PERFORMANCE ANALYSIS OF SWIPT ENABLED NON-ORTHOGONAL MULTIPLE ACCESS ASSISTED MULTIPLE RELAY COOPERATIVE NETWORKS

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2021

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THESIS SUBMITTED IN FULFILMENT OF THE REQUIREMENTSFOR THE DEGREE OF DOCTOR OF PHILOSOPHY

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

2021

UNIVERSITY OF MALAYA

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Matric No: 17006141/1 (KHA160033)

Name of Degree: Doctor of Philosophy

Title of Project Paper/Research Report/Dissertation/Thesis: Performance Analysis of SWIPT Enabled Non Orthogonal Multiple Access Assisted Multiple Relay Cooperative Networks

Field of Study: Wireless Communication

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PERFORMANCE ANALYSIS OF SWIPT ENABLED NON ORTHOGONAL MULTIPLE ACCESS ASSISTED MULTIPLE RELAY COOPERATIVE NETWORKS

ABSTRACT

Non-orthogonal multiple access (NOMA) scheme is emerging as a favorable multiple access scheme for future 5G networks. Compared to orthogonal multiple access (OMA) techniques, NOMA provides spectral efficiency, user fairness, better connectivity, enhanced data rate and reduced latency. On the other hand, in wireless networks, cooperation is a well-recognized technique for performance enhancement. Cooperative networks offer multiple desirable advantages, including high performance, reliability and greater coverage area. NOMA has features that can provide opportunities of improved performance and better spectral utilization for downlink cooperative networks.

Modern communication systems operate under energy constraints. Simultaneous wireless information and power transmission (SWIPT) is a way of energy harvesting (EH), which allows to exploit the same RF signal for both EH and information processing. Integration of Cooperation, NOMA and SWIPT can provide energy efficient, reliable and spectral efficient networks. Therefore, this study aims to design energy harvesting enabled cooperative NOMA (C-NOMA) networks. In the first part, multiple relay downlink cooperative NOMA network with SWIPT is investigated where both useful signal and interfering signals are used to harvest energy. The closed form analytical expressions of outage probability are derived. Subsequently, impact of various parameter, including, number of available relay nodes, interfering signals, energy harvesting parameter, and energy conversion efficiency is shown on performance of proposed networks. The finding showed that system performance improves with the number of intermediate relaying nodes, transmit power, power of external interfering source and energy harvesting efficiency. It was identified that optimal location of relaying nodes is nearest to source.

For device to device communication, it is important to consider spatial distribution of dynamically distributed users. Second part of the research focused to investigate the SWIPT enabled C-NOMA networks in the presence of interference with cooperation among spatially distributed NOMA users. The mathematical model to evaluate the outage probability and system throughput are provided and analyzed. The results demonstrated the positive impact of transmit SNR, number of available cooperating device, interference power and conversion efficiency, while performance was deteriorated with increase in radius of cooperative area and higher data rates.

Due to energy harvesting, multiple channel gains get involved and best relay cannot be selected straightforwardly. In the third part of the work, a new relay selection scheme for C-NOMA networks with SWIPT is proposed. The selection scheme was designed by carefully considering all involved channels and circuit power consumption at relay node. Additionally, the selection scheme was extended of dynamic power allocation factors of NOMA users. For the proposed two-stage relay selection analytical expression of outage probability for delay-limited transmission are provided. A comparative analysis of partial relay selection and two-stage relay selection was conducted to find which schemes performs better under certain conditions. It was revealed that proposed scheme provides significant performance improvement, particularly at higher transmit SNR and number of relays. For all relay selection schemes, the optimal relay location was found closer to source node.

Keywords: 5G networks, Cooperative NOMA, Energy harvesting, Relay Selection.

ANALISIS PRESTASI RANGKAIAN KERJASAMA PELBAGAI GEGANTI SWIPT DIPERBOLEHKAN TERBANTU CAPAIAN PELBAGAI BUKAN ORTHOGONAL

ABSTRAK

Skema pelbagai akses tanpa ortogon (NOMA) muncul sebagai skema akses pelbagai yang paling bersesuaian untuk rangkaian 5G akan datang. Berbanding dengan teknik pelbagai akses ortogon (OMA), NOMA menyediakan kecekapan spektrum, kesaksamaan buat pengguna, ketersambungan yang lebih baik, kadar data yang dipertingkatkan dan kependaman yang dikurangkan. Sebaliknya, dalam rangkaian tanpa wayar, koperatif adalah teknik yang diiktiraf dan baik untuk peningkatan prestasi. Rangkaian koperatif menawarkan pelbagai kelebihan yang diingini, termasuk prestasi yang tinggi, kebolehpercayaan dan kawasan liputan yang lebih besar. NOMA mempunyai ciri-ciri yang boleh memberi peluang kepada prestasi yang lebih baik dan penggunaan spektrum yang lebih baik untuk rangkaian koperatif paut turun.

Sistem komunikasi moden beroperasi di bawah kekangan tenaga. Maklumat tanpa wayar serentak dan transmisi kuasa (SWIPT) adalah cara memperolehi tenaga (EH), yang membolehkan eksploitasi isyarat RF yang sama untuk kedua-dua EH dan pemprosesan maklumat. Kerjasama antara Koperatif, NOMA dan SWIPT dapat menyediakan tenaga yang efisien , boleh dipercayai dan rangkaian spektrum yang cekap. Oleh itu, kajian ini bertujuan untuk mereka bentuk rangkaian perolehan tenaga yang membolehkan koperatif NOMA (C-NOMA). Pada bahagian pertama, rangkaian pelbagai geganti paut turun koperatif NOMA dengan SWIPT dikaji di mana isyarat berfungsi dan isyarat mengganggu digunakan untuk mendapatkan tenaga. Ungkapan analisis bentuk tertutup kebarangkalian gangguan elektrik diperoleh. Seterusnya, kesan pelbagai parameter, termasuk bilangan nod geganti yang ada, isyarat mengganggu, parameter perolehan tenaga, dan kecekapan penukaran tenaga ditunjukkan pada prestasi rangkaian cadangan.

Dapatan ini menunjukkan bahawa prestasi sistem bertambah baik dengan bilangan nod geganti perantaraan, penghantaran kuasa, kuasa sumber gangguan luaran dan kecekapan perolehan tenaga. Telah dikenalpasti bahawa lokasi optimum nod geganti adalah yang paling hampir dengan sumber.

Bagi komunikasi di antara peranti, adalah penting untuk mempertimbangkan pengagihan ruang bagi pengguna yang diedarkan secara dinamik. Bahagian kedua penyelidikan ini memberi tumpuan kepada kajian terhadap rangkaian SWIPT membolehkan C-NOMA dengan kehadiran gangguan dan koperatif di kalangan pengguna NOMA yang diedarkan secara spasial. Model matematik untuk menilai kebarangkalian gangguan dan sistem menyeluruh disediakan dan dianalisis. Keputusan menunjukkan kesan positif penghantaran SNR, bilangan peranti koperatif yang ada, gangguan kuasa dan kecekapan penukaran, manakala prestasi merosot dengan peningkatan radius kawasan koperatif dan kadar data yang lebih tinggi.

Disebabkan oleh perolehan tenaga, pelbagai saluran dapatan terlibat dan pemilihan geganti terbaik tidak boleh dilakukan dengan cara yang jelas atau nyata. Pada bahagian ketiga, skema pemilihan geganti baru untuk rangkaian C-NOMA dengan SWIPT dicadangkan. Skema pemilihan direka dengan teliti dengan mempertimbangkan semua saluran yang terlibat dan penggunaan kuasa litar pada nod geganti. Di samping itu, skema pemilihan telah diperluaskan atas faktor peruntukan kuasa dinamik pengguna NOMA. Bagi cadangan dua peringkat ungkapan analisis pemilihan geganti kebarangkalian gangguan bagi kelewatan penghantaran terhad disediakan. Analisis perbandingan pemilihan geganti separa dan pemilihan geganti dua peringkat telah dijalankan untuk mencari skema mana yang berfungsi dengan lebih baik di bawah situasi atau keadaan tertentu. Kajian ini telah mendedahkan bahawa skema cadangan dapat menyediakan peningkatan prestasi yang ketara, terutamanya pada penghantaran SNR yang lebih tinggi dan bilangan geganti. Untuk semua skema pemilihan geganti, lokasi optimum bagi geganti didapati lebih dekat dengan nod sumber.

Kata kunci: Rangkaian 5G, Koperatif NOMA, Perolehan Tenaga, Pemilihan Geganti.

ACKNOWLEDGEMENTS

First of all, innumerable thanks to Allah Almighty for giving me the ability and wisdom. It was due to His blessing and guidance that I was able to write this thesis for requirement of my degree.

Then I would like to thank from the core of my heart to my advisors Assoc. Prof. Dr. Kamarul Ariffin, Prof. Dr. Kaharudin, and Dr. Tarik for their enormous help for resolving the difficulties faced during my studies. Their encouragement made it possible to complete this task.

My special thanks goes to my husband, Dr. Arslan Ahmad for his undoubted believe in me and letting me achieve my ambitions. His wise opinions, moral and financial support kept me motivated to complete it. I am grateful to my husband and my son Abdul Wahab for their sacrifices and concerns for me and my career. My utmost gratitude goes to my family specially my parents, my parents-in-law and my brother for their prayers, encouragement, support and love. My special thanks to my mother and my sister for their limitless help in completing my thesis. I really appreciate their sympathetic ear and concerns for my career, without their help it was very difficult for me to complete this thesis. I am also grateful to my friends for their support throughout my Ph.D., my special thanks to Ayesha Imtiaz for her help and encouragement.

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LIST OF SYMBOLS AND ABBREVIATIONS

AF	:	Amplify and forward
CSI	:	Channel state information
DF	:	Decode and forward
IDMA	:	Interleaver division multiple access
NOMA	:	Non-Orthogonal Multiple Access
PDMA	:	Pattern division multiple access
PS	:	Power Splitting
RF-EH		Radio frequency energy harvesting
SWIPT		Simultaneous wireless information and power transmission
SI	:	Signal interference
SIC	:	Successive interference cancellation
SC	:	Superposition coding
RS	:	Relay Selection
TS	:	Time Switching

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CHAPTER 1: INTRODUCTION

1.1 Overview

Over the past three decades, the telecommunication industry has undergone a remarkable evolution. The traditional wired telephony system has emerged into fully wireless communication systems. Particularly, mobile communication gained more popularity due to its availability and expansion. The advancement in mobile technology helped to save time and resources. This technology has introduced quick reforms to fulfill the requirements of customers and its ever-increasing demands. Mobile communication has undergone dramatic changes throughout its development from first-generation (1G) to fourth generation (4G). Each generation introduced updated services, compatible transmission technologies, and transmission frequency bands.

The recent decade involves the evolution of 4G LTE-A (Long term evaluation-Advanced), which was aimed to maximize the system throughput at minimal cost while satisfying the requirements regulated by ITU for IMT-A Standard. The following main features were target buy LTE; a) increased data throughput, reduced transmission latency, reduced cost, spectral efficiency, reduced power consumptions, and improved coverage. To achieve the set targets, underlying mobile radio technology was improved. Three core technologies that were introduced to shape LTE system are multiple antenna technology (MIMO), multiplexing, and packet switching on the radio interface. For LTE-A, 3GPP introduced several new technologies and services including heterogeneous networks (HetNet), massive multiple-input-multiple-output (MIMO), carrier aggregations (CA) and, coordinated multipoint (Comp). Despite all the advanced technologies introduced by LTE-A, it was needed to introduce the new 5G.

The 5th generation (5G) wireless networks are expected to fulfill the growing demands of mobile data. With the fast growth of the internet of things, fifth-generation networks have to support immense connectivity of devices or/and consumers. Compared to the existing fourth-generation (4G) of cellular network, 5G is expected to meet the following key features: 10-100 times increased data rate, up to 99.99% availability, reduced delays, 10-100 times greater number of connected devices, guaranteed coverage, 10 times reduced energy consumption, and efficient incorporation of existing wireless technologies with new 5G techniques (Panwar, Sharma, & Singh, 2016; Pirinen, 2014; Yilmaz et al., 2015). The growing demands of improved quality of services (QoS) invoked the researchers and industries to develop more efficient wireless communication networks.

NOMA is being considered as an important enabling technology for next-generation networks. The key idea behind NOMA technique is that multiple users are served in a single resource block, e.g., frequency channel, time, or spreading code. In the power domain NOMA (PD-NOMA), which serves multiple users at the same time, channel frequency, or spreading code, multiple access is implemented by using power domain multiplexing i.e., different power levels are allocated to different users. In PD-NOMA, a single frequency channel is allotted to multiple users in the same cell, thus PD-NOMA provides better connectivity compared to OMA. Available bandwidth is not divided among multiple users and each user can use the whole available spectrum for transmission which results in high system throughput (Ding, Liu, et al., 2017). Additionally, multiple users are served simultaneously and users are not required to make scheduling requests from the base station (BS), which guarantees low latency in transmission. PD-NOMA is also compatible with existing OMA schemes, i.e., TDMA and FDMA; therefore it can be easily adopted by existing wireless networks.

Physical layer cooperation is a well-recognized wireless communication technique that promises high power efficiency and throughput gains. Among all other cooperative strategies, cooperative relaying, which uses the concept of spatial cooperative diversity is more significant. By taking advantage of the broadcast nature of the wireless medium, cooperative relaying is enabled by getting assistance from a node between sender and user. This intermediate node, called a relay, can help in relaying the information and provides communication path between source and destination. By using a relay, multiple copies of the signal are received at the destination which improves the reliability of the system. Additionally, long-distance transmission is also possible if a direct channel between two communicating nodes does not exist. The increasing number of cell edge users can be efficiently served with the help of relaying technology (Fodor et al., 2012). By using less transmission power, the relay to destination(R-D) distance will be shorter. This causes a more preferred condition of relay destination (R-D) channel which paves the way towards the better signal to noise ratio (SNR) of cell edge users than the direct transmission from source to destination (S-D). In short relaying ensures reliability, broader coverage area, and reduced transmit power, which are the required features of 5G. But this cooperation is possible at the expense of extra spectral resources to cooperate.

Cooperation with NOMA (C-NOMA) can achieve significant spectral gain over cooperative orthogonal multiple access schemes. This superiority is because in PD-NOMA, shared resources can be used for cooperation (Ding, Peng, & Poor, 2015). Two types of cooperation in downlink scenario is possible, cooperation among NOMA users and cooperation with the help of dedicated/fixed relays. Cooperation among NOMA user is motivated by signal interference cancellation (SIC) adapted at the strong users of NOMA. Users with good channel conditions have prior information about the messages of other users and strong users can exploit this redundant information by acting as relays to improve the reliability of other users who have a weak connection with BS. Dedicated relay networks are employed to increase reliability and/or coverage. Cooperation demands extra spectrum; however, NOMA can improve spectral usage by serving multiple users on shared resources.

Along with improved spectral efficiency, which is the basic positive feature of NOMA, the maximization of energy efficiency is another key objective of future 5G networks. To design energy-efficient networks, energy harvesting (EH) techniques which enable the devices to capture energy from external sources can be useful. As most devices are surrounded by radio-frequency (RF) signals to carry both energy and information, thus RF signal has been considered a viable source for EH. Simultaneous wireless information and power transmission (SWIPT) is a new way for RF-EH in which the same RF signal is used for both the EH and information processing. In conventional wireless networks, interference is considered problematic and it caused deterioration in system performance. However, the impact on interference in the energy harvesting system is twofold. While interference signal makes the communication system more vulnerable, it can serve as a source of energy harvesting and might improve the system performance by improving relay transmit power. SWIPT is an emerging technology to harvest energy particularly for networks in which replacement of batteries is cumbersome, hazardous and cost prohibitive (mainly due to inconvenience to get physical access to such networks).

In short, relay networks are usually employed to increase reliability and/or coverage, and NOMA can improve the spectral efficiency of cooperative networks. However, relaying node can be reluctant to provide help on the expense of their battery/resources. In this case implementation of SWIPT can provide some motivation to the intermediate node for relaying the information by using harvested energy from the source signal. Another possible situation is that SWIPT might activate and takes assistance from inactive available intermediate devices. Thus investigating SWIPT in cooperative NOMA (C-NOMA) networks becomes particularly desirable. This motivation has invoked researchers to explore energy harvesting in cooperative NOMA networks, but very little research work on the coexistence of these techniques exist in literature.

1.2 Problem Statement

In wireless cooperative networks, the relay nodes may have limited power sources, so external sources may be required by such nodes to remain active in the network. Therefore, energy harvesting in relay networks is desirable. Also, the spectral efficiency of cooperative relay networks can be improved by using NOMA. Therefore, integration of Cooperative relay networks, SWIPT, and NOMA can be beneficial to design energy and spectral efficient networks.

In today's dense communication networks, the device are always exposed to some external interference. Mitigation of interference has been challenging in designing wireless networks, however, interference power can be used as a source of energy harvesting. In C-NOMA with SWIPT, energy can be harvested from transmitted source signals and external interference. In EH networks, harvested energy becomes random and unpredictable due to the random nature of channels between source to relay, and interference to relay link. Investigation of such a network is challenging and complicated. Conventionally, relay-assisted cellular cooperative networks are featured with dedicated/fixed relay stations. These dedicated relay nodes neither serve as source nor users, they are deployed to facilitate the communication between source and users. The dedicated relay nodes help to improve reliability and coverage area. This is one possible scenario of cooperation, another possibility is that the device might also work as a relay. Since recent communication systems facilitate device-to-device communication, it is important to consider the cooperation among users. Along with technical and security issues to designs such networks, a big challenge is to convince the users to the expenditure of their resources, particularly batteries to facilitate other users in the networks. Thus, energy harvesting becomes more important for devices willing to work as a relay nodes. The use of SWIPT demands some important changes in the design of cooperative networks, and to design energy-efficient 5G networks, it is required to investigate the combination of these techniques.

Deploying multiple relay network performance of traditional cooperative rely on network is increased. However, multiple relay networks provide performance gain at the expense of complexity and spectral resources. The best technique to implement cooperative diversity through multiple relaying is relay selection. Through relay selection only one best available relay operates at a time, a strict time and carrier synchronization among all relays is not required which results in reduced complexity and overhead. This study emphasizes to design of energy harvesting enabled multiple relay cooperative networks with advanced non-orthogonal multiple access (NOMA) techniques. Additionally, it is aimed to design energy-efficient networks by utilizing the interference as a potential source of energy. In this area following gaps are identified:

1. Multiple relay, SWIPT enabled C-NOMA networks with dedicated relaying in the presence of interference have not been investigated.
2. The performance of SWIPT enabled multiple relay C-NOMA in the presence of interference with cooperation among spatially distributed users is unknown.
3. The conventional relay selection schemes cannot be optimal for novel SWIPT enable C-NOMA networks, new relay selection schemes are required to design considering the amount of harvested energy and dynamic power allocation factors.

