relaying. In this study double threshold scheme is investigated with coherent AF and differential modulation-based AF and DiffAF relaying scheme.

- Complexity analysis of double threshold-based relay selection is studied based on the average number of channel estimation and average number of relays selected.
- Analysis of the double-threshold based scheme raised new concerns, especially, the chances of combining multiple weaker relay-to-destination link degrades the e2e performance. This problem was overcome by the multi-threshold scheme proposed in this study, by introducing the combiner input threshold to select the best relayed paths.
- Physical layer security enhancement in the cooperative wireless network studied in Chapter 5. The approach followed in this study combines the existing optimal relay selection scheme with the proposed double threshold scheme as discussed in Chapter 4. The intercept probability analysis of the proposed double threshold-based optimal relay selection shows substantial improvement compared to the existing optimal relay selection technique without threshold.

The major research findings of this thesis are as follows:

- In Chapter 3, the performance of the proposed single-relay selection scheme with unequal power allocation at the source and relay are analyzed and compared with the equal power allocation scheme. The results show that the unequal power allocation with AF and DiffAF based on the distance significantly improve the e2e performance as compared to the equal power allocation scheme.
- Comparative analysis of double threshold-based relay selection with AF and DiffAF relaying schemes shows the coherent AF outperform differential modulation-based AF and DiffAF relaying schemes.
- Comparative analysis of multi-threshold-based relay selection scheme with AF and DiffAF relaying schemes shows multi-threshold based coherent AF scheme outperforms differential AF and DiffAF relaying scheme.

- Comparison of double-threshold and multi-threshold based AF relaying using coherent modulation shows double-threshold AF outperforms multi-threshold AF.
- Comparison of double-threshold and multi-threshold based DiffAF relaying using differential modulation shows multi-threshold DiffAF outperforms double-threshold DiffAF.
- The intercept probability analysis of the proposed double threshold based optimal relay selection scheme is less and this shows the physical layer security enhancement of the proposed scheme compared to the existing optimal relay selection schemes.

6.2 Further Recommendations

The further recommendations of this research are as follows:

- Double threshold and multi-threshold relay selection schemes can be extended with the distance based adaptive threshold and power allocation for cooperative D2D network.
- Threshold based relay selection schemes and physical layer security enhancement proposed in this research can be extended to D2D out-band controlled mode and D2D in-band underlay modes.
- This research can be extended to the cooperative vehicular network use case with mobile source, relay and destination nodes using distance based adaptive double threshold and multi-threshold with physical layer security.
- This research considers the half-duplex mode of communication, and it can be extended to the full-duplex mode that suits for the cooperative cellular network.
- Performance gap exists between the coherent and differential modulation-based relay selection scheme, so the double threshold and multi-threshold relay selection

scheme with double differential modulation scheme can be considered to reduce this gap.

- Physical layer security enhancement based on multi-threshold optimal relay selection in the cooperative D2D network is also an area for further study.

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Appendices

A. **Additional results on the Comparative Analysis of the proposed double threshold and Multi-threshold-based relay selection schemes**

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Appendix-A

Additional Results on the Comparative Analysis of DiffAF and AF based Double Threshold Relay Selection Scheme

The results shown in figure A1 provides a comparison between DiffAF and AF based double threshold scheme with equal power allocation. Similar performance observed up to an SNR of 19dB for both DiffAF and AF relaying. Furthermore, this comparison considers 5-relay and 20-relay scenario with an input threshold set as 10dB and the output threshold of 5dB. The DiffAF shows performance improvement at high SNR compared to AF relaying with equal power allocation for the relay and the source. The difference of 1dB is notice between DiffAF and AF for 5-relay scenario with the DQPSK modulation scheme. Moreover, a difference in BER of 0.03553 noticed at an SNR of 26dB between DiffAF and AF for 20-relay scenario. DiffAF scheme shows improved performance compared to AF in this case.