1.3 Research Objectives

This work aims to investigate the performance of downlink multiple relay cooperative NOMA networks with SWIPT in the presence of interference. In the first and second objectives of the thesis, the multiple relay networks in the presence of interference are investigated for both dedicated and users' cooperation using NOMA. In the third part, new relay selection schemes for SWIPT enabled C-NOMA network is proposed. Following objectives are intended to fulfill in this research;

1. To investigate the performance of multiple relay SWIPT enabled C- NOMA networks in the presence of interference with dedicated relaying.
2. To investigate the outage performance of SWIPT enabled C- NOMA networks in the presence of interference with cooperation among spatially distributed users.
3. To propose and analyze the new two-stage relay selection method for multiple relay SWIPT enabled C-NOMA networks.

The first two objectives aim to investigate the SWIPT in C-NOMA networks in the presence of interference. The designed model will be investigated by analyzing the impact of the involved parameter on system performance. Outage probability and sum throughput are used to evaluate the performance and success of the proposed system. In the third part of the thesis, the outage probability of various relay selection schemes would be evaluated and compared.

1.4 Scope of the Study

Multiple access schemes have played a vital role in designing the communication schemes. Every generation of wireless networks brought a new multiple access schemes to facilitate the higher number of devices. NOMA has proved its potential to be used as the most spectral efficient multiple access schemes for future wireless networks. NOMA can be easily integrated with other 5G technologies, including cognitive radio, full-duplex radio, and wireless energy harvesting. With the exponential growth of wireless devices, it has become challenging to the full energy demand of devices. The energy consumption of wireless devices can be reduced by reusing the energy available in the surrounding environment.

SWIPT provides a practical approach to harvest energy from surrounding RF signals. Energy harvesting is being considered as one of the important candidates of future networks. Harvesting energy can provide a solution to many existing wireless networks. For example, the biggest deployment challenge for the Internet of thing (IoT) is to maintain reliable communication with low energy and limited cost. IoT devices such as sensors are generally small in size, and these devices are placed in remote areas where they cannot be accessed by humans. To provide a stable power source or replace the battery in these nodes is difficult. SWIPT can be used to keep these nodes active in the network. Another possible application of SWIPT is body area removed networks, where body implants can be wirelessly charged.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter provides related details about the protocols and schemes used in this work. Additionally, existing literature related to set objectives is listed.

2.1.1 Cooperation and Cooperative Relay Protocols

The diversity which enables to send or receive multiple copies of a signal is a promising technique to mitigate the effects of fading in a wireless environment. Among other diversity schemes, spatial cooperative diversity is more preferable, because by using cooperation and antenna sharing, cooperative diversity makes it possible to take the advantage of multiple antenna diversity with networked devices of a single antenna. Multiple devices with a single antenna create a virtual array by cooperation and antenna sharing. In a wireless environment, any idle node can overhear the message of other users of the network. By using the concept of cooperation, this idle node can help in relaying the information of its peer. This cooperation guarantees enhanced reliability by sending multiple signals through relaying. Moreover, for far users who have bad channel conditions, and a direct link between BS and a user cannot be established, relaying can help in transmitting the information of such users. Generally, a relay is chosen because it is comparatively closer to BS, less power is required at BS to transmit the signal at relay. It concludes that relay networks have more advantages in terms of reliability, broader coverage area, and power saving (Laneman, Tse, & Wornell, 2004).

By considering different forms of information processing at the relay terminals, a number of cooperation techniques and protocols have been developed and investigated over the years. The relaying protocols have been mainly categorized into three groups known as amplify-and-forward (AF), decode-and-forward (DF), and compress-and-forward (CF) relaying. The AF and DF schemes are mostly adopted in communication systems because of their comprehensive design and maturity. In the AF scheme, also termed as non-regenerative relaying, the relay node amplifies and forwards the overheard signal to the desired destination, however, noise also gets amplified along with actual information. In the DF scheme, the signal received from the source is completely decoded by the relay and a re-encoded signal is sent to the destination. Consequently, when the relay sends an erroneously decoded signal, the problem of error propagation can emerge, which may interfere in the detection at the destination and overall system performance. In the DF scheme, processing delays are introduced due to encoding/decoding at the relay node. In a CF-based scheme (also termed as an estimate and forward or quantize-map-forward (QMF)), the relay sends a quantized /compressed form of the signal received from the source. This scheme requires channel information only at relay and it is relatively simpler than decoding in DF scheme but at the expense of performance (Kramer, Gastpar, & Gupta, 2005; Simoens, Muñoz-Medina, Vidal, & Del Coso, 2010) (Hanzo, Alamri, El-Hajjar, & Wu, 2009). For multiple relays, some hybrid protocols in which different relaying strategies are combined have been developed to take full advantage of relaying (Bao & Li, 2007). Table 2.1 summarizes the well-known relaying protocols.

Table 2.1: Summary of Commonly Adapted Relaying Protocols

Relaying Protocol	Description	Advantages	Disadvantages
AF	Relay performs power amplification and forwards the amplified signals.	Easy implementation Inexpensive	Noise amplification
DF	Relay decodes the received information and forwards the re-encoded information	Noise elimination at relay	Complexity Higher latency Error propagation
CF	Relay forward an compressed/estimated version of source information	Noise Elimination	Higher latency Error propagation

2.1.2 Non Orthogonal Multiple Access (NOMA)

Non-orthogonal multiple access (NOMA) is becoming an important enabling technique for future generation wireless networks. Various forms of NOMA techniques have been proposed and investigated. In all NOMA schemes, information of multiple users is transmitted on shared resources, and at the receiver, joint detection is performed to detect the signal. Joint detection algorithms such as message passing algorithms (MPA) or successive interference cancellation (SIC) is adapted by the receiver to detect the non-orthogonal signals. While the key principle of all NOMA schemes is similar, NOMA schemes are categorized based on the domain in which non-orthogonally is achieved. Users are differentiated by using different signature designs e.g., spreading sequences, spreading codes, interleaver, and power allocation ratios. For example, in low density spreading multiple access (LDS) (Mohammed, Imran, Tafazolli, & Chen, 2012) and Sparse code multiple access (SCMA) (Nikopour & Baligh, 2013; Taherzadeh, Nikopour, Bayesteh, & Baligh, 2014), information of the single user is spread over multiple subcarriers. Particularly, in LDS, user-specific spreading sequences are used; these sequences are either sparse or non-orthogonally cross-correlated with a low correlation factor. The sparse features ensure that the same subcarrier is not utilized by a large number of users, which keeps the complexity of the system manageable. In SCMA, a multidimensional codebook is designed to confirm that multiple users are effectively spread over subcarriers. At the transmitter, both bit spreading and bit mapping are combined and input data bits are directly mapped to the code-words of the multidimensional codebook. As the message of a user at multiple subcarriers is jointly encoded at the transmitter, at receiver, joint decoding is required which is realized by MPA.

Table 2.2: Types of Non Orthogonal Multiple Access Schemes

NOMA Type	Multiplexing Domain	Receiver Type	Advantages	Disadvantages
LDS	Spreading codes	MPA	Channel state information(CSI) is not required	Coding causes redundancy
SCMA	Codebook	MPA	Channel state information(CSI) is not required Good performance	Complex detection/decoding Limited number of code words may lead to collision (when user share same resources)
IDMA	Interleaver	Elementary signal estimation with/ without iterative detection	High user overload High spectral efficiency	High latency in case of iterative detection Extra signaling for channel detection
Power-domain NOMA	Power	SIC	High performance Less receiver complexity	Error propagation Low user overloading because user pairing is required

In Pattern division multiple access (PDMA) (Zeng, Li, Su, Rong, & Xing, 2015), multiplexing can be performed in various domains including spatial, code, or power domain. At the transmitter, non-orthogonal patterns are designed to minimize the overlapping of users. The subcarrier allocation matrix, known as pattern matrix determines the spreading of multiple users. At the receiver, MPA can be adapted to detect the spread information, and when users are multiplexed on both power and space domain, MPA-SIC is applied. In *interleave-division multiple-access (*IDMA) (Akbil & Aboutajdine, 2015), different users are distinguished by inter-leavers. Due to the interleaver, extra bandwidth resources and memory resources are required at transmitter and receiver. An elementary signal estimator with or without iteration is used at the receiver to get better performance. In PD-NOMA multiplexing is performed in the power domain. Signals from different users are superposed at the transmitter by allocating optimal power to each user and the subsequent signal is then transferred using the same subcarriers. Table 2.2 provides a summary of the types of NOMA discussed above. In this thesis, PD-NOMA-based downlink cooperative network has been used, after PD-NOMA will be referred to as NOMA throughout the dessert.

2.1.2.1 Working Principle of NOMA

Basic techniques such as superposition coding (SC) and signal interference cancellation (SIC) which are important to understand NOMA are described in brief. The super composition (SC) techniques make it possible to process the information of several users transmitted simultaneously by a single source. To implement SC, each user is allocated a power coefficient to guarantee the required preferences of systems. In the downlink scenario, SC is implemented at BS by linearly adding the signal of different users. Particularly, the BS transmits superposed signals of numerous users by selecting the transmit power coefficients for each user with a constraint on total transmitted power. In NOMA, power allocation is performed by considering two preferences of the system; users' fairness and users' Quality of service (QoS) requirements. To ensure fairness among all users, users are ordered by channel conditions; higher power levels are assigned to the users with bad channel gains and lower power is allocated to the ones with good channel gains. When it comes to guaranteeing users' QoS requirements, a cognitive radio inspired NOMA (CR-NOMA) approach is adopted. In the second scenario, users are ordered according to QoS requirements, and a power allocation scheme is designed to meet QoS requirements of all users.

At the reception, multi-user detection at the receiver is realized by SIC. Significant variations among the channel conditions of different users may exist due to the near-far effect. The main idea behind SIC is that message of each user is decoded successively. When one signal is decoded, this decoded signal is subtracted from the joint message before decoding the signal of the next user. SIC implies that when the signal of one user is decoded, the messages of other users are treated as interference, thus the signal from the rest of the users will be decoded with the advantage of having no interference from the former as it would have already been subtracted. To implement SIC, firstly, all users are ordered according to their received strength where the message of the strongest user is decoded first and subtracted from the combined signal, and weaker users are separated from the residue. Note that, in signal reception, the signal of other users is treated as interference.

For example, consider a two-user downlink NOMA network shown in Fig. 2.1, where two single-antenna users sharing the same resources, block are simultaneously served by BS. Consider user 1 (UE1) is having better channel condition than that of user 2 (UE2), i.e., $|h_1| > |h_2|$. The message of both users (s_1 and s_2) are superposed by BS by allocating appropriate power coefficient (α_1, α_2), message transferred by BS is $\alpha_1 s_1 + \alpha_2 s_2$. According to the working principle of SC, more power is allocated to the weak user, i.e., $\alpha_1 < \alpha_2$, where $\alpha_1^2 + \alpha_2^2 = 1$. At the reception, UE2 directly decodes its message considering UE1's message as interference, while UE1 employs SIC i.e., the message of UE2 is first decoded and subtracted from information received at UE1, and afterward its own message is decoded. If ρ is transmit signal to noise ratio (SNR), achievable rates at UE1 and UE2 are given as $\log_2(1 + \rho\alpha_1^2|h_1|^2)$ and $\log_2(1 + \frac{\rho\alpha_2^2|h_2|^2}{\rho\alpha_1^2|h_2|^2+1})$ respectively. From these expressions, it is evident that power allocation factors (α_1, α_2) determines system rate and fairness among users.

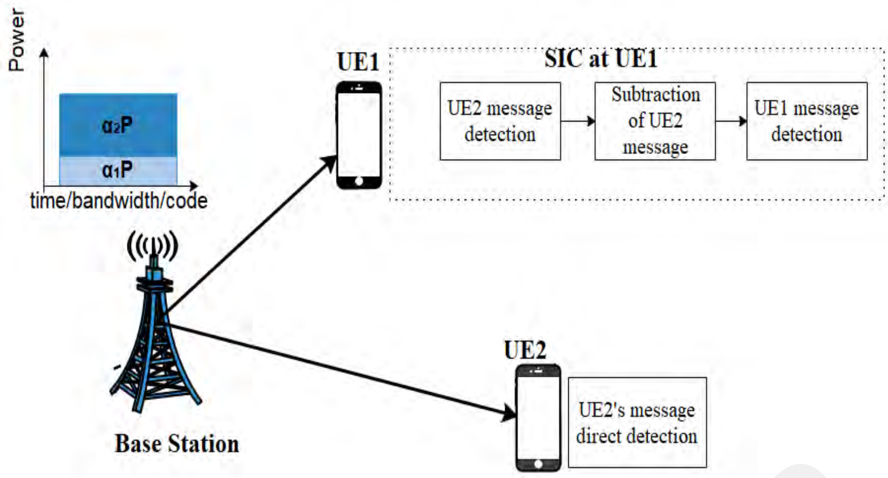


Figure 2.1: Two-User Downlink NOMA Network Illustration

Multiuser NOMA is a more general realization of the NOMA concept, where multiple users are divided into different groups. All users in a group are served by a single subcarrier using PD-NOMA approach and different groups are assigned orthogonal resources. Multi-user NOMA can be considered as a hybrid multiple access scheme, which can help in reducing system complexity. For example, if all users are assigned to the same subcarriers, SIC implies that the best user have to decode message of all users served on the same subcarriers, this may cause long delays and high complexity. The hybrid NOMA/OMA approach can give a better trade-off between system complexity and performance. In this case, system performance highly depends upon user pairing (users grouped to be served on the same subcarriers). For the fixed power allocation strategy, the highest gain over OMA can be achieved by grouping users with more distinct channel conditions (Ding, Fan, & Poor, 2016).

2.1.2.2 Research Trends in PD-NOMA

From the last few years, PD-NOMA has attracted the attention of researchers working on the requirement of 5G. As a result, many research contributions exist in this field of communication. For future cellular networks, the idea of PD- NOMA was put forward (Saito, Kishiyama, et al., 2013), and its superiority in terms of spectral efficiency and user fairness was illustrated. Performance of PD-NOMA networks was investigated for different single input single output (SISO) system models (Ding, Yang, Fan, & Poor, 2014; Saito, Benjebbour, Kishiyama, & Nakamura, 2013; Timotheou & Krikidis, 2015). The effect of user pairing on overall system performance was considered (Ding, Fan, et al., 2016). Multiple antennas systems i.e., multiple input single output (MISO) and multiple input multiple output (MIMO) can further improve the performance efficiency of NOMA networks by providing a spatial degree of freedom, and thus it is important to design NOMA for MIMO networks. With different objectives and performance metrics, NOMA based multi-antenna systems have been investigated (Chen, Ding, Dai, & Karagiannidis, 2016; Choi, 2015; Z. Ding, L. Dai, & H. V. Poor, 2016b; Zhiguo Ding & H Vincent Poor, 2016; Ding, Schober, & Poor, 2016; Yuanwei Liu, Ding, Elkashlan, & Yuan, 2016; Yuanwei Liu, Elkashlan, Ding, & Karagiannidis, 2016; Q. Sun, Han, Chin-Lin, & Pan, 2015b).

As power allocation coefficient highly affects system performance of PD-NOMA networks, the power allocation strategies for fairness and other metrics have been designed (Cui, Ding, & Fan, 2016; Lei, Yuan, Ho, & Sun, 2016; F. Liu, Mähönen, & Petrova, 2015; Otao, Kishiyama, & Higuchi, 2012; Timotheou & Krikidis, 2015). Some other applications of NOMA on which researchers have focused include resource allocation (Di, Bayat, Song, & Li, 2015; F. Liu et al., 2015; Otao et al., 2012; Saito, Benjebbour, et al., 2013; Saito, Kishiyama, et al., 2013; Shi, Yang, & Zhu, 2016; Y. Sun, Ng, Ding, & Schober, 2016), and energy efficiency (S. Han, Chih-Lin, Xu, & Sun, 2014; Q. Sun, Han, Chin-Lin, & Pan, 2015a). Additionally, several researchers have attempted to improve the performance of wireless systems by combining PD-NOMA with other technologies, such as visible light communications (Marshoud, Kapinas, Karagiannidis, & Muhaidat, 2016), wireless energy harvesting (Diamantoulakis, Pappi, Ding, &

Karagiannidis, 2016; Yuanwei Liu, Ding, Eïkashlan, & Poor, 2015), cognitive radio networks (Yuanwei Liu, Zhiguo Ding, Maged Elkashlan, & Jinhong Yuan, 2016; Zhou et al., 2018), massive machine type communication (Shirvanimoghaddam, Condoluci, Dohler, & Johnson, 2017) and ultra-dense networks (Z. Zhang, Sun, & Hu, 2017). Till this point, research issues and areas of interest in PD-NOMA have been broadly highlighted. Detailed surveys on PD-NOMA can be found in multiple review articles (Basharat, Ejaz, Naeem, Khattak, & Anpalagan, 2018; Dai et al., 2015; Ding, Lei, et al., 2017; Ding, Liu, et al., 2017; Islam, Avazov, Dobre, & Kwak, 2016; Song, Li, Ding, & Poor, 2016; Wei, Yuan, Ng, Elkashlan, & Ding, 2016). This work, however, specifically focuses on cooperation in PD- NOMA networks, which will be discussed thoroughly in the thesis and will be referred to as NOMA afterwards.

2.1.3 Applications of PD-NOMA

Due to the attractive features of NOMA, it is believed that this scheme will find applications in many upcoming wireless systems. 3GPP has launched a study on 5G radio access network in March 2016. NOMA has been proposed for the 3GPP, LTE-A standard, where it is termed as multiuser superposition transmission (MUST). In the MUST scheme, two users can be simultaneously served by using the same subcarrier frequency without any modification in the resource blocks of LTE-A ((3GPP)). Recently, the idea of NOMA has been effectively applied to next-generation broadcasting standard in US, ATSC 3.0, where it has been termed as layered-division multiplexing (LDM)(L. Zhang et al., 2016). The spectral efficiency of digital TV is enhanced by superimposing multiple streams using NOMA principle.