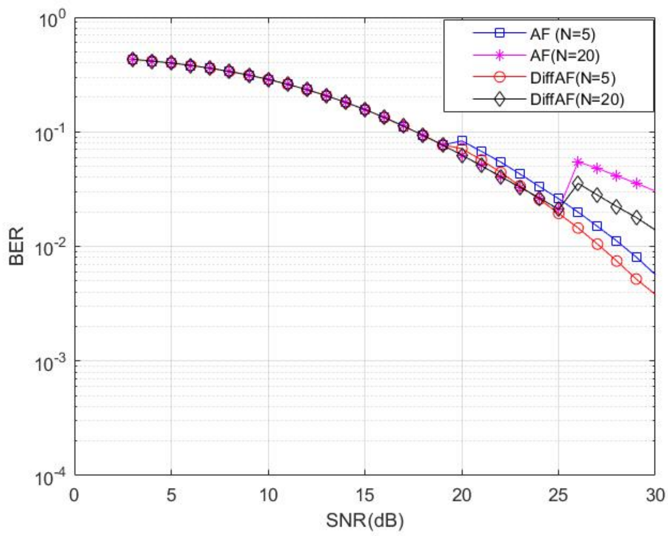

Figure A1. Comparative Multi-relay Double-Threshold with DQPSK with Equal Power and Th_In=10 and Th_Out=5 (AF Vs DiffAF)

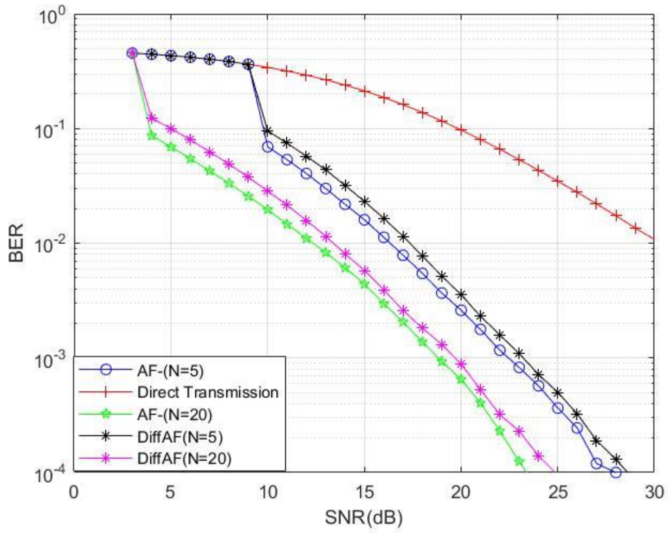

Figure A2. Comparison of AF vs DiffAF for Multi-relay Double-Threshold with DQPSK with $P_s = 0.3P_t$ and $P_r = 0.7P_t$ and Th_In=10 and Th_Out=5

Figure A2 shows the comparative analysis of double threshold with DiffAF and AF relaying for case (iii) with relays near to the source. The difference of 1dB observed between 20-relay and 5-relay scenario for DiffAF and AF relaying. Furthermore, in the comparative results, it is noticed that AF relaying with the double threshold outperform DiffAF relaying in this case.

Additional Results on the Comparative Analysis of DiffAF and AF based Multi-Threshold Relay Selection Scheme

Comparative analysis of multi-threshold AF and DiffAF relaying schemes based on the number of relays shown in figure A3 for case(i). In this simulation input threshold of 20dB and combiner input threshold of 9dB and combiner output threshold of 25dB is considered. Multi-threshold 3-relay AF outperforms 3-relay DiffAF with a difference of 1dB, and 7-relay scenario shows similar performance as that of direct transmission. Threshold comparative analysis of AF and DiffAF, shown in figure A4. Furthermore, similar performance observed between AF and DiffAF for the threshold considered in the simulation.

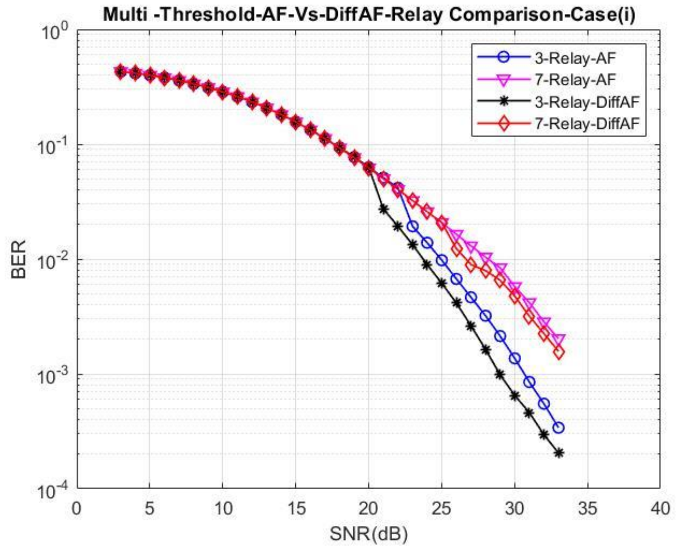

Figure A3. Comparative Analysis of Multi-Threshold AF Vs DiffAF Relay Comparison with for Case(i)

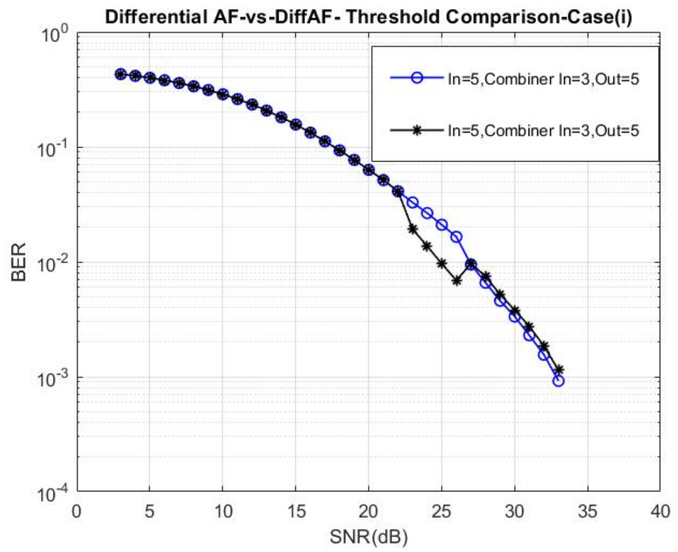

Figure A4. Comparative Analysis of Multi-Threshold AF Vs DiffAF Threshold Comparison with N=5 for Case(i)

Figure A5 depicts the comparative analysis for the case(ii) with power ratios shown, and the input threshold consider in the simulation is 5dB and combiner input and output threshold are 7dB and 15dB. Multi-threshold AF shows minor performance improvement compared to DiffAF in this case.

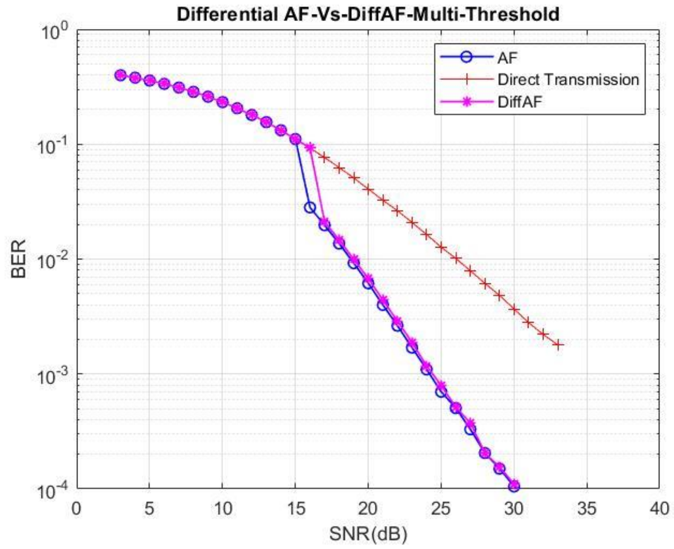

Figure A5. Comparative Analysis of Multi-Threshold AF Vs DiffAF for
$P_s = 0.8P_t\,, P_r = 0.2P_t$