2.1.4 Radio Frequency Energy Harvesting (RF-EH)

Radio-frequency (RF) energy harvesting is a radiative energy transfer technique. In RF-EH radio signals, in electromagnetic radiations carry energy and information transmission. RF signals with a frequency range of 3 kHz to 300 GHz can be used as a medium of energy transmission. In this technique, signal strength in RF transmission is reduced by the reciprocal of the distance between transmitting node and receiving node. RF energy harvesting is a far-field energy transfer technique and it can be used to power a large number of devices distributed in a wide area. Effective distance for RF energy harvesting depends upon the distance between transmitter and receiver and frequency of the transmitter (Lu, Wang, Niyato, Kim, & Han, 2015). Typically, its effective area varies from several meters to few kilometers. A huge number of communication devices including tablets, smartphones, and sensor networks require a connection to the power cord to operate, which restricts true mobility. RF- EH can be a strong candidate to counter this limitation by replacing batteries with a super capacitor. However, it cannot completely eliminate the battery, but low energy consumption levels can be attained. It becomes particularly important when recharging and replacing the battered is dangerous, and difficult. SWIPT exploits the same signal for EH and signal detection. It is envisioned that deployment of SWIPT-enabled networks is a natural choice for structural health monitoring, environmental monitoring, in chemical process industries and in oil platforms (Perera, Jayakody, Chatzinotas, & Sharma, 2017).

Small supercapacitors are used for energy conversion because the charge and operate the nodes in a matter of seconds. These super capacitors, however, becomes insufficient to perform the energy-intensive tasks, such as communication. Larger capacitors may harvest the required energy, however, their charging time is large. Long charging time is troublesome for mobile users, since the communication cannot be delayed. For mobile communication, the impact of mobility and the storage capacity need to be design carefully. The approaches are advised to handle these problems are, 1) hybrid energy storage, 2) harvest-then-use and 3) task scheduling. The hybrid storage comprises of supercapacitors of different sizes. The small capacitors which charge quickly are used to operate the circuitry and perform minimal tasks, while large capacitor accumulate enough energy in high energy areas to perform the communications (Munir & Dyo, 2018). To employ harvest- then- use technique, the nodes spend specified time to harvest energy and then consume it for communication (Mekikis, Antonopoulos, Kartsakli, Alonso, & Verikoukis, 2016). The task scheduling schedules the light task which require less energy and larger tasks according to the energy storage status of the capacitors (Zhu, Zhong, He, & Zhang, 2013).

2.1.4.1 Architecture of SWIPT

RF signals carry both information and energy. Using SWIPT, the energy contained by RF signal can be harvested. SWIPT allows that the same antenna/antenna can be used for energy harvesting and information processing. However, existing information receiver architecture design cannot work for SWIPT, because the energy harvesting receiver and information processing receiver work at different power sensitivities (-60 dBm for information receiver and -10 dBm) for energy harvesting receiver. It means that signal used for energy harvesting cannot be used for information decoding, receiver architecture needs to be modified for SWIPT. Some practical solution for information receiver and energy receiver to observe the same channels and share the same receiving antenna have been proposed, among which the two most famous techniques are time switching and power splitting. In the circuitry of wireless energy, convertor diodes are involved, which are non-linear devices. However, the nonlinearity is ignored to keep the system simple. Two types of energy harvesting models are adapted in literature; linear and non-linear energy harvesting.

(a) ***Time Switching (TS) Protocol***

In TS, the receiver switches between information decoding and wireless EH modes. For a block-based transmission, in TS protocol, energy is harvested for some percentage of total transmission time (αT), and remaining time (1- α)T is used for information processing i.e., energy harvesting receiver turns on for αT time and information processing receiver works for (1- α)T time.

(b) ***Power Splitting (PS) Architecture***

Power is split into two different parts; one part is fed to the energy receiver and the other is used at the information receiver. In PS protocol a portion 'ξ' of total received power is used for energy harvesting and the remaining (1- ξ) P is used for information processing. Information receiver keeps on for the whole transmission period.

(c) ***Linear and Non-Linear Energy harvesting model***

In literature, two energy harvesting models are commonly adapted; linear and non-linear EH model. For linear EH circuitry, the conversion efficiency of EH circuitry is considered constant. The conversion is defined as the ratio of output power to input RF signal power, for the linear EH model, these input and output powers are independent. The constant conversion efficiency is assumed to lie between [0,1]. The conversion efficiency defines the conversion capability of RF- DC convertor. In literature, the linear EH model has been investigated for MIMO broadcasting channel for optimal beamforming (Shi, Liu, Xu, & Zhang, 2014; Zhang & Ho, 2013), scheduling and resource allocation of multicarrier system(Ng, Lo, & Schober, 2013), beamforming with imperfect CSI (Basar, 2019).

Although in literature, the linear EH model is widely adopted, the EH circuit is practically better characterized as a non-linear model due to the involvement of nonlinear component diode. Work in [43] deals with the design of non-linear EH SWIPT model and a significant gain over linear model was demonstrated in terms of total harvested power (Boshkovska, Ng, Zlatanov, & Schober, 2015). Recently non-linear EH model has been investigated for intelligent reflecting surfaces (Zargari, Khalili, Wu, Mili, & Ng, 2021).

2.1.5 Interference as a Source of Energy Harvesting

Interference has been a problematic feature in wireless networks. It has made wireless propagation more challenging. For decades, researchers have worked to solve the interference problems and multiple interference management techniques have been introduced. Nevertheless, some core benefits can be attained, if interference is properly utilized. Since the interfering signal carry energy and the redundant source of interference can be exploited for energy harvesting. Energy harvested through interference can be used to operate the operation of small wireless nodes.

Interference is an ever-existing challenging factor of wireless networks, which is considered a detrimental factor that affects the QoS of the transmission. Multiple techniques exist to manage the adverse effects of interference on the performance of networks including OMA, interference alignment, interference cancellation and, dirty paper. However, the fact is interference itself is RF signal, which carries both energy and information. Thus the unwanted interference can be exploited as a useful source of energy harvesting**.**

The use of interfering signal for EH is more suitable for the dense small cell networks, where a relatively large number of users coexist in small areas and interference from the nearby user is strong. To exploit interference for EH is difficult, since it needs to be removed to recover the transmitted signal. Another possible scenario to use interference for EH is from the adversarial jammer. These jammers are employed to ensure legitimate transmission and have strong transmission power. The jamming signal can be successfully used to harvest energy and managed for a legitimate user. For network security, artificial noise is generated to suppress the eavesdroppers, without having any effect on legitimate transmission. The artificial noise can be used for EH at an authentic receiver.

2.2 NOMA Assisted Cooperative Fixed Relay Networks with SWIPT

2.2.1 Basic Concept and Working Principle of C-NOMA

Among the effective concepts under consideration for 5G, involve considering wireless cooperative networks through which the receiver signal-to-noise ratio (SNR) is highly boosted over a limited distance. The cooperative transmission has particularly enticed broad interests due to its potential to increase performance as well as to ensure reliability across the wireless networks. Furthermore, NOMA, which seemingly holds a brighter future for 5G spectral competent platforms, might augment the relaying system's throughput. The spectral efficiency of NOMA can be further developed by the relaying technology to support multiple cell-edge users. In this way, it is desirable to the consider concept of cooperation in NOMA-based communication systems. Two types of cooperation in downlink scenario is possible, cooperation among NOMA user and cooperation with the help of dedicated/fixed relays.

2.2.1.1 Cooperation with Dedicated Relays

The use of dedicated relays to help NOMA users is a form of C-NOMA network. By using dedicated relays, cell edges users can be approached with greater spectral efficiency. For example, consider a scenario, where a dedicated/fixed relay helps two cell edge users. In the case of cooperative OMA, four-time slots are required for this cooperative transmission. Particularly, two slots are required for information transmission of two user from BS to relay and another two slots are needed by relay for transmitting information of two users. While NOMA requires only two-time slots, one for sending superposed information from BS to relay and the second for NOMA-based transmission from relay to two users. In the above case, the use of NOMA doubled the efficiency by reducing time slots to half. Fig. 2. 2 explains the cooperation with dedicated relays. Another positive aspect of this sort of cooperation is that the idle nodes available in wireless networks can serve as dedicated relays to improve coverage. For example, wireless networks are located at places, where they are not frequently used e.g., convention centers or sports stadiums. These idle nodes can be used as dedicated relay nodes. In this way, cost-effective and spectral-efficient communication can be realized(Ding, Lei, et al., 2017).

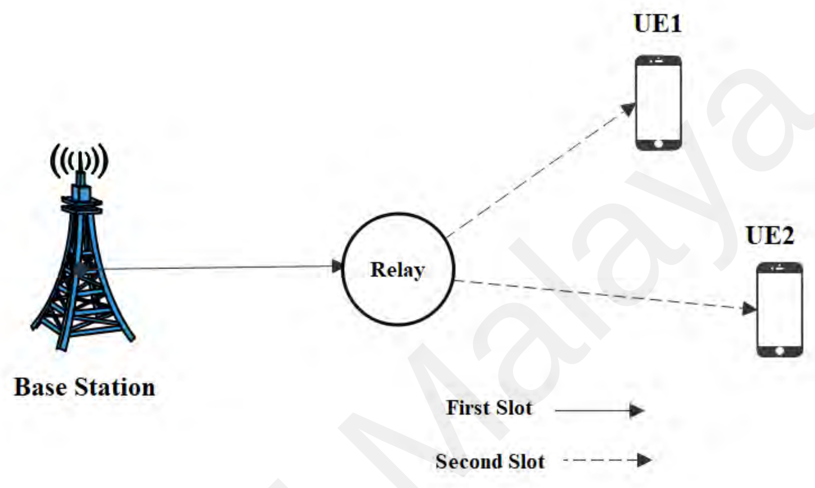


Figure 2.2: Two-User Downlink C-NOMA Network with Dedicated Relay

2.2.1.2 Performance Analysis of Dedicated Cooperative NOMA Networks

C-NOMA gives a better performance which makes it a suitable candidate for future wireless networks. In this section, we intend to present the research articles which prove the performance superiority of NOMA networks over traditional cooperative OMA. In a cellular network, the performance of C-NOMA can be evaluated using two metrics. The first situation considers the allocated quality of service (QoS) that each user needs to meet some data rate, and in this case outage probability (OP) is a suitable metric to analyze the performance. In the second scenario, data rates of users are opportunistically determined by considering channel conditions, and the performance of C-NOMA can be evaluated by ergodic capacity or ergodic sum rate. The performance of C-NOMA networks has been evaluated for different relaying protocols and system models, with different antenna configurations.

Researchers have examined the performance of C-NOMA cooperative networks against the Nakagami-*m* and Rician fading channels, which are more versatile and general fading models. C-NOMA systems considering Nakagami-*m* fading model, where the BS simultaneously connects with multiple mobile users, with the assistance of a dedicated AF relay was studied (Men, Ge, & Zhang, 2017). The comparative study of NOMA and the traditional OMA networks confirmed that NOMA is better in performance compared to the traditional OMA as it offers enhanced spectral efficiency alongside confirming the fairness among users. Similarly, the C-NOMA system, considering fixed-gain AF relaying has been studied for the Nakagami-*m* channel model, with one dedicated relay and two paired end users. In the system model, direct communication between source and destination was also considered (Yue, Liu, Kang, & Nallanathan, 2017). Outage performance and sum-rate C-NOMA network with partial CSI was investigated for both DF and AF relaying (Wan, Wen, Ji, Liu, & Huang, 2018). By considering buffer-aided relaying, concept of NOMA was investigated (Luo & Teh, 2017). During each time slot, the use of NOMA in the cooperation phase was adaptively decided by a dedicated relay node. System throughput was improved by considering this adaptive transmission.

The concept of C-NOMA was also extended to multiple antennas systems. Network with dedicated AF relay was considered, where transmits antenna selection at the BS and the maximal ratio combining (MRC) at mobile users were adopted (Men & Ge, 2015). The performance of MIMO C-NOMA for the proposed model is affected by the number of antennas and relay position. Results indicated that outage performance can be improved by increasing the number of antennas or the number of end users. C-NOMA performs better than traditional OMA relay networks only when relay node is closer to the source/BS. It is different from the traditional relay systems, where equal power is allocated to all users and optimal relay location is just in the middle of source and end-user(Lin, Huang, Luo, & Yue, 2007) whereas in NOMA, less power is allocated to near user having better channel conditions (working as relay node). In this case, the optimal the relay location is closer to the source so that high SNR can be achieved at the relay. For multiple relays, hybrid decode-forward and amplify-forward with NOMA (HDAF-NOMA) transmission scheme for a cellular system have been studied (Yang Liu, Pan, Zhang, & Song, 2016). System throughput for HD AF-NOMA schemes was studied, where the information of two sources was forward by multiple AF/DF relays. Throughput analysis indicated that the proposed HDAF gives better performance in terms of channel capacity and average system throughput, an optimal number of DF relay were also determined. Massive MIMO is a potential candidate of spectral efficiency and enhanced performance in 5G and its performance can be further enhanced by introducing NOMA-assisted AF relaying along with OFDM(D. Zhang et al., 2017).

Under the 5G standard of small cells in a macro cell environment, various users might establish direct links with the BS, though some users might remain barred. Coordinated transmission alternatively contributes to improve the spectral efficiency by realizing non-orthogonal transmission at multiple users. However, coordinated transmission requires side information for interference cancellation. In NOMA, other users' messages are attained at a user, and it can help to provide side information required for coordinated direct transmission. The researchers have focused on the ability of C-NOMA networks to accommodate coordinated and relay transmission by considering two end-users, where one user can directly communicate through BS while the other user needs assistance from the relay (Kim & Lee, 2015b). The outcome indicated that the performance might be extensively enhanced using an integrated direct and decode and forward relaying transmission. The above-mentioned coordinated direct and relaying system was also investigated with AF (Liang et al., 2017). Table 2.3 summarizes the important findings of different C-NOMA system models developed to analyze the performance of these networks.

Table 2.3: Summary of Performance Analysis of C-NOMA networks

Ref.	System Model	Relaying Protocol	Channel Model	Metrics	Inference
(Men et al., 2017)	One source, one relay and multiple users	Dedicated variable gain AF	Nakagami -*m* fading	OP Ergodic sum rate	NOMA gives better performance to the traditional OMA, additionally it ensures user fairness. Superiority of PD-CNOMA over C-OMA is independent of the location of the relay node
(Yue et al., 2017)	One BS, one relay, two paired users	Dedicated Fixed gain AF	Nakagami -*m* fading	Diversity order OP	Cooperation helps in achieving higher diversity and better outage performance.
(Wan et al., 2018)	One source, one relay and multiple users	Dedicated DF AF	Nakagami -*m* fading	OP Ergodic sum rate	When CSI is only available at system , sum rate for DF performs better than AF
(Luo & Teh, 2017)	One source, buffer aided-relay, two users	Dedicated DF	Rayleigh fading	System Throughput	System throughput of PD-CNOMA systems is improved by adaptive transmission
(Men & Ge, 2015)	Multiple antenna source, single antenna relay, multiple users with multiple antennas	Dedicated AF	Rayleigh fading	OP	Outage performance can be improved by increasing the number of antennas or the number of end users, C-NOMA performs better than traditional OMA when relay node is closer to source

Table 2.3: Continued

(Yang Liu et al., 2016)	Two sources, multiple relays and single user	Dedicated hybrid DF-AF (HDAF)	Rayleigh fading	Channel capacity	Hybrid C-NOMA schemes (HDAF-NOMA) can attain larger sum channel capacity and throughput
(D. Zhang et al., 2017)	Massive multiple antenna BS, multiple relays, multiple users	Dedicated and user relaying AF	Rayleigh fading	Capacity Sum rate	Compared to massive MIMO OMA, massive MIMO NOMA has better system performance and it can be improved when transmitting antennas grow larger.
(Liang et al., 2017)	One BS, one relay, two end user, (coordinated direct and relay transmission)	Dedicated AF	Rayleigh fading	OP	C-NOMA achieves superior coding gain over Cooperative OMA If transmit power of relay is less than BS, outage performance is improved when the relay is closer to the user which does not have direct link with BS
(Kim & Lee, 2015b)	One BS, one relay, two end user, (coordinated direct and relay transmission)	DF	Frequency-flat block-fading	OP Sum Capacity	Performance can be extensively enhanced using an integrated 'direct and decode and-forward' transmission

Cooperative networks with multiple relays can help in enhancing the signal reliability by creating a virtual antenna array. However, due to limited network resources, it is not wise to use all available nodes for relaying. By deploying multiple relays, the performance of traditional cooperative relay network is increased. Multiple relay networks provide performance gain at the expense of complexity and spectral resources. The best technique to implement cooperative diversity through multiple relaying is relay selection (RS). Through RS only one selected relay forwards the message, the spectral loss due to multiple relays does not exist. Additionally, unlike multiple relay network, a single relay operates at a time, a strict time and carrier synchronization among all relays is not required which results in reduced complexity and overhead. It is important to highlight that for practical perspective, RS is highly required to fulfil application of future networks. The best technique to implement cooperative diversity through multiple relaying is relay selection (Kim & Kim, 2010). Fig. 2.3 shows the single relay selection in multi relay C-NOMA systems.

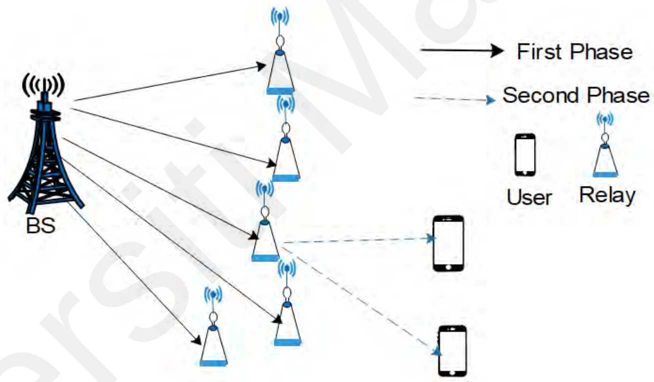


Figure 2.3: Single Relay Selection in Multi Relay C-NOMA Network

Multiple relays C-NOMA networks with relay selection have been investigated in a few research articles. Jung-Bin Kim et al.(Kim, Song, & Lee, 2016) analyzed the effect of best relay selection to maximize the sum rate of SISO system based on C-NOMA with a single source and destination. Using the partial relay selection method, the best relay can be selected using the information of only one hop. Considering AF relaying protocol, an investigation of NOMA scheme's outage performance through partial relay selection for dual hops system was conducted (Lee, Da Costa, Vien, Duong, & de Sousa Jr, 2016). The outage results indicated that at high SNR, a two-user C-NOMA system with partial relay selection does not require more than two relaying nodes. Relay selection schemes for Underlay spectrum sharing cognitive relay networks based on NOMA were presented and analyzed (Sultan, 2020). Two optimal relay selection strategies named weighted max-min(WMM) and max- weighted-harmonic mean (MWHM) with fixed and adaptive power allocation respectively, were proposed, optimal user ordering scheme based on CSI was also proposed(Xu, Yang, Ding, & Zhang, 2018). Multiple relay selection can perform better than single relay selection by limiting the spectral efficiency. Dual relay selection was proposed for C-NOMA multiple relay networks, where distributed space coding was used to deal with the loss of spectral efficiency (Zhao, Ding, Fan, Yang, & Karagiannidis, 2018). Unlike above-discussed selection schemes, where only relay selection was considered, work in (Deng, Fan, Lei, Tan, & Xie, 2017) deals with joint user and relay selection for AF C-NOMA network.