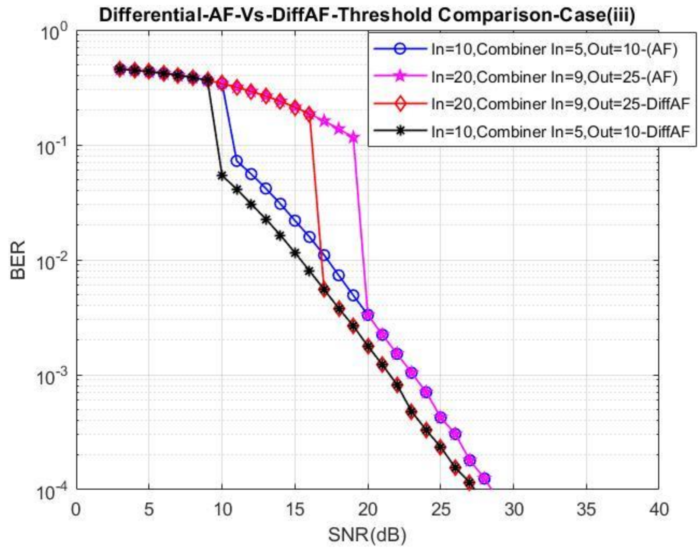

Figure A6. Comparative Analysis of Multi-Threshold AF Vs DiffAF Threshold Comparison with N=5 for Case(iii)

Figure A6 presents the comparative threshold analysis of AF and DiffAF for the 5-relay scenario. For the analysis, two threshold sets considered, and the results show DiffAF outperform AF in case(iii). Furthermore, for the high input and combiner input threshold values considered degradation in the performance observed.

The relay comparison of AF and DiffAF for case(iii) shown in figure A7. The comparative analysis consider 10-relay scenario, and results show that 10-relay AF outperform 10-relay DiffAF with a difference of 1dB for the BER of 10^{-3}.

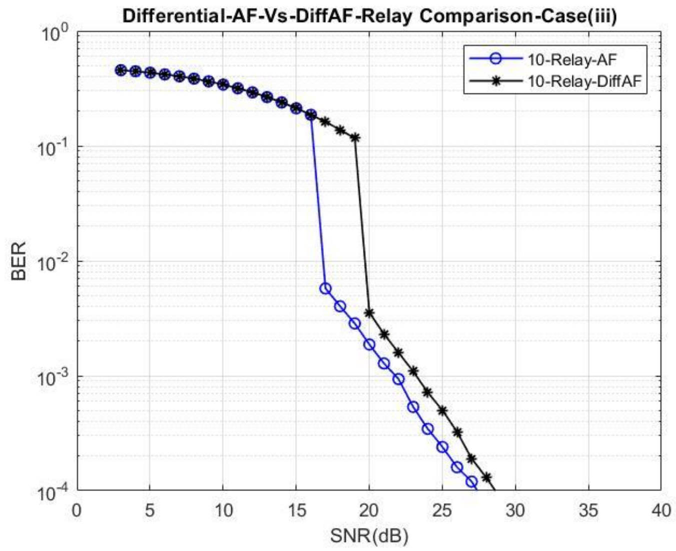

Figure A7. Comparative Analysis of Multi-Threshold AF Vs DiffAF Relay Comparison with In=20, Combiner In=9 and Out=25 for Case(iii)

Comparative Analysis of Double-Threshold and Multi-Threshold based AF relaying schemes using Coherent Modulation

Figure A8 presents the relay comparison of Multi-threshold and Double threshold coherent AF schemes for 5-relay scenario. This comparison does not consider the same threshold values since the inclusion of additional threshold at the combiner input in the multi-threshold scheme. This comparison consider the case(ii) with relays located at a distance from the source and the power ratios of the source and relay are $P_s = 0.7P_t$, $P_r = 0.3P_t$. In the result, 5-relay double threshold shows a minor performance improvement compared to the multi-threshold AF scheme.