2.2.2 SWIPT Enabled Fixed Relay C-NOMA Networks

Energy efficiency is considered an important metric in designing modern communication networks. Along with improved spectral efficiency, which is the basic positive feature of NOMA, the maximization of energy efficiency is another key objective of future 5G networks, that can be attained through SWIPT. There are relatively few research articles which investigated SWIPT enabled dedicated relaying with NOMA. The effect of power allocation for downlink C-NOMA network with two users and energy harvesting dedicated relay node was studied (Yang, Ding, Fan, & Al-Dhahir, 2017). Particularly, authors investigated two types of C-NOMA networks, 1)C-NOMA with fixed power allocation (SWIPT-F-NOMA),2) cognitive radio inspired NOMA with fixed QoS requirement (CR-NOMA(F)), which guarantees data rate of the poor user and cognitive radio inspired NOMA with dynamic QoS requirements (CR-NOMA(D)) and opportunistically maximize data rate of strong user. Results reveal that outage performance of SWIPT-F-NOMA is better than SWIPT–OMA provided that data rates and power allocation coefficient are chosen correctly. For SWIPT-CR-NOMA (F) weak user shows better outage performance while outage performance of a strong user is degraded. For SWIPT-CR-NOMA (D)), the outage performance of week user is improved, while a strong user has same outage as in case of OMA. CR based C-NOMA spectrum sharing scheme with EH secondary transmitter, for both TS and PS SWIPT architecture, was proposed (Kader, Shahab, & Shin, 2017). Based on partial relay selection, a secondary transmitter, which was capable of harvesting maximum energy was selected to act as DF relay. In (W. Han, Ge, & Men, 2016), the authors investigated multiple antenna C-NOMA networks where multiple mobile users were simultaneously served by SWIPT enabled AF dedicated relay node. Antenna selection was adapted at BS and MRC was applied to mobile users.

2.2.3 Exploiting Interference in SWIPT Enabled Networks

Interference aided EH system for cooperative relay networks was studied for both PS and TS relaying schemes. The source signals and interference both were used to harvest energy at the relay node (Gu & Aissa, 2015). The authors in (Elmorshedy, Leung, & Mousavifar, 2016) studied three EH relaying protocols namely time-switching relaying (TSR), power splitting relaying (PSR) and, hybrid TSR-PSR in the presence of interference. For delay-sensitive transmission mode, the expressions for outage probability and throughput of the three mentioned protocols were derived. The impact of interference on the performance of dual hop AF relay network with two sources and EG relay was investigated (D.-T. Do & Nguyen, 2016). The work deals with performance analysis of dual hop EH relay networks in the presence of co-channel interferences considering Nakagami-*m* fading channels (Shaik & Naidu, 2019; Tran, Phan, & Vien, 2020).

A detailed review of literature related to exploiting interference for energy harvesting was provided (Zou et al., 2019). The impact of inter cell interference on outage performance of SWIPT enabled C-NOMA network with AF relaying was demonstrated (Nguyen & Do, 2018). Mathematical expressions for the coverage probability of two NOMA end-users were derived. In the presence of a single interfering signal, outage performance and sum throughput For EH based IoT relay system was studied (Rauniyar, Engelstad, & Østerbø, 2019). In this work, data of IoT relay node and source node were transmitted together using NOMA considering both TS and PS architectures for EH.

2.3 NOMA Assisted SWIPT enabled User's Cooperative Network

2.3.1 Cooperation among NOMA Users

The underlying idea of C-NOMA by user cooperation is inspired by the working principle of SIC. An important aspect of NOMA using SIC is that users with good channel conditions have prior information about the messages of other users. More specifically, in NOMA the successive detection at receiving node implies that messages of weak users are first decoded by the user whose channel condition is better. Hence, better users can exploit this redundant information by acting as relays to improve the reliability of other users who have a weak connection with BS. For example, consider a two-user downlink C-NOMA, with one BS and two end-users as shown in Fig.2.4. Downlink transmission takes place in two time slots, the direct phase and, cooperative phase. In the direct transmission phase, a superposed message of both users UE1 and UE2 ($\sqrt{P\alpha_1}s_1 + \sqrt{P\alpha_2}s_2$) is broadcasted by BS. Here channel condition of UE1 is assumed to be better, or UE1 is being considered high priority user, thus SIC is applied at UE1. According to the working principle of SIC, UE1 decodes the message of UE2, before decoding its message. During the second time slot, UE1 works as a relay and forwards the prior decoded information $\sqrt{P}s_2$ of UE2. Due to cooperation, two copies of signals are received at UE2 through different paths. This cooperation is particularly required at weak users since the throughput of the weak user is affected by interference from strong user, i.e., SNR of UE2 is $\frac{\rho\alpha_2^2|h_2|^2}{\rho\alpha_1^2|h_2|^2+1}$, where, ρ is transmit signal to noise ratio. Hence, the reliability of signal reception of users with poor channel conditions is improved by having two copies of its message.

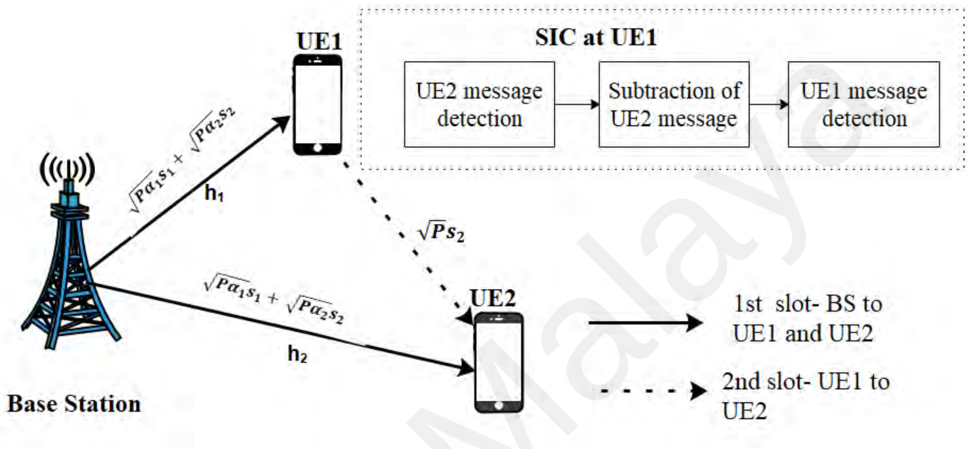


Figure 2.4: Two-User Downlink C-NOMA Network with Users' Cooperation

This cooperation is possible at the expense of extra spectral resources for cooperation. However, it can be compensated by using short-range communication channels i.e., ultra wide band and Bluetooth. Even if short range communication channels are not used, C-NOMA can achieve significant performance gain over cooperative orthogonal multiple access schemes. This superiority is because C-NOMA requires only two time slots, while cooperative OMA needs three-time slots; two slots for transmission between BS and two users, and an extra time slot is needed for the cooperative phase (Ding et al., 2015).

2.3.2 Cooperative NOMA Networks with Users' Cooperation

The concept of cooperative NOMA was proposed by Ding et al. (Ding et al., 2015), by considering a users' cooperation network with one BS and multiple users. Multiple copies received at each user were combined by maximum ratio combining

(MRC). The diversity order and outage probability attained by the proposed C-NOMA networks were investigated and the results indicated that for all users maximum diversity gain can be attained. Compared to OMA schemes, in PD-NOMA, SC and SIC are relatively complex to implement, since the strong user needs to decode the information of other users. Due to high complexity, it might not be realistic to invite all network users to contribute to C-NOMA. To lessen system complexity, the pairing of users can be an effective solution. High performance improvement over cooperative OMA can be achieved if users with more distinctive channel gains are grouped to perform C-NOMA. C-NOMA can be employed at each group and different groups can be separated by using orthogonal spectral resources.

The idea of NOMA based cooperation was employed for basic three-node relaying network in (Kim & Lee, 2015a). Asymptotic and exact rate analytical expressions were developed to analyze the performance. Analytical analysis indicated that compared to the traditional relaying with TDMA, the C-NOMA system attained more spectral efficiency when the channel gain of the source to relay (S-R) is better than the channel between relay to destination (R-D) or direct link between source to destination (S-D). The performance of three-node C-NOMA network was investigated under Rician fading channel (Jha & Kumar, 2018; Jiao, Dai, Zhang, MacKenzie, & Hao, 2017). An improved version of DF relaying, called lossy DF relaying which provides reduce complexity and better performance was investigated for C-NOMA network (He et al., 2018). Outage performance of cooperative relay system with imperfect SIC was investigated, where source participated in transmission in both direct and cooperation phase (Singh & Bansal, 2020). Users selection schemes for Underlay spectrum sharing cognitive relay networks based on NOMA were presented and analyzed (Sultan, 2020).

2.3.3 SWIPT Enabled NOMA with Cooperation among NOMA Users

By designing energy harvesting networks, the energy efficient future networks can be designed. The need of harvesting energy becomes stronger when devices cooperate to relay information. The benefits of using SWIPT in C-NOMA networks can be explained as follow; in the cooperative phase, strong user works as a relay, practically, this user may not be willing to relay the information of weaker users, because it has to consume its own battery for relaying the information. SWIPT can enable the strong user to harvest energy from the signal transmitted by the source and use that harvested energy for information relaying. As a result, the strong user will get the motivation to perform as a relay. For example, consider a scenario, where a superposed message of NOMA is transferred to near user and a far user. If far user is unable to establish direct communication with BS, the intermediate near user can help by relaying information of far user obtained by performing SIC. Without SWIPT, the near user needs to spend its energy resources for transmission, and cooperation may be avoided by this near user. However, the use of SWIPT motivates the near user to act as a relay without any hesitation. This scenario is illustrated in Fig. 2.5.

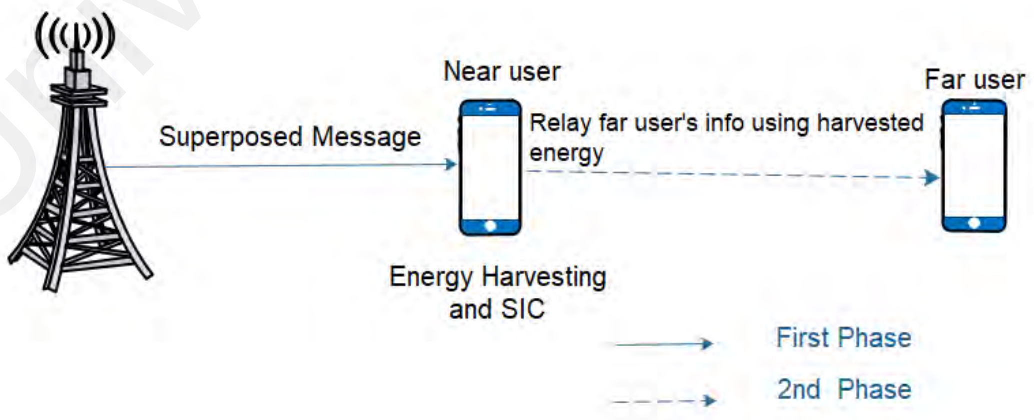


Figure 2.5: Illustration of the Motivation of Using SWIPT in PD-CNOMA Systems

This motivation has invoked researcher to explore energy harvesting in C-NOMA networks, and the following work on the coexistence of these techniques exist in literature. In SWIPT based C-NOMA networks, the location of selected relay user and far user, which participate in cooperation, can play an important role in improving throughput (Yuanwei Liu, Ding, Elkashlan, & Poor, 2016). For a single source, a cluster of near user and a cluster of far users' SWIPT enabled SISO network, outage performance was investigated for AF, DF, and hybrid AF/DF relaying, where PS architecture was adopted (N. T. Do, da Costa, Duong, & An, 2016). A best near and best far (BNBF) users were selected, where energy harvesting was performed at near user which acted as a relay. Results revealed that for BNBF scheme, diversity order depends on the number of far users only, and it is independent of the number of near users.

In EH system, the choice of multiple antennas at source or relay can increase energy transfer efficiency and spectral efficiency. An energy harvesting-based C-NOMA system with multiple antennas' source, relay, and single-antenna destination was considered, where a direct link between source and destination was not present (R. Sun, Wang, Wang, & Zhang, 2016). To maximize the rate at the relay node, authors jointly designed transmitter beamforming, receiver filter design, and power splitting ratio, with a constraint on transmitted power of source and QoS of destination. Performance of a similar system, in the presence of a direct link between source and destination, was also investigated (Ashraf, Shahid, Jang, & Lee, 2017). Antenna selection for MISO PD-CNOMA system, with hybrid PS/TS SWIPT architecture was investigated (T. N. Do, da Costa, Duong, & An, 2018). A downlink communication network, combining SWIPT, beamforming, and full-duplex was studied (Alsaba, Leow, & Abdul Rahim, 2018). For a two-user, full-duplex NOMA network with an energy harvesting relay node, expressions of outage performance and ergodic capacity were derived (Toan, Hoang, Duy, & Dung, 2020).

2.3.4 Spatially Distributed Users

Terminal distribution of nodes is important in evaluating the performance of cooperative networks. Mostly the inter-nodes distance is considered a constant value which manifests in the signal path loss. This consideration is particularly impractical when users cooperate for relaying, since relaying-users cannot be available at a fixed distance. A more practical assumption is to reflect all the source-relay and relay-user distances as random quantities. Most of the existing literature on performance analysis of NOMA either completely ignores or only implicitly take into account the effect of nodes/users distribution. This simplest approach by ignoring the distribution of users may not be always applicable. The reason is that the assumption of fixed distance does not provide any analytical description of inter-node distances, and subsequently, path losses.

Following research work considered the users' distribution; the performance of cellular downlink system with multiple randomly deployed users served by NOMA was first investigated by Ding et al.(Ding et al., 2014). For SWIPT based cooperative NOMA network, the outage performance of randomly deployed groups of near and far users was investigated (Yuanwei Liu, Zhiguo Ding, Maged Elkashlan, & H. Vincent Poor, 2016). The authors proposed three near and far user selection schemes based on the location of near and far users. For C-NOMA networks with spatially distributed relays, two relay selection schemes namely single stage and two-stage relay selection were proposed, where relays were capable of working in half-duplex and full-duplex (Yue, Liu, Kang, Nallanathan, & Ding, 2018). In the mentioned work (Ding et al., 2014; Yuanwei Liu, Zhiguo Ding, Maged Elkashlan, & H. Vincent Poor, 2016; Yue et al., 2018) on NOMA based randomly deployed uses, the analytical framework was developed using the quadrature method. These methods involve the impact of parameters on the overall performance. Recently, novel analytical expressions for the generalized fading channel were developed for NOMA based downlink cellular networks with the randomly located user (Papanikolaou, Karagiannidis, Mitsiou, & Diamantoulakis, 2020).

2.4 New Relay Selection Scheme for SWIPT Enabled Cooperative Network

Relay selection technique in multiple relay cooperative communication networks is a simple and effective way to improve spectral efficiency and avail advantages of space diversity. For conventional multi-relay cooperative networks, partial relay selection and opportunistic (max-min) relay selection protocols have been commonly adopted. Partial relay sections consider the selection based on the best available single link. Opportunistic relay selection which elects the relay with the strongest instantaneous end-to-end channel has been considered more diversity optimal. Partial relay selection is a less complex selection scheme compared to opportunistic relay selection since it requires the channel state information (CSI) of both hops (i.e., channel conditions between S-R and R-D). Using the partial relay selection method, the best relay can be selected using the information of only one hop. Since for EH enabled networks and C-NOMA, existing relay selection schemes cannot be always optimal. Some novel relay selection schemes were proposed for SWIPT enabled relaying and C-NOMA networks. In the following subsections a survey of existing research contributions for relay selection schemes in SWIPT enabled cooperative networks, C-NOMA networks and SWIPT enabled C-NOMA networks is provided.

2.4.1 Relay Selection in SWIPT Enabled Multi Relay Networks

Outage performance of multiple relay cooperative networks where relays were equipped with finite battery was studied (K.-H. Liu, 2016). A new relay selection scheme based on both the battery status and channel information was proposed. Moreover, a new time structure to enable the proposed schemes was defined, it considered the feedback overhead and training time for relay selection. The same authors provided a new relay selection scheme, named selected-max min (S-MMRS) for EH relaying network (K.-H. Liu & Kung, 2017). To improve the effective transmission time a full-duplex time structure was proposed. By taking into account channel estimation error an energy constraint two-way relaying network was investigated (Y. Zhang, Ge, Men, Ouyang, & Zhang, 2016). The authors provided outage analysis and joint relay selection and optimal power allocation factors to minimize the overall outage. Illuminating research was conducted on SWIPT enabled general cooperative networks with multiple source destination pairs (Zhiguo Ding & H. Vincent Poor, 2016). For the special case of single source–destination pair the scheduling problem was similar to relay selection. It was revealed that max-min criteria losses diversity gains for EH networks. Work by (Wang, Zhang, Cheng, Yang, & Chen, 2017) considered PS based full duplex multiple relay network, where relay selection was performed to minimize the outage probability and maximize the sum capacity.

The outage analysis of SWIPT enables multiple relay cooperative system was provided (Xia, Li, & Lu, 2019). The optimal power allocation/power splitting parameter and relay selection based on statistical and perfect channel conditions were proposed. Firstly, the relays with correct detection of user's message were selected and among those, the node with the best relay to source channel was chosen. The results demonstrated the superiority of the proposed scheme over max-min relay selection**.** A dual-hop cooperative communication system with SWIPT enabled multiple relays network was investigated where partial relay selection method was practiced to best relay (Hoang, Nguyen, Tran, & Dung, 2020). The main contribution was to provide mathematical expression of outage probability for Nakagami–*m* fading channel for both integer and non-integer values of fading parameter m. optimal time switching parameter which minimized the outage probability was also derived.

2.4.2 Relay Selection in C-NOMA Networks

Multiple relays C-NOMA networks with relay selection have been investigated in a following research article. Jung-Bin Kim et al.(Kim et al., 2016) analyzed the effect of best relay selection to maximize sum rate of SISO system based on PD-CNOMA with a single source and destination. Expressions for an approximated average rate of the proposed scheme were derived by considering Rayleigh fading channels. Numerical results indicated that a higher rate gain can be achieved by NOMA-based best relay selection system compared to conventional best relay selection when the number of relay nodes is large. Considering AF relaying protocol, an investigation of NOMA scheme's outage performance through partial relay selection for dual hops system was conducted (Lee et al., 2016). The outage results indicated that at high SNR, a two-user PD-CNOMA system with partial relay selection does not require more than two relaying nodes.

For DF relaying, a novel two-stage max-min RS scheme was proposed for C-NOMA and its superiority over traditional max-min RS was shown by Ding et al. (Z. Ding, H. Dai, & H. V. Poor, 2016a). Work in (Yang, Ding, Wu, & Fan, 2017), deals with two-stage RS in C-NOMA networks for both AF and DF relaying NOMA networks with adaptive power allocation factors. Two optimal relay section schemes based on two-stage RS, termed as weighted max-min and max- weighted-harmonic mean with optimal user ordering were proposed (Xu et al., 2018). Two-stage dual RS strategies for C-NOMA with AF relaying and space-time block code were proposed (Zhao et al., 2018). In (Deng et al., 2017), joint user and RS scheme for AF C-NOMA network was studied. For C-NOMA networks, two-stage RA schemes with relays capable of working in half-duplex and full-duplex network were investigated (Yue et al., 2018). For physical-layer security of C-NOMA networks, a two-stage RS scheme was proposed to maximize the capacity while ensuring secure transmission in the presence of eavesdroppers (Feng, Yan, Liu, Yang, & Yang, 2019). For multiple C-NOMA networks, the effect of channel correlation on outage performance of three-stage RS scheme was studied (Zou et al., 2019). Briefly, two-stage RS scheme has shown the performance gain over conventional relay selection schemes in C-NOMA networks.

2.4.3 Relay Selection in SWIPT Enabled C-NOMA Networks

Relay selection has been frequently adapted for C-NOMA networks, and its effectiveness in terms of spatial efficiency and diversity was proven. However, very few research articles considered relay selection for energy harvesting C- NOMA networks. SWIPT enabled multi/single relay C-NOMA network in the presence of direct link was studied (Ha & Nguyen, 2017). Expression for outage probability for partial relay selection was provided. Outage probability and ergodic capacity were evaluated for multi relay C-NOMA network with partial relay selection criteria. The authors also investigated the impact of perfect and imperfect SIC on the outage and ergodic performance of the network. (Hoang, Tan, Hoang, & Hiep, 2018).

The impact of imperfect CSI and hardware impairment on the performance of multi-AF relay C-NOMA network with EH relays were investigated (X. Li et al., 2018). Partial relay selection protocol was employed to forward the message of two end-users. The results revealed that the outage performance is degraded with power channel estimation quality and hardware impairments. It was also concluded that the negative effect of imperfect channel and hardware impairments can be compensated by using multiple relays. Secrecy outage probability of SWIPT enabled untrusted multi relays C-NOMA network was provided (Le & Kong, 2019). For evaluation imperfect SIC was considered and partial relay selection considering both best first link and the best second link was used. For multiple relay network with multiple users, the error rate performance of SWIPT enables AF relaying network was considered (S. Li et al., 2020). Exact analytical expressions of error probability were derived, while the best relay was selected based on partial relay selection criteria. Table 2.4 Summarize the existing literature on SWIPT enabled C-NOMA networks.

Table 2.4: Relay Selection in SWIPT enabled C-NOMA Networks

Ref.	System Model	SWIPT/ Relaying Protocol	Relay Selection Technique	Performance metric
(Ha & Nguyen, 2017)	Source, multiple relays, two end users	PS/ DF	Partial relay Selection	Outage probability
(Hoang et al., 2018)	Source, multiple relays, two end users	TS DF	Partial relay Selection	Outage probability Ergodic capacity
(X. Li et al., 2018)	Source, multiple relays, two end users	PS AF	Partial relay selection	Outage probability
(Le & Kong, 2019)	Source, multiple relays, two end users	PS AF	Partial relay selection	Secrecy outage probability
(S. Li et al., 2020)	Source, multiple relays, multiple end users	PS AF	Partial relay selection	Error Probability

2.5 Motivation

The mentioned literature elucidated the existing research on multiple relay cooperative networks with SWIPT. SWIPT has been thoroughly investigated for wireless cooperative networks which involved orthogonal multiple accessing. NOMA is the recent multiple accessing technique, which serves multiple users over the same time and frequency resources. Therefore, the structure and enabling techniques of SWIPT enabled cooperative networks with orthogonal multiple access cannot be applied to SWIPT enabled C-NOMA networks. SWIPT with NOMA brings new challenges, and new techniques are required to design these networks. This work is designed after identifying the research gap in SWIPT enabled cooperative NOMA networks.

CHAPTER 3: METHODOLOGY

3.1 Introduction

To explain the methods adapted to achieve the goals of this research work, this chapter provides all the necessary details about simulations and analytical details. System models, channel models, and assumptions are explained in detail first. The available energy at relay node does not remain constant as harvested energy is used to enable the relay node. The random nature of wireless medium makes the energy random. This randomness makes the analysis of the system difficult. The energy harvesting model and amount of harvested energy will be illustrated in this chapter. Afterward mathematical steps to obtain closed-form expressions are provided. Simulation parameters to obtain results will be listed.

3.2 SWIPT Enabled Multi Relay C-NOMA Networks in Presence of Interference

The concept of cooperation in compunction system has been beneficial in wireless networks for many years. Cooperation provides multiple advantages, i.e., performance efficiency, reliability, extended coverage area, and less transmission power. As NOMA is a proven spectral efficient multiple access technique. Combining NOMA with cooperation can provide spectrally efficient and reliable communication network. C-NOMA with dedicated relays has been explained in section 2. 2.1.

The dedicated relay node might be energy-constrained, in this scenario a possible cooperative network can be regulated by enabling the relay nodes with RF signals using SWIPT. The motivation for dedicated relay nodes is that in wireless networks multiple idle nodes might be available such as networks in stadiums or convention centers. These idle nodes might not be active most of the time, and thus cannot be used to improve system coverage. SWIPT enables these nodes to operate by harvesting energy and help in transmission. When a cluster of nodes is present at one location, a relevant issue is to select the best node to operate as a relay.

With a remarkable increase in the number of devices and advancement of access techniques, multiple users can communicate over shared access networks. However, the use of shared resources brings in the unwanted signal, termed as interference. Thus the fundamental challenge to future generation wireless 5G networks and beyond, is to implement interference management mechanisms. In wireless communication, interference management has been considered a big challenge. System performance is degraded due to interference. On the other hand, the interfering signal also carries energy and information, and thus it could be considered a potential source of energy harvesting.

The impact of interference in SWIPT enabled multi-relay C-NOMA networks is undetermined. This work aims to utilize both useful and unwanted interfering signals to harvest energy. The performance of relay selection in downlink SWIPT enabled multi relay C-NOMA network is analyzed by evaluating outage probability when the cluster of relay nodes suffer from external interference. In the proposed system, relay node is expected to be energy-constraint, and it is powered by harvesting energy from source and interfering signals.

3.2.1 System Model

A wireless downlink, NOMA based relay network with a source (S), energy-constrained ‘M’ relay nodes (R_1, R_2, …R_M) and two end-users (U_1 and U_2) is considered. It is assumed that direct link between source and users does not exist and all data is transmitted with the help of a single selected relay node. All nodes are assumed to be equipped with a single antenna and work in half-duplex mode. Relay nodes are affected by some external interferers. The channel coefficient between each interferer and relay is modeled as Rayleigh fading channel. The relays are not equipped with power source and they harvest energy from the interfering signals and RF signal received from source using PS SWIPT protocol. The amount of harvested energy at relay is improved due to the presence of interfering signal. System model is explained in Fig. 3.1.

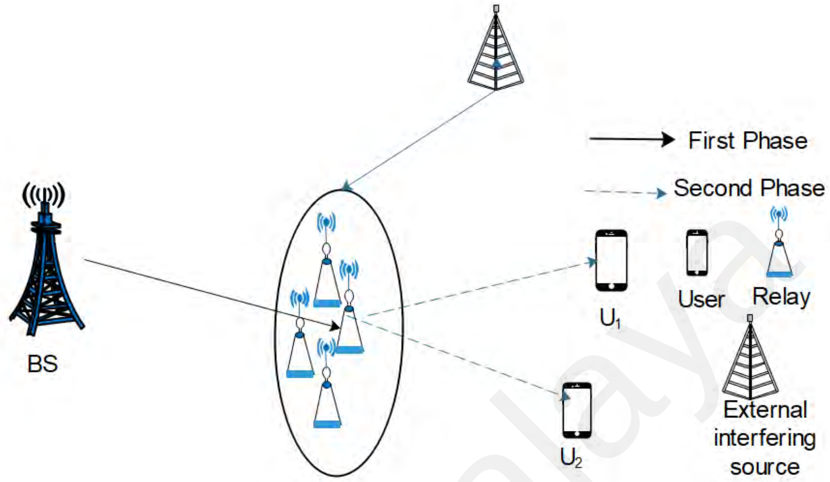


Figure 3.1: Downlink Multi-Relay C-NOMA Network in the Presence of Interference

TS mode of SWIPT is comparatively simpler to implement, however, it is proven theoretically that it achieves superior tradeoffs between harvested energy and transmission rates. Additionally, TS mode requires strict time synchronization, receivers need to adjust their switching function according to the time shared by transmitter. Therefore, PS mode is practically more suitable and it gained more attention from researchers working on SWIPT. For this reason, this work considers PS relaying mode. Transmission takes place in two time phases; half of the block time ($T/2$) is used for source to relay information transmission and half time ($T/2$) is used for relay to destination information transmission. In first half total transmitted power is divided in two parts, $\xi P_s : (1-\xi)P_s$, where $0< \xi < 1$,the fraction of power ξP_s is used for energy harvesting and remaining $(1-\xi)Ps$ is used for information transmission. Use of power splitting relaying protocol for energy harvesting at relay node employs a power splitter that divides the received signal for energy harvesting and information processing. Signal is divided in ξ : 1-ξ proportion where 0< $\xi < 1$, such that fraction of signal ξy_r^n is used for energy harvesting and remaining $(1 - \xi)y_r^n$ is used for information transmission. The system model and important parameters for energy harvesting and information processing are explained in Fig. 3.2.

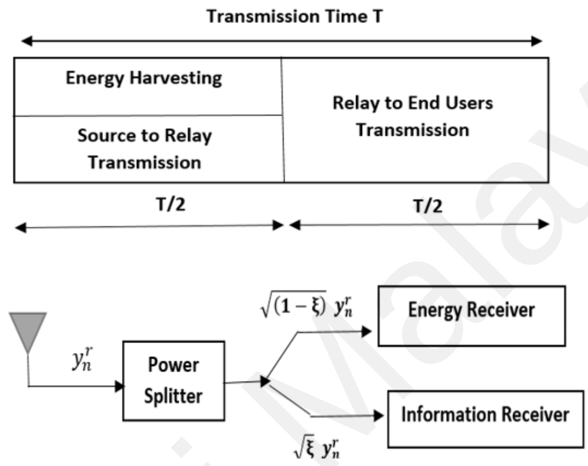


Figure 3.2: Illustration of the PS Relaying Protocol

3.2.2 SNR Expressions for End Users

The superimposed message at source is given as $x = \sum_{i=1}^{2} \alpha_i\, x_i,$ where α_1, α_2 are power allocation factors. Power allocation is being made according to QoS requirement, i.e, more power is allocated to the user with high priority. This allocation method is preferred since it reduces the complexity by omitting the need to estimate the channel condition for end users. Additionally, if channel conditions of NOMA users are not very distinctive, the user with high priority is allocated more power. Considering U_1 has high priority user with less data rate requirement, more power is allocated to U_1 , i.e., $\alpha_1 > \alpha_2$ and $\alpha_1 + \alpha_2 = 1$. Assuming relay is using PS relaying protocol for of SWIPT with power splitting factor ξ . During the first phase, message received at any relay n 'R_n' is given as;

$$y_n^r = \sqrt{\frac{(1-\xi)P_s}{1+d_R^m}} \sum_{i=1}^{2} \sqrt{\alpha_i}\, x_i g_n' + (1-\xi) \sum_{i=1}^{L} P_i x_i h_{i_n} + w_n^r, \tag{3.1}$$

where P_s is the transmit power, d_R is the distance between source and relays; it is assumed that all relays are located in close proximity and thus their distance from source is almost same (this assumption is same as (Ding, Dai, et al., 2016a; Xu et al., 2018; Yang, Ding, Wu, et al., 2017)), m is path loss exponent, g_n is the Rayleigh fading channel coefficient between the S to relay R_n, and channel gain $|g'_n|^2$ is exponential with parameter λ_g, w_n^r is additive white Gaussian noise (AWGN) at R_n with zero mean and variance N_0. Note that this noise is due to baseband signal conversion at relay. We assume that interfering sources are located in close area and thus they are equidistant from the cluster of relay.

Let's consider message of U_1 is decoded first at R_n, and message of U_2 is decoded after employing SIC. So, the rates at R_n to decode x_1 and x_2 are given as;

$$R_1^n = \frac{1}{2}\log_2\left(1 + \frac{(1-\xi)P_s\alpha_1|g_n|^2}{(1-\xi)P_s\alpha_2|g_n|^2 + (1-\xi)\sum_{i=1}^{L} P_i|g_i|^2 + N_0}\right). \tag{3.2}$$

Where $g_n = \frac{|g_n'|}{\sqrt{1+d_R^m}}$, If SIC is performed successfully, i.e., x_1 is decoded successfully at relay, achievable rate of U_2 is given as;

$$R_2^n = \frac{1}{2}\log_2\left(1 + \frac{(1-\xi)P_s\alpha_2|g_n|^2}{(1-\xi)\sum_{i=1}^{L} P_i|g_i|^2 + N_0}\right), \tag{3.3}$$

where factor ½ in (3.2) and (3.3) comes from the fact that half of the transmission block time is used for source to relay transmission. If relay 'R_n' is selected for transmission, message received at user U_k, k=1,2 is given as;

$$y_k^d = \sqrt{\frac{P_r^n}{1+d_k^m}} \sum_{i=1}^{2} \sqrt{\alpha_i}\, x_i h_{nk}' + w_k^d, \tag{3.4}$$

where P_r^n is transmit power of relay R_n, $h_{nk} = \frac{h'_{nk}}{\sqrt{1+d_k^m}}$ is channel between R_n and user k,

Note that due to NOMA, U_1 contains the interference from U_2, Achievable rate at U_1 is given as;

$$R_1^1 = \frac{1}{2}\log_2\left(1 + \frac{\alpha_1 P_r^n |h_{n1}|^2}{\alpha_2 P_r^n |h_{n1}|^2 + N_0}\right), \tag{3.5}$$

where $h'_{nk} = \frac{h'_{nk}}{1+d_k^m}$ .After successful SIC, rate at U_2

$$R_2^2 = \frac{1}{2}\log_2\left(1 + \frac{P_r^n \alpha_2 |h_{n2}|^2}{N_0}\right). \tag{3.6}$$

Successful SIC employs successful detection of x_1 at U_2

$$R_{1\to 2}^2 = \frac{1}{2}\log_2\left(1 + \frac{P_r^n \alpha_1 |h_{n2}|^2}{P_r^n \alpha_2 |h_{n2}|^2 + N_0}\right) \geq R_1. \tag{3.7}$$

3.2.2.1 Energy Harvesting Model

This work assumed the linear energy harvesting model to avoid the complexity. A linear EH model assumes constant RF-to-direct current (DC) power conversion and it is also assumed to be independent of the input power of the energy harvester. However, practically the energy harvester works in nonlinear mode and there is a possibility that the nonlinear model may not characterize the practical energy harvester. The derived analytical model of this research can be extended for the nonlinear energy model.

The power harvested at energy harvesting receiver of R_n is $P_R^n = \eta\xi(P_s|g_n|^2 + \sum_{i=1}^{L} P_i|g_i|^2)T/2$, where $0 < \eta < 1$ is conversion efficiency which depends on energy harvesting receiver circuitry. Since transmission time for relay in PS relaying protocol is T/2, the transmission power of relay is given as;

$$P_r^n = \eta\xi(P_s|g_n|^2 + \sum_{i=1}^{L} P_i|g_i|^2) \tag{3.8}$$

3.2.2.2 Relay Selection Criteria

Partial RS requires the channel state information (CSI) of single hops (i.e., channel conditions between S-R or R-D), and therefore this scheme reduces system complexity. Using partial RS method, the best relay can be selected using best S-R link. This selection ensures maximum harvested energy and detection of source signal at relay. Mathematically, the best relay is given as follow;

$$n^* = \arg \max_{n \in \{1.,\dots,M\}} \{|g_n|^2\} \tag{3.9}$$

3.2.2.3 Fading Model of Channels

The CDF of source to relays and relay to end-user links for selected relay i.e., $|g_n|^2, |h_{n,1}|^2$ and $|h_{n,2}|^2$ is given as $F_{|g_n|^2}(x) = \left(1 - e^{-\lambda_g x}\right)^M = \sum_{n=1}^{M} \binom{M}{n} (-1)^n e^{-n\lambda_g x}$, $F_{|h_{n,1}|^2}(x) = (1 - e^{-\lambda_1 x})$, and $F_{|h_{n,2}|^2}(x) = (1 - e^{-\lambda_2 x})$ respectively. The pdfs of $|g_n|^2, |h_{n,1}|^2$ and $|h_{n,2}|^2$ are $f_{|g_n|^2}(x) = \sum_{n=1}^{M} \binom{M}{n} (-1)^{n-1} n\lambda_g \, e^{-n\lambda_g x}$, $f_{|h_{n,1}|^2}(x) = \lambda_1 e^{-\lambda_1 x}$, $f_{|h_{n,2}|^2}(x) = \lambda_2 e^{-\lambda_2 x}$ respectively. The channel gains of interfering channels are independent and exponentially distributed with parameter λ. Interference $X_I = \sum_{i=1}^{L} |g_i|^2$ with $\lambda_1 = \lambda_2 \dots = \lambda_i$ follows the distribution $f_{X_I}(x) = \frac{\lambda_i^L}{\Gamma(\mathrm{L})} x^{L-1} \, e^{-\lambda_I x}$.