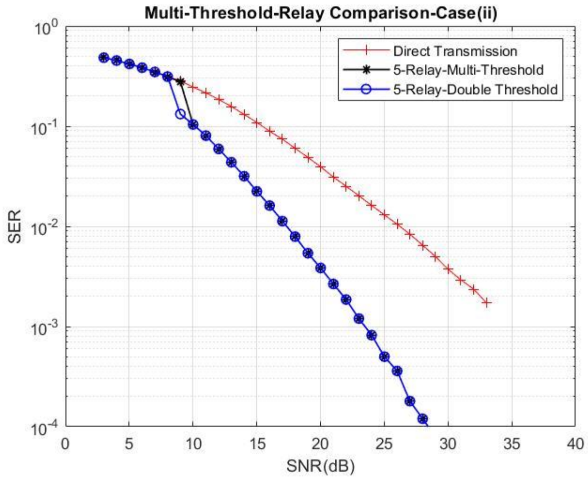

Figure A8. Comparative Analysis of Multi-Threshold Vs Double-Threshold Coherent AF with Double Threshold (In=3, Out=5)-Multi-Threshold (In=5, Combiner In=3 and Out=5) for Case(ii)

Comparative Analysis of Double-Threshold and Multi-Threshold based DiffAF relaying using Differential Modulation

Comparison of double threshold and multi-threshold DiffAF scheme shown in figure A9 for the 20-relay scenario. As opposed to the comparative results shown in figure A8 for AF, the results in figure A9 show substantial performance improvement for multi-threshold DiffAF compared to the double-threshold scheme. Moreover, above 8dB SNR both schemes show similar performance.

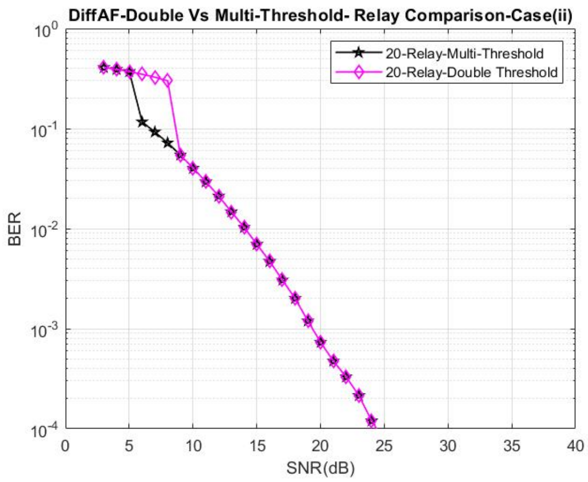

Figure A9. Comparative Analysis of Multi-Threshold Vs Double-Threhsold DiffAF with Double Threshold (In=3, Out=5)-Multi Threshold (In=5, Combiner In=3 and Out=5) for Case(ii)

Comparative Analysis of Double-Threshold and Multi-Threshold based AF relaying schemes using Differential Modulation

Comparative analysis of double threshold and multi-threshold AF using DQPSK shown in figure A10 for case(ii). Moreover, the results significant performance improvement for the double threshold AF scheme compared to the multi-threshold alternative. The comparison considers 20-relay scenario. Furthermore, similar performance observed above 17dB.

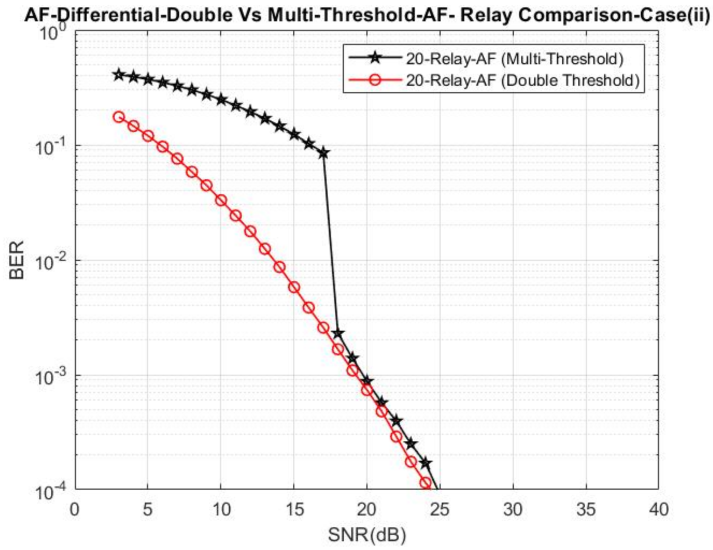

Figure A10. Comparative Analysis of Multi-Threshold Vs Double-Threhsold AF with Double Threshold (In=3, Out=5)-Multi Threshold (In=5, Combiner In=3 and Out=5) for Case(ii)

Appendix-B

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