3.2.3 Performance Evaluation

3.2.3.1 Outage at U1

U_1 will be in outage if following events occur, 1) x_I is not decoded at selected relay node, or (2) Relay can decode x_I but it is not decoded at U_1

$$P_1 = \Pr(R_1^n < R_1) + \Pr(R_1^n > R_1, R_1^1 < R_1), \tag{3.10}$$

$$P_1 = \Pr(\frac{(1-\xi)P_s\alpha_1|g_n|^2}{(1-\xi)P_s\alpha_2|g_n|^2 + (1-\xi)\sum_{i=1}^{L} P_i|g_i|^2 + N_0} < \epsilon_1) +$$

$$\Pr\left(\frac{(1-\xi)P_s\alpha_1|g_n|^2}{(1-\xi)P_s\alpha_2|g_n|^2+(1-\xi)\sum_{i=1}^{L} P_i|g_i|^2+N_0} > \epsilon_1, \frac{\alpha_1\eta\xi(P_s|g_n|^2+\sum_{i=1}^{L} P_i|g_i|^2)|h_{n1}|^2}{\alpha_2\eta\xi(P_s|g_n|^2+\sum_{i=1}^{L} P_i|g_i|^2)|h_{n1}|^2+N_0} \leq \epsilon_1\right) \quad (3.11)$$

Theorem 1: The outage probability of U_1 is given by

$$P_1 = 1 - \lambda_I^L \lambda_1 \sum_{n=1}^{M} \binom{M}{n} \frac{(-1)^{n+1}}{\left(\lambda_I - \frac{n\rho_I\lambda_g}{\rho_S}\right)^L} \sqrt{\frac{4nC_2\lambda_g}{\rho_S\lambda_1}}\, K_1\sqrt{\frac{4nC_2\lambda_g\lambda_1}{\rho_S}} \quad , \quad (3.12)$$

where $\epsilon_1 = 2^{R1-1}$, $\rho_S = \frac{P_S}{N_0}$, $\rho_I = \frac{P_I}{N_0}$, $and\ C_2 = \frac{\epsilon_1}{\eta\xi(\alpha_1 - \alpha_2\epsilon_1)}$.

Proof: Refer to Appendix A.

3.2.3.2 Outage at U2

User 2 will be in outage if following events occur, 1) relay cannot perform SIC or decode message of U2, 2) U2 performs SIC successfully but U2 cannot detect message of its own.

$$P_2 = \Pr(R_{1\to2}^n < R_1, R_2^n < R_2) + \Pr(R_{1\to2}^n > R_1, R_2^n < R_2, R_{1\to2}^2 < R_1, \mathrm{R}_2^2 < \mathrm{R}_2) \quad (3.13)$$

$$P_2 = \Pr\left(\frac{(1-\xi)P_s\alpha_1|g_n|^2}{(1-\xi)P_s\alpha_2|g_n|^2+\sum_{i=1}^{L} P_i|g_i|^2+N_0} < \epsilon_1, \frac{(1-\xi)P_s\alpha_2|g_n|^2}{\sum_{i=1}^{L} P_i|g_i|^2+N_0} < \epsilon_2\right) + \Pr(\frac{(1-\xi)P_s\alpha_1|g_n|^2}{(1-\xi)P_s\alpha_2|g_n|^2+\sum_{i=1}^{L} P_i|g_i|^2+N_0} >$$

$$\epsilon_1, \frac{(1-\xi)P_s\alpha_2|g_n|^2}{\sum_{i=1}^{L} P_i|g_i|^2+N_0} > \epsilon_2, \frac{\alpha_1 P_r^n|h_{n2}|^2}{\alpha_2 P_r^n|h_{n2}|^2+N_0} \leq \epsilon_1, \frac{\alpha_1 P_r^n|h_{n2}|^2}{N_0} < \epsilon_2) \quad (3.14)$$

Theorem 2: The outage probability of U_2 is given by

$$P_2 = \lambda^L \sum_{n=1}^{M} \binom{M}{n} (-1)^{n+1} \left(\frac{1}{\left(\lambda_I + \frac{n\lambda_g C C_3}{\rho_s}\right)^L} e^{-\frac{n\lambda_g C_3}{\rho_s}} + \frac{1}{\left(\lambda_I - \frac{n\rho_I \lambda_g}{\rho_s}\right)^L} \sqrt{\frac{4nC_4\lambda_g\lambda_2}{p_s}}\ K_1\sqrt{\frac{4nC_4\lambda_g\lambda_2}{\rho_s}} - \right.$$

$$\left. \frac{1}{\left(\lambda_I + \frac{n\lambda_g C C_5}{\rho_s}\right)^L} e^{-\frac{n\lambda_g C_5}{\rho_s}} \right), \tag{3.15}$$

where $C_3 = \min\left(\frac{\epsilon_1}{(\alpha_1-\alpha_2\epsilon_1)(1-\xi)}, \frac{\epsilon_2}{\alpha_2(1-\xi)}\right)$, $C_4 = \min\left(\frac{\epsilon_1}{(\alpha_1-\alpha_2\epsilon_1)\eta\xi}, \frac{\epsilon_2}{\alpha_2\eta\xi}\right)$ and $C_5 = \max(\frac{\epsilon_1}{(\alpha_1-\alpha_2\epsilon_1)(1-\xi)}, \frac{\epsilon_2}{\alpha_2(1-\xi)})$.

Proof: Refer to Appendix B.

3.2.4 Sum Throughput of System

For delay-limited transmission mode, system throughput is measured by determining the outage probability at a fixed source transmission rate (bits/s/Hz). Mathematically, $R = \log_2(1+\gamma_0)$, where γ_0 is required received SNR for correct detection. Given that R_1 and R_2 are transmitting data rate for U_1 and U_2 and T/2 is transmission time for a block of time T, the sum throughput of system is given as

$$\tau = \frac{(1-P_1)R_1}{2} + \frac{(1-P_2)R_2}{2}, \tag{3.16}$$

where P_1 and P_2 can be calculated from (3.12) and (3.15).

3.2.5 Simulations Parameters

This section presents the simulation setup to corroborate the analytical theoretical model. Rayleigh fading model has been used to realize the actual fading environment. The path loss exponent (*m*) is set as 3.67, which is a suitable value for line-of-sight (LOS) of rural environment. BS is set to be located at origin of the cell with coordinates (0,0). Simulations results have been obtained by using 10^5-10^6 realizations of exponential channels $|g_n|^2$, $|h_{n,1}|^2$ and $|h_{n,2}|^2$.Table 3.1 summarizes all the simulations parameters set to obtain the results in chapter 4.

Table 3.1: Simulation Parameters

Parameters	**Value**
Number of Monte Carlo Simulations	10^5
Range of Transmit Power (P_s)	20-50 dBm
Power allocation factors for U_1 (α_1)	0.8
Power allocation factors for U_1 (α_2)	0.2
Energy harvesting efficiency η	40%
Power Splitting factor/Ratio ξ	0.5
Noise Variance N_0	-50 dBm
Coordinates Of Source(O) , Cluster Of Relay(0,x_R), Users U_1 And U_2	(0,0), (5,0), (10, 5),(10,-5)
Normalized Distances Between Source And Relays, And Relay To End User (meter)	$d = \|x_R\|, d1 = \sqrt{(10 - x_R)^2 + 5^2}, and\ d2 = \sqrt{(10 - x_R)^2 + (-5)^2},$
Distance between relay and external interfering source d_i	5 meter
Channel Parameters for S-R, ($\|g_n\|^2$)	$\lambda_g = d^{-m}$
Channel Parameters for R-U_1 ($\|h_{n1}\|^2$)	$\lambda_1 = d_1^{-m}$
Exponential Channel for R-U_2 ($\|h_{n2}\|^2$)	$\lambda_2 = d_2^{-m}$
Interference power (P_i) range	0-10 dBm

3.3 Performance Analysis of SWIPT Enabled Multiple Relay Cooperative Networks with Spatially Random Users in the Presence of Interference

3.3.1 Introduction

The objective of the research is to investigate the RF energy harvesting based cooperative NOMA networks with cooperation among spatially distributed NOMA users in the presence of interference. The closed-form expression of outage probability for NOMA relay user and end user are derived by considering signal-to-interference-plus-noise ratio (SINR). To the best of our knowledge spatial impact of dynamically distributed NOMA users in the presence of interference has not been investigated for the SWIPT assisted cooperative NOMA networks. Motivated by this, the locations of near relay users and end-users are modeled by invoking the uniform distribution. Through this work, it is intended to investigate the impact of harvested energy and overall outage performance due to interfering signal and users' spatial distribution.

3.3.2 System Model

Considering a downlink EH cooperative NOMA system with one BS, two groups of randomly deployed near users and a cell edge users. M nears users are uniformly distributed within a disk D_R with radius R_R and far user is distributed within ring D_U within radius R_{U_1} and $R_{U_2}$and the BS is located at the origin of both discs. Complexity of NOMA systems is reduced by dividing all users into several orthogonal groups and NOMA is implemented on each group. It is assumed that the one random cell edge user is grouped with one selected near user. BS broadcasts the combined message of each uniformly distributed near user and one cell edge use 'U' using same frequency resources(over the same channel) using NOMA.

The DF protocol is employed at near user. One user form disk is selected to assist BS in conveying the information to one cell edge user U. Near user which act as relay is affected by L external interferers. Amount of harvested energy at relay is improved due to presence of interfering signal. The channel co-efficient between each interferer and relay is modeled as Rayleigh fading channel. Fading channels between BS to near user, BS to end-user and relay to end-user are modeled as Rayleigh fading channel. Moreover, all channels are independent and identically distributed. Fig. 3.3 illustrates the system model.

Transmission takes place in two time phase; first half of block time (*T/2*) is used for source to end user direct transmission and source to relay information transmission energy harvesting and remaining time (*T/2*) is used for relay to destination information transmission. In first half total transmitted power is divided in two parts, ξP_s : $(1-\xi)P_s$, where $0< \xi < 1$, fraction of power ξP_s is used for energy harvesting and remaining $(1 - \xi)Ps$ is used for information transmission.

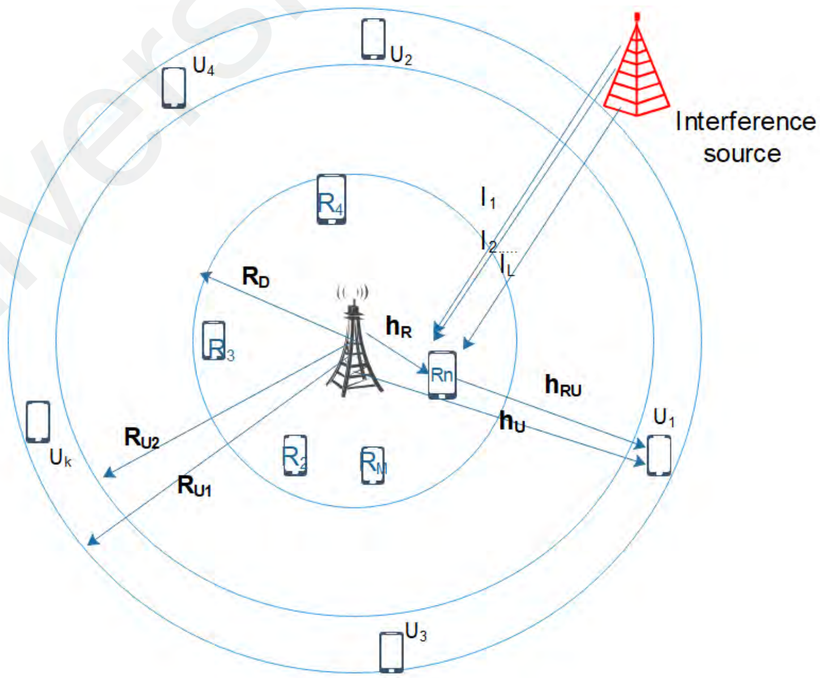


Figure 3.3: Downlink SWIPT Enable C-NOMA Network with Spatially Distributed Users in the Presence of Interference

3.3.3 Channel Model

By (Ding et al., 2014), the CDF of source to relays links for spatially random relays is given as;

$$F_{|h_R|^2}(x) = \frac{1}{R_D}\sum_{n=1}^{N} b_n(1 - e^{-c_n x}), \tag{3.17}$$

where N is complexity-accuracy trade-off parameter, $b_n = w_n\sqrt{1 - \emptyset_n^2}\left(\frac{R_D}{2}\emptyset_n + \frac{R_D}{2}\right)$,

$\emptyset_n = \cos\left(\frac{2n-1}{N}\right)$, $c_n = 1 + \left(\frac{R_D}{2}\emptyset_n + \frac{R_D}{2}\right)^m$, and $w_n = \frac{\pi}{N}$.

For relay selection partial RS method is adapted, best relay is selected using best S-R link which ensures the best detection of signal at relay. CDF of largest order statistics is given as $F_{X_1}(x) = \left[F_{|h_R|^2}(x)\right]^M$, where $X_1 = \max(h_{R_1}^2, h_{R_2}^2, h_{R_3}^2 .. h_{R_M}^2)$.

Let $X_2 = \frac{|h_{RU}^{`}|^2}{1+d_u^m}$ and its CDF and pdf are given as;

$F_{X_2}(x) = \frac{1}{R_{U_1}+R_{U_2}}\sum_{k=1}^{K} b_k^{'}(1 - e^{-c_k^{'}x})$, and

$$f_{X_2}(x) = \frac{1}{R_{U_1}+R_{U_2}}\sum_{k=1}^{K} b_k^{'} * c_k^{'} e^{-c_k^{'}x}, \tag{3.18}$$

where K is complexity-accuracy trade off parameter, $b_k^{'} = w_k\sqrt{1 - \emptyset_k^2}\, s_k$, $s_k = \left(\frac{R_{U_1} - R_{U_2}}{2}(\emptyset_k + 1) + R_{U_2}\right)$, $c_k^{'} = 1 + s_k^m$, $\emptyset_k = \cos\left(\frac{2k-1}{K}\right)$, , and $w_k = \frac{\pi}{K}$. The channel gains of interfering channels are independent and exponentially distributed with parameter λ. The pdf of interference, $X_i = \sum_{i=1}^{L} P_i|g_i|^2$ follows the given distribution, $f_{X_i}(x) = \frac{\lambda^L}{\Gamma(\mathrm{L})} x^{L-1} e^{-\lambda x}$,where λ is the channel parameter.

3.3.4 Signal to Noise Ratio (SNR) Expressions

The superimposed message at source is given as $x = \sum_{i=1}^{2} \alpha_i x_i$, where α_1, α_2 are power allocation factors. As R is in close proximity of BS, more power is allocated to user U , i. e., $\alpha_2 > \alpha_1$ and $\alpha_1 + \alpha_2 = 1$. In the first phase, message received at any relay n 'R_n' is given as

$$y_n^r = \sqrt{(1-\xi)P_s}\ \sum_{i=1}^{2} \sqrt{\alpha_i}\, x_i h_R + \sqrt{(1-\xi\ )} \sum_{i=1}^{L} P_i x_i h_{i_n} + w_n^r, \tag{3.19}$$

where P_s is the transmit power, $h_{R_n} = |h_{SR_n}|/\sqrt{1+d_R^m}$, d_R is the distance between source and relays, m is path loss exponent,; it is assumed that interference source is located in close proximity and thus distance of all interference from relay is almost the same. Interfering channels are modeled as Rayleigh fading channel with same channel parameter λ. w_n^r is additive white Gaussian noise (AWGN) at R_n with zero mean and variance N_0. Message of U is decoded first at R_n, and R_n decodes its own message after employing SIC. So, the SNR at R_n, to decode x_2 and $x_1$are given as;

$$\gamma_{R \to U}^n = \frac{(1-\xi)P_s \alpha_2 |h_{R_n}|^2}{(1-\xi)P_s \alpha_1 |h_{R_n}|^2 + (1-\xi)\sum_{i=1}^{L} P_i |g_i|^2 + N_0} \tag{3.20}$$

If SIC is performed successfully, i.e., x_1 is decoded successfully at relay, SNR of R is given as;

$$\gamma_R^n = \frac{(1-\xi)P_s \alpha_1 |h_{R_n}|^2}{(1-\xi)\sum_{i=1}^{L} P_i |g_i|^2 + N_0 d^m} \tag{3.21}$$

The message received at end-user U through direct transmission, during first phase is given as

$$y_U^1 = \sqrt{P_s}\ \sum_{i=1}^{2} \sqrt{\alpha_i}\, x_i h_U^{`} + + w_U\,, \tag{3.22}$$

The SNR ratio for detection of near user's own message during first phase of transmission is

$$\gamma_U^1 = \frac{\alpha_2 P_s |h_U|^2}{\alpha_1 P_s |h_U|^2 + N_0}, \tag{3.23}$$

where $|h_U|^2 = \left|\grave{h}_U\right|^2/(1 + d_u^m)$, $\left|\grave{h}_U\right|^2$ is the direct link between source and user, and d_U is the distance between source and far user. If relay 'R_n' is selected for transmission, message received at end-user 'U' during 2nd phase of transmission is given as;

$$y_U^2 = \sqrt{P_R^n}\; h_{RU} + w_U. \tag{3.24}$$

The power harvested at energy harvesting receiver of R_n is

$$P_R^n = \eta\xi\left(P_s|h_R|^2 + \sum_{i=1}^{L} P_i|g_i|^2\right), \tag{3.25}$$

$$\gamma_U^2 = \frac{\left(\eta\xi\left(P_s|g_n|^2 + \sum_{i=1}^{L} P_i|g_i|^2\right)|h_{RU}|^2\right)}{N_0}, \tag{3.26}$$

where $0 < \eta < 1$ is conversion efficiency which depends on energy harvesting receiver circuitry, $|h_{RU}|^2 = \frac{\left|\grave{h}_{RU}\right|^2}{1+d_u^m}$. Considering that near user exist relatively closer to source, and distance between relay and end user is almost same as d_u. Let the end-to-end SNR of far user is

$$\gamma_{e2e,U} = \max(\gamma_U^1, \gamma_U^2). \tag{3.27}$$

3.3.5 Performance Evaluation

In this section, outage probability will be evaluated as a performance metric for near and far users.

3.3.5.1 Outage at Nearly Located Relay User

Nearly located near user can be in outage if following two event occur, 1) message of end user U is not decoded at selected relay node or successful SIC does not occur, (2) message of end user is detected but relay user cannot detect its own message

$$\mathrm{P}_1 = \Pr(\gamma_{\mathrm{R}\to\mathrm{U}}^{\mathrm{n}} < \gamma_{\mathrm{U}}^{*}, \gamma_{\mathrm{R}}^{\mathrm{n}} < \gamma_{\mathrm{R}}^{*}), \tag{3.28}$$

where γ_{R}^{*} and γ_{U}^{*} are required threshold SNR for successful detection of reay and user's messages, respectively.

$$P_1 = \Pr\left(X_1 < \frac{\gamma_{\mathrm{U}}^{*}(X_i+1)}{\rho(1-\xi)(\alpha_2-\alpha_1\,\gamma_{\mathrm{U}}^{*})}, X_1 < \frac{\gamma_{\mathrm{R}}^{*}(X_i+1)}{\rho(1-\xi)\alpha_2}\right) \tag{3.29}$$

Let $\mathrm{A} = \min\left(\frac{\gamma_{\mathrm{U}}^{*}}{\rho(1-\xi)(\alpha_2-\alpha_1\,\gamma_{\mathrm{U}}^{*})}, \frac{\gamma_{\mathrm{R}}^{*}}{\rho(1-\xi)\alpha_2}\right)$, then the above probability can be written as

$$P_1 = \Pr(X_1 < A(\rho_I X_i + 1)) \tag{3.30}$$

$$P_1 = \int_0^{\infty} F_{X_1}\big(A(\rho_I x + 1)\big)\; f_{X_i}(x)\, dx \tag{3.31}$$

From (3.18)

$$P_1 = \frac{\lambda^L}{\Gamma(\mathrm{L})} \int_0^{\infty} \left(\frac{1}{R_D} \sum_{n=0}^{N} b_n e^{-c_n A(\rho_I x+1)}\right)^M x^{L-1}\, e^{-\lambda x} dx \tag{3.32}$$

Using multinomial expansion,

$$\left(\sum_{n=0}^{N} b_n e^{-c_n A(x+1)}\right)^M = \sum_{k_0,\dots,k_N} \binom{M}{k_0,\dots,k_N} \left(\prod_{n=0}^{N} b_n^{k_n}\right) e^{-\sum_{n=0}^{N} k_n c_n A(\rho_I x+1)} \tag{3.33}$$

$$P_1 = \frac{\lambda^L}{R_D^M \Gamma(\mathrm{L})} \sum_{k_0,\dots,k_N} \binom{M}{k_0,\dots,k_N} \left(\prod_{n=0}^{N} b_n^{k_n}\right) e^{-A\sum_{n=0}^{N} k_n c_n} *$$

$$\int_0^{\infty} e^{-A\rho_I x \sum_{n=0}^{N} k_n c_n}\, x^{L-1}\, e^{-\lambda x} dx \tag{3.34}$$

$$P_1 = \frac{\lambda^L}{R_D^M \Gamma(\mathrm{L})} \sum_{k_0,\dots,k_N} \binom{M}{k_0,\dots,k_N} \left(\prod_{n=0}^N b_n^{k_n}\right) e^{-A \sum_{n=0}^N k_n c_n} *$$

$$\int_0^\infty x^{L-1} e^{-x(A\rho_I \sum_{n=0}^N k_n c_n + \lambda)}\, dx \qquad (3.35)$$

From (3.381.4) of (Gradshteyn & Ryzhik, 2014) , $\int_0^\infty x^{v-1} e^{-\mu x} dx = \frac{1}{\mu^v} \Gamma(v)$, above equation becomes

$$P_1 = \frac{\lambda^L}{R_D^M (A\rho_I \sum_{n=0}^N k_n c_n + \lambda)^L} \sum_{k_0,\dots,k_N} \binom{M}{k_0,\dots,k_N} \left(\prod_{n=0}^N b_n^{k_n}\right) e^{-A \sum_{n=0}^N k_n c_n}, \qquad (3.36)$$

where $\mathrm{A} = \min\left(\frac{\gamma_{\mathrm{U}}^*}{\rho(1-\xi)(\alpha_2 - \alpha_1 \gamma_{\mathrm{U}}^*)}, \frac{\gamma_{\mathrm{R}}^*}{\rho(1-\xi)\alpha_2}\right)$, Eqn. (3.34) provides closed form expression of near user outage probability.

3.3.5.2 Outage at End/Far User

End user 'U' will be in outage through if following events occur, 1) message of end user U is not decoded at selected relay node and direct message through source is not decoded or (2) relay user can detect message of U but U cannot detect its own message.

$$\mathrm{P}_2 = \Pr(\gamma_{\mathrm{R}\to\mathrm{U}}^{\mathrm{n}} < \gamma_{\mathrm{U}}^*, \gamma_U^1 < \gamma_U^*) + \Pr(\gamma_{\mathrm{R}\to\mathrm{U}}^{\mathrm{n}} > \gamma_{\mathrm{U}}^*, \gamma_{\mathrm{e2e,U}} < \gamma_{\mathrm{U}}^*) \qquad (3.37)$$

Theorem 3: Outage at far user "U" is given as

$$P_2 = \frac{1}{R_{U_1} + R_{U_2}} \sum_{k=1}^K \sqrt{1-\varphi_k}\, s_k \left(1 - e^{-(1+s_k^m)A_4}\right) *$$

$$\Bigg[\frac{\lambda^L}{R_D^M (A_1 \rho_I \sum_{n=0}^N k_n c_n + \lambda)^L} \sum_{k_0,\dots,k_N} \binom{M}{k_0,\dots,k_N} \left(\prod_{n=0}^N b_n^{k_n}\right) e^{-A_1 \sum_{n=0}^N k_n c_n} +$$

$$\frac{b_0^M}{R_D^M (R_{U_1} + R_{U_2})} \sum_{k=1}^K b_k' + \frac{\lambda^L \sum_{k=1}^K b_k}{R_D^M (R_{U_1} + R_{U_2})} \sum_{k_0,\dots,k_N} \binom{M}{k_0,\dots,k_N} \prod_{n=0}^N b_n^{k_n} \Bigg\{ \frac{1}{\left(\lambda - \frac{\rho_I}{\rho} \sum_{n=0}^N k_n c_n\right)^L} *$$

$$\sqrt{4c_k \left(\frac{A_3}{\rho}\right) \sum_{n=0}^N k_n c_n}\, K_1 \sqrt{4c_k \left(\frac{A_3}{\rho}\right) \sum_{n=0}^N k_n c_n} - \frac{1}{(A_2 \rho_I \sum_{n=0}^N k_n c_n + \lambda)^L} e^{-A_2 \sum_{n=0}^N k_n c_n} \Bigg\} \Bigg],$$

(3.38)

where $\rho = \frac{P_S}{N_0}$, $A_1 = A_2 = \frac{\gamma_U^*}{\rho(1-\xi)(\alpha_2 - \alpha_1 \gamma_U^*)}$, , $A_3 = \frac{\gamma_{U*}^* * N0}{\eta\xi}$, and $A_4 = \frac{\gamma_U^*}{(\rho(\alpha_2 - \alpha_1 \gamma_U^*))}$.

Proof: Please refer to Appendix C.

3.3.6 Sum Throughput of System

For delay-limited transmission mode, system throughput is measured by determining the outage probability at a fixed source transmission rate (bits/s/Hz). Mathematically, $R = \log_2(1+\gamma_0)$, where γ_0 is required received SNR for correct detection. Given that R_1 and R_2 are transmitting data rate for U_1 (near user) and U_2 (far user) simultaneously, T/2 is transmission time for a block of time T, the sum throughput of system is given as

$$\tau = \frac{(1-P_1)R_1}{2} + \frac{(1-P_2)R_2}{2}. \quad (3.39)$$

3.3.7 System Parameters

Until and unless status, the parameters enlisted in table 3.3 will be used for evaluation of system.

Table 3.2: System Parameters

Parameters	Value
Number of Monte Carlo Simulations	10^6
Range of Transmit Power (P_s)	10-35 dBm
Power allocation factors for U_1 (α_1)	0.8
Power allocation factors for U_2 (α_2)	0.2
Energy harvesting efficiency η	40%
Power Splitting factor/Ratio ξ	0.5
Noise Variance N_0	0.001
Radius of disk with cooperative area R_d	5 meter
Inner Radius of Ring R_{U2}	7 meter

Table 3.2: Continued

Outer Radius of Ring R_{U1}	8 meter
Complexity-accuracy trade off parameter for cooperative disk N	10
Complexity-accuracy trade off parameter for ring K	10

3.4 Two-Stage Relay Selection Scheme for SWIPT Enabled C-NOMA Networks

3.4.1 Motivation

In previous sections, SWIPT enabled multiple relay C-NOMA networks in the presence of interference have been investigated for partial relay selection scheme, for both cooperation with dedicated relays and cooperation among NOMA users. Relay selection was performed considering the best first link. This selection was reasonable because of two reasons. Firstly, partial relay selection is easy to implement, the relay node with best source to relay link is selected. Secondly, in SWIPT enabled networks, both signal detection and energy harvesting are dependent on first link. The first link becomes more important. However, it was observed that performance gain of partial relay selection does not improve significantly with increased transmit SNR or number of available relays. Since both source to relay and relay to end user channels are involved in transmission, a simple relay selection cannot be optimal under all conditions.

RF-EH system has an additional control system (e.g., AC/DC converter, analogue RF amplifier, and processor) which consumes power. If the signal strength received at relay node is less than required fixed threshold value, EH cannot be performed. Practically, total harvested energy by EH relay node is consumed in operating the circuitry of relay node and transmission of the signal from relay to destination. The existing literature considered that all harvested energy is consumed for information transmission and circuit power consumption has been neglected. It is important to investigate multiple relay C-NOMA SWIPT networks with realistic circuit power consumption. Additionally, in power domain NOMA users are multiplexed by different power level. For fixed power allocation among NOMA users, a wrong choice of power allocation factors or rates can degrade the performance of the system. Such a system degradation can be avoided by selecting dynamic power allocation factors which depend upon the channel conditions. In this regard, it was identified that new RS schemes are required by carefully considering all involved channels and circuit power consumption at relay node. Novel relay selection scheme is proposed and performance of the system will be improved by selecting dynamic power allocation.

3.4.2 System Model

A wireless downlink NOMA based relay network with a source (S), energy constrained 'M' relay nodes (R_1,R_2,…R_M) and two end users (U_1 and U_2) is considered. It is assumed that direct link between source and users does not exist and all data is transmitted with the help of a single selected relay node. All nodes are assumed to be equipped with single antenna and work in half duplex mode. Intermediate relay is not equipped with external power source; and first it harvests energy from the RF signal received from source using PS SWIPT protocol and then uses this energy to maintain its circuit and signal transmission towards destination node. Only when the relay can successfully harvest enough energy to operate its circuitry, it is able to decode and transmit information to end users.

It is assumed that U_1 is high priority and low data rate user, while U_2 is high data rate user with less priority. It is important to highlight that users can be ordered according to CSI, but it requires the knowledge of all relay to end users channel at relay node, which increase system overhead. This issue becomes more significant with increase in number of relays or NOMA users. In this work, the decoding order based on QoS requirement is adapted which means NOMA can be implement even if channel conditions between relay and users are statistically similar and relays do not need to gather CSI for links between relays and end user. This assumption of decoding order is inconsistence to some existing studies (Yang, Ding, Wu, et al., 2017; Zhao et al., 2018). C- NOMA with fixed PA and dynamic PA strategy are adopted at relay node. For fixed PA, user with high priority services requirement has greater power allocation factor. The channel gains of all links remain constant for a block time T and then attain another independent values following Rayleigh fading. Furthermore, source has channel state information (CSI) of all links. Transmission takes place in two time phase; half of block time (*T/2*) is used for source to relay information transmission and half time (*T/2*) is used for relay to destination information transmission. System model is illustrated in Fig. 3.4.

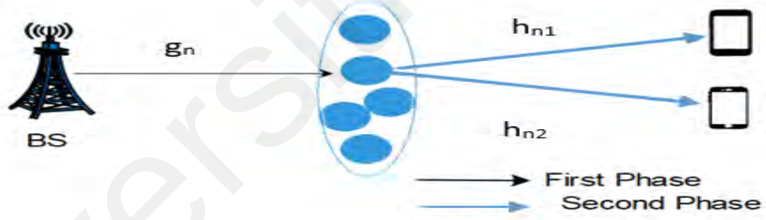


Figure 3.4: Downlink SWIPT enable C-NOMA Network

3.4.3 SNR Expressions for End Users

The superimposed message at source is given as $x = \sum_{i=1}^{2} \alpha_i x_i$, where α_1, α_2 are power allocation factors. As U_1 has high priority, more power is allocated to U_1 , i.e., $\alpha_1 > \alpha_2$ and $\alpha_1 + \alpha_2 = 1$. During the first phase of transmission, message received at any relay n 'R_n' is given as

$$y_n^r = \frac{1}{\sqrt{d^m}}\sqrt{(1-\xi)P_s}\ \sum_{i=1}^{2}\sqrt{\alpha_i}\,x_i g_n + w_n^r, \qquad (3.40)$$

where P_s is the transmit power, d is the distance between source and relays. It is assumed that all relays are located in close proximity and thus their distance from relay is almost the same (this assumption is same as (Ding, Dai, et al., 2016a; Xu et al., 2018; Yang, Ding, Wu, et al., 2017)), m is path loss exponent, g_n is the Rayleigh fading channel coefficient between the S to relay R_n , and channel gain $|g_n|^2$is exponential with parameter λ_g, w_n^r is additive white Gaussian noise (AWGN) at R_n with zero mean and variance N_0. Note that this noise is due to baseband signal conversion at relay. Typically, antenna noise is very small as compared to the baseband noise, therefore it is neglected without loss of generality. Let's consider message of U_1 is decoded first at R_n, and after employing SIC, message of U_2 is decoded. So, the rates at R_n, to decode x_1 and $x_2$are given as

$$R_1^n = \frac{1}{2}\log_2\left(1 + \frac{(1-\xi)P_s\alpha_1|g_n|^2}{(1-\xi)P_s\alpha_2|g_n|^2 + N_0 d^m}\right). \qquad (3.41)$$

If SIC is performed successfully, i.e., x_1 is decoded successfully at relay, achievable rate of U_2 is given as;

$$R_2^n = \frac{1}{2}\log_2\left(1 + \frac{(1-\xi)P_s\alpha_2|g_n|^2}{N_0 d^m}\right), \qquad (3.42)$$

where factor ½ in (3.41) and (3.42) comes from the fact that half of the transmission block time is used for source to relay transmission. If relay 'R_n' is selected for transmission, message received at user U_k, k=1,2 is given as

$$y_k^d = \sqrt{\frac{P_r^n}{d_k^m}}\ \sum_{i=1}^{2}\sqrt{\alpha_i}\,x_i h_{nk} + w_k^d, \qquad (3.43)$$

where P_r^n is transmit power of relay R_n, h_{nk} is channel between R_n and user k. Achievable rate at U_1 is given by

$$R_1^1 = \frac{1}{2}\log_2\left(1 + \frac{\alpha_1 P_r^n |h_{n1}|^2}{\alpha_2 P_r^n |h_{n1}|^2 + N_0 d_1^m}\right). \tag{3.44}$$

After successful SIC, rate at U_2 is;

$$R_2^2 = \frac{1}{2}\log_2\left(1 + \frac{P_r^n \alpha_2 |h_{n2}|^2}{d_2^m N_0}\right). \tag{3.45}$$

Successful SIC employs successful detection of x_1 at U_2 given as;

$$R_{1\to 2}^2 = \frac{1}{2}\log_2\left(1 + \frac{P_r^n \alpha_1 \left|h_{n,2}\right|^2}{P_R \alpha_2 \left|h_{n,2}\right|^2 + d_2^m N_0}\right) \geq R_1. \tag{3.46}$$

3.4.4 Energy Harvesting Model

The power harvested at energy harvesting receiver of R_n is

$$P_h^n = \frac{\eta \xi P_s |g_n|^2}{d^m}, \tag{3.47}$$

where $0 < \eta < 1$ is conversion efficiency which depends on energy harvesting receiver circuitry. Total harvested energy is used in operating circuit of relay and transmission of signal towards end users.

$$P_h^n = P_r^n + P_c , \tag{3.48}$$

P_c is fixed power required to maintain circuit of relay and P_r^n is transmission power at relay n. We consider that 'a' part of harvested energy aP_h^n is used for circuit power consumption and remaining power is used for signal transmission where 0<a<1, $a = \frac{P_c d^m}{\eta \xi P_s \lambda_g}$, where λ_g is mean of $|g_n|^2$. The available transmission power at relay node 'n' is given by;

$$P_r^n = P_h^n - P_c = (1-a)P_h^n \ . \quad (3.49)$$

$$P_r^n = \frac{(1-a)\eta\xi P_s |g_n|^2}{d^m}. \quad (3.50)$$

3.4.5 Relay Selection Criteria's

In this Section, RS schemes for above described network are analytically modeled. Three RS schemes namely, two-stage RS with fixed power allocation (TS-F), two-stage RS with dynamic power allocation (TS-D) and partial RS will be discussed.

3.4.5.1 Two-Stage RS Criteria with Fixed Power Allocation

Any relay 'n' can help in transmission if following conditions are satisfied

Condition 1-Message for U_1 and U_2 should be detected successfully at relay, i.e., $R_1^n \geq R_1$. Any relay "n" can be selected in first stage if

$$\frac{1}{2}\log_2\left(1 + \frac{(1-\xi)P_s\alpha_1|g_n|^2}{(1-\xi)P_s\alpha_2|g_n|^2 + N_0 d^m}\right) \geq R_1, \text{ and}$$

$$\frac{1}{2}\log_2\left(1 + \frac{(1-\xi)P_s\alpha_2|g_n|^2}{N_0 d^m}\right) \geq R_2. \quad (3.51)$$

Above condition is satisfied if

$$|g_n|^2 \geq \frac{\epsilon_1 d^m}{\rho(1-\xi)(\alpha_1 - \alpha_2\epsilon_1)} \text{ and } |g_n|^2 \geq \frac{\epsilon_2 d^m}{\rho\alpha_2(1-\xi)}, \quad (3.52)$$

where $\rho = {P_s}/{N_0}$, $\epsilon_1 = 2^{2R_1} - 1$ and $\epsilon_2 = 2^{2R_2} - 1$.

Relay is able to harvest minimum required energy for circuit power consumption

$$P_h^n \geq P_c, \text{ which gives } |g_n|^2 \geq \frac{P_c\, d^m}{\eta\xi P_s}. \quad (3.53)$$

Condition 2-Message of high priority user x_1 should be successfully detected at U_1

$$\frac{1}{2}\log_2\left(1+\frac{P_r^n\alpha_1|h_{n,1}|^2}{P_r^n\alpha_2|h_{n,1}|^2+N_0d_1^m}\right)\geq R_1\,. \tag{3.54}$$

Putting value of P_r^n from eq. (3.48) gives,

$$|h_{n,1}|^2 \geq \left|\frac{\epsilon_1 d^m d_1^m}{(1-a)\eta\xi\rho|g_n|^2(\alpha_1-\alpha_2\epsilon_1)}\right|. \tag{3.55}$$

In the first stage of the proposed relay selection scheme, a subset of all those relays are selected which fulfill condition 1 and 2.

$$S_n=\left\{n{:}\,1\leq n\leq M,\ |g_n|^2\geq\frac{\varphi}{\rho}\ ,|h_{n,1}|^2\geq\frac{T_1}{\rho|g_n|^2}\ \right\}, \tag{3.56}$$

where $\varphi=\max\left\{\frac{\epsilon_1 d^m}{(1-\xi)(\alpha_1-\alpha_2\epsilon_1)},\frac{\epsilon_2 d^m}{\alpha_2(1-\xi)},\frac{P_c d^m}{\eta\xi N_0}\right\}$, $C=\eta(1-a)\xi$, and $T_1=\frac{\epsilon_1 d^m d_1^m}{C\,(\alpha_1-\alpha_2\epsilon_1)}$.

In the second stage, the single relay among set of selected relay is chosen which maximizes the data rate of U_2,

$$n^*=\arg\max_{n\in S_n}\{\ |h_{n,2}|^2\}.. \tag{3.57}$$

For proposed two-stage RS, centralized manner of RS is considered. A central unit (e.g., BS) collects all the channel state information of BS to relay nodes (which can be selected at first stage), and relay node to end-users. Based on channel information, best relay is selected. This centralized manner is adopted for simplicity and avoiding CSI knowledge at relay nodes. However, centralized RS requires more signaling overhead and computational complexity at BS. To overcome this, distributed manner of RS can also be adapted in the same manner. For distributed RS, BS will only need to decide the relays selected at first stage, and best relay node is chosen by set of selected relay nodes by comparing their SNR from high data rate user. It is worth mentioning here that two-stage relay selection increases the system complexity, as a relay need to qualify certain conditions to be allowed of relaying the information.

3.4.5.2 Two-Stage RS with Dynamic Power Allocation

In the previous Section, we investigated the performance of system two-stage RS with fixed PA (TS-F) factors, where, PA are not function of users' CSI. Above described systems can perform better than OMA under the condition$\alpha_1 > \alpha_2 \in_1$, i.e., wrong choice of users' targeted rate and power allocation factors can lead to outage. This issue can be solved by using dynamic PA factors, where PA coefficient is related to user's CSI and are selected such that QoS requirement of priority user is confirmed. In the following subsection, we focus on two-stage RS with dynamic PA factors.

As U_1 is high priority user and QoS requirement of high priority user should be satisfied. Therefore U_1 needs to meet this constraint:

$$\frac{1}{2}\log_2\left(1+\frac{P_r^n\alpha_1|h_{n,1}|^2}{P_r^n\alpha_2|h_{n,1}|^2+N_0d_1^m}\right) \geq R_1\,. \tag{3.58}$$

Rather than selecting the relay node which confirms the detection of priority user at first stage, PA factors are set such as they confirm the successful detection of U_1. This dynamic PA removes the risk of outage due to wrong choice of users' rate and PA factors. The maximum PA factor that can be allocated to U_2 is given as

$$\alpha_2 = \max\left(0, \frac{\rho_r^n|h_{n,1}|^2 - \in_1 d^m d_1^m}{\rho_r^n|h_{n,1}|^2(1+\in_1)}\right) = \max\left(0, \frac{\rho|g_n|^2|h_{n,1}|^2 - C_1}{\rho|g_n|^2|h_{n,1}|^2(1+\in_1))}\right) \tag{3.59}$$

where $\rho_r^n = \frac{P_r^n}{N_0} = \rho C|g_n|^2$ and $C_1 = \frac{d^m d_1^m \in_1}{C}$. From above expression of α_2, it is clear that U_1 can always decode its message when$|h_{n,1}|^2 > \frac{C_1}{\rho|g_n|^{2,}}$.

From (3.51) and (3.56) all those relays can be activated at first stage which follow the following condition; $S_n = \left\{n: 1 \leq n \leq M,\ |g_n|^2 \geq \frac{\varphi}{\rho}, |h_{n,1}|^2 > C_1/\rho|g_n|^{2,}\right\}$, and similar to fixed PA, in second stage the single relay is chosen which maximizes the data rate of U_2, i.e., $n^* = \arg\max_{n \in S_n}\left\{ \left|h_{n,2}\right|^2 \right\}$.

3.4.5.3 Partial RS Criteria

Partial RS requires the channel state information (CSI) of single hops (i.e., channel conditions between S-R or R-D), thus, scheme reduces system complexity. Using partial RS method, best relay can be selected using best S-R link which ensures maximum harvested energy and detection of source signal at relay. Mathematically, the best relay is given as follow;

$$n^* = \arg\max_{n \in \{1.,\dots,M\}}\{|g_n|^2\} \tag{3.60}$$

3.4.6 Performance Evaluation

3.4.6.1 Performance Evaluation of Two-Stage RS with Fixed PA

(a) ***Outage of U_1***

In case of TS-F, U_1 faces outage if no relay is selected at first stage. This is the case when not a single relay can harvest enough energy to operate the circuitry or performs signal detection. Let P_s be the probability that a relay is selected at first stage. Then probability P_s for the selection of a relay 'n' at first stage is

$$P_s^{\mathrm{TS-F}} = \Pr\left(|g_n|^2 \geq \frac{\varphi}{\rho},\ \ \left|h_{n,1}\right|^2 \geq \frac{T_1}{\rho|g_n|^2} \right). \tag{3.61}$$

As all channels are independent and identically distributed, outage probability of not selecting any relay can be rewritten as;

$$P_1^{\mathrm{TS-F}} = (1 - P_s^{\mathrm{TS-F}})^M. \tag{3.62}$$

CDF of channel gain $|g_n|^2$, and $\left|h_{n,1}\right|^2$ are given as $F_{|g_n|^2}(x) = 1 - e^{-\lambda_g x}$ and $F_{\left|h_{n,1}\right|^2}(x) = 1 - e^{-\lambda_{h,1} x}$ respectively, where λ_g and $\lambda_{h,1}$ are mean of $|g_n|^2$, and $\left|h_{n,1}\right|^2$ respectively.

$$P_s^{TS-F} = \sum_{k=0}^{\infty} \frac{(-1)^k}{k!} \left(\frac{\lambda_g \lambda_{h_1} T_1}{\rho}\right)^k \Gamma\left(1 - k, \lambda_g \frac{\varphi}{p}\right). \quad (3.63)$$

(3.61) is obtained by applying Taylor's expansion $e^{-a/x} = \sum_{k=0}^{\infty} \frac{(-1)^k}{k!} \left(\frac{a}{x}\right)^k$ and incomplete Gamma function $\int_u^{\infty} x^{v-1} e^{-\mu x} dx = \frac{1}{\mu^v} \Gamma(v, \mu u)$ (3.381.3) (Gradshteyn & Ryzhik, 2014).

Lemma 1: At high SNR, approximation of P_1^{TS-F} is given as;

$$P_1^{TS-F} \approx \left(-\frac{\lambda_g \lambda_{h_1} T_1}{\rho} \ln \frac{\lambda_g \lambda_{h_1} T_1}{\rho}\right)^M. \quad (3.64)$$

Proof: When transmit SNR is high, $\frac{\varphi}{\rho} \to 0$, using (3.324.1) (Gradshteyn & Ryzhik, 2014), eqn. (23) can be approximated as

$$P_s^{TS-F} \approx \left(\sqrt{\frac{4\lambda_g \lambda_{h_1} T_1}{\rho}}\, \mathrm{K}_1 \sqrt{\frac{4\lambda_g \lambda_{h_1} T_1}{\rho}}\right), \quad (3.65)$$

where K_1 is modified Bessel function of first kind. As $x \to 0$, Bessel function can be approximated with series representation (8.446) (Gradshteyn & Ryzhik, 2014), $x\mathrm{K}_1(x) \approx 1 + \frac{x^2}{2} \ln\left(\frac{x}{2}\right)$,

$$P_s^{TS-F} \approx \left(\frac{\lambda_g \lambda_{h_1} T_1}{\rho} \ln \frac{\lambda_g \lambda_{h_1} T_1}{\rho}\right). \quad (3.66)$$

Putting (3.66) in (3.62) gives eqn. (3.64), which proves the lemma.

(b) ***Outage of U₂***

For TS-F, outage at U_2 occurs if S_n is not empty and U_2 fails to perform SIC successfully, or U_2 is unable to decode its own message. So outage at U_2 is given by

$$P_2^{TS-F} = 1 - \Pr\left(R_{1\to 2}^2 \geq R_1, R_2^2 \geq R_2, |S_n| > 0\right). \tag{3.67}$$

$$= 1 - \Pr\left(\left|h_{n,2}\right|^2 \geq \frac{T_1}{\rho|g_n|^2}, \left|h_{n,2}\right|^2 \geq \frac{\epsilon_2\, d^m d_2^m}{\alpha_2 \rho C |g_n|^2}, |S_n| > 0\right). \tag{3.68}$$

The following theorem gives exact expression for the outage probability of U_2 achieved by two-stage RS.

Theorem 4: The outage probability of U_2 in C-NOMA with SWIPT network with proposed two-stage RS scheme is given by

$$P_2^{TS-F} = 1 - \lambda_g \sum_{k=1}^{M} \binom{M}{k} (1 - P_S^{TS-F})^{M-k} (P_S^{TS-F})^{k-1} *$$

$$\sum_{i=1}^{k} \binom{k}{i} (-1)^{i-1} \sum_{j=0}^{\infty} \frac{(-1)^j}{j!} \left(\frac{i\lambda_{h,2} X_1 + \lambda_{h,1} T_1}{\rho}\right)^j \Gamma\left(1 - j, \lambda_g \frac{\varphi}{p}\right), \tag{3.69}$$

where $X_1 = \max\left(T_1, \frac{\epsilon_2\, d^m d_2^m}{\alpha_2 C}\right)$. High SNR approximation of P_2^{TS-F} is given as

$$P_2^{TS-F} \approx 1 - \lambda_g \sum_{k=1}^{M} \binom{M}{k} \left(1 - P_S^{app}\right)^{M-k} \left(P_S^{app}\right)^{k-1} *$$

$$\left(1 + \sum_{i=1}^{k} \binom{k}{i} (-1)^{i-1} \frac{B}{p} \ln\left(\frac{B}{p}\right)\right), \tag{3.70}$$

where $B = \lambda_g (i\lambda_{h,2} X_1 + \lambda_{h,1} T_1)$

Proof: See Appendix D. Note that, power allocation factors need to be chosen carefully such that $\alpha_1 > \alpha_2 \epsilon_1$.

3.4.6.2 Outage Probability of Two-Stage Relay Selection with Dynamic PA (TS-D)

(a) ***Outage at U_1***

By using dynamic PA the probability of selecting a relay node at first stage is

$P_S^{TS-D} = \sum_{k=0}^{\infty} \frac{(-1)^k}{k!} \left(\frac{\lambda_g \lambda_{h_1} C_1}{\rho}\right)^k \Gamma\left(1-k, \lambda_g \frac{\varphi}{p}\right)$. Thus, outage probability at U_1 with TS-D is given as,

$$P_1^{TS-D} = (1 - P_S^{TS-D})^M \tag{3.71}$$

At high SNR, outage at U_1 is approximated as $P_1^{ts-D} \approx \left(-\frac{\lambda_g \lambda_{h_1} T_1}{\rho} \ln \frac{\lambda_g \lambda_{h_1} T_1}{\rho}\right)^M$.

(b) ***Outage at U_2***

Use of dynamic PA with fixed QoS requirement of high priority user, yields following outage probability at U_2.

$$P_2^{TS-D} = 1 - \Pr\left(R_2^2 \geq R_2, |S_n| > 0\right) \tag{3.72}$$

An expression of occurrence of outage at U_2 is provided in following theorem.

Theorem 5: The outage probability of U_2 in C-NOMA with SWIPT network with proposed TS-D scheme is given as

$$P_2^{TS-D} = 1 - \lambda_g \sum_{k=1}^{M} \binom{M}{k} (1 - P_S^{TS-D})^{M-k} (P_S^{TS-D})^{k-1} *$$

$$\sum_{i=1}^{k} \binom{k}{i} (-1)^{i-1} \int_{\emptyset/p}^{\infty} \frac{\sqrt{4a_1 i \lambda_{h_1} \lambda_{h_2} C_1}}{px} K_1\left(\frac{\sqrt{4a_1 i \lambda_{h_1} \lambda_{h_2} C_1}}{px}\right) e^{-\frac{C_3}{px} - \lambda_g x} dx\ , \tag{3.73}$$

where $C_2 = \epsilon_2\, d^m d_2^m / C$, $a_1 = C_2(1 + \epsilon_1)$ and $C_3 = a_1 i \lambda_{h_2} + C_1 \lambda_{h_1}$.

Proof: Refer to Appendix E.

3.4.6.3 Outage Performance of Partial Relay Selection

(a) ***Outage at U_1***

In the case of partial RS, U_1 can be in outage if following three event occur, 1) x_1 is not decoded at selected relay node*, or (*2) x_1 is not decoded at U_1, or (3) x_1 is not decoded at U_2 for SIC.

$$P_1^{par} = \Pr(R_1^n < R_1\,, or\; R_1^1 < R_1\,, or\; R_{1\to 2}^2 < R_1). \tag{3.74}$$

$$P_1^{par} = 1 - \Pr(R_1^n > R_1,\; or\; R_1^1 > R_1, or\; R_{1\to 2}^2 > R_1). \tag{3.75}$$

Theorem 6- The outage probability of U_1 in C-NOMA with SWIPT network with partial RS scheme is given as

$$P_1^{par} = 1 - \sum_{n=1}^{M}\binom{M}{n}(-1)^{n-1}\sum_{k=0}^{\infty}\frac{(-1)^k}{k!}\left(\frac{n\lambda_g b}{\rho}\right)^k \Gamma\left(1-k, \frac{n\lambda_g T}{p}\right), \tag{3.76}$$

where $T = \frac{\epsilon_1 d^m}{(1-\xi)(\alpha_1-\alpha_2\epsilon_1)}$, $T_1 = \frac{\epsilon_1 d^m d_2^m}{C\,(\alpha_1-\alpha_2\epsilon_1)}$, $T_2 = \frac{\epsilon_2 d^m d_2^m}{C\,(\alpha_1-\alpha_2\epsilon_1)}$, and $b = \lambda_{h,1}T_1 + \lambda_{h,2}T_2$.

High SNR approximation of P_1^{par} is given as;

$$P_1^{par} \approx -\sum_{n=1}^{M}\binom{M}{n}(-1)^{n-1}\left(\frac{n\lambda_g b}{\rho}\right)\ln\left(\frac{n\lambda_g b}{\rho}\right). \tag{3.77}$$

Proof: Refer to appendix F

(b) ***Outage at U_2***

U_2 can suffer outage if the following two events occur: the selected best relay cannot decode x_2 and U_2 cannot detect its message successfully.

$$P_2^{par} = 1 - \Pr\left(R_2^n \geq R_2\,, R_2^2 \geq R_2\right). \tag{3.78}$$

$$P_2^{par} = 1 - \Pr\left(|g_n|^2 \geq \frac{\epsilon_2 d^m}{\alpha_2 \epsilon_2 (1-\xi)\rho}, \left|h_{n,2}\right|^2 \geq \frac{\epsilon_2 d^m d_2^m}{\alpha_2 C\rho |g_n|^2}\right). \quad (3.79)$$

By following the same steps as for outage of U1, outage probability of U2 is given as

$$P_2^{par} = 1 - \sum_{n=1}^{M} \binom{M}{n} (-1)^{n-1} \sum_{k=0}^{\infty} \frac{(-1)^k}{k!} \left(\frac{n\lambda_g \lambda_{h,2} b_2}{\rho}\right)^k \Gamma\left(1-k, \frac{n\lambda_g b_1}{\rho}\right), \quad (3.80)$$

where $b_1 = \frac{\epsilon_2 d^m}{\alpha_2 (1-\xi)}$ and $b_2 = \frac{\epsilon_2 d^m d_2^m}{\alpha_2 C}$.

High SNR approximation of P_2^{par} is given as;

$$P_2^{par} \approx -\sum_{n=1}^{M} \binom{M}{n} (-1)^{n-1} \left(\frac{n\lambda_g\, b_2}{\rho}\right) \ln\left(\frac{n\lambda_g\, b_2}{\rho}\right). \quad (3.81)$$

3.4.7 Benchmark for Partial and Two-Stage Relay Selection Schemes

In this subsection, to provide comparison, OMA scheme (time division multiple access (TDMA)) and random RS are considered as a benchmark for two-stage and partial RS.

3.4.7.1 Outage Probability of OMA

For NOMA based communication systems, OMA is an appropriate benchmark scheme. For energy constrained relay network, if a source need to communicate with two remote users through relay, use of OMA (TDMA) demands four time slots to serve both users. Achievable rate at each end user U_i becomes $R_i = 1/4 \log_2(1+\gamma_i)$, where γ_i is received SNR at each user.

For two-stages RS the outage probability of U_1 using OMA is given as $P_1^{ts-OMA} = (1 - P_s^{OMA})^N$, P_s^{OMA} is given as;

$$P_s^{OMA} = \sum_{k=0}^{\infty} \frac{1}{k!} \left(\frac{\lambda_g \lambda_{h_1} T_1'}{\rho}\right)^k \Gamma\left(1-k, \lambda_g \frac{\varphi'}{p}\right), \quad (3.82)$$

where $\in_i' = 2^{4R_i} - 1$, $\varphi' = \max\left\{\frac{\in_1' d^m}{(1-\xi)}, \frac{\in_2' d^m}{(1-\xi)}, \frac{P_c d^m}{\eta\xi N_0}\right\}$ and $T_1' = \frac{\in_1' d^m d_1^m}{(1-\xi)}$. Outage probability of U_2 using TDMA is;

$$P_2^{ts-OMA} = 1 - \lambda_g \sum_{k=1}^{M} \binom{M}{k} (1 - P_S^{OMA})^{M-k} (P_S^{OMA})^{k-1} *$$

$$\sum_{i=1}^{k} \binom{k}{i} (-1)^{i-1} \sum_{j=0}^{\infty} \frac{(-1)^j}{j!} \left(\frac{i\lambda_{h,2} X_1' + T_1'}{\rho}\right)^j \Gamma\left(1 - j, \lambda_g \frac{\varphi'}{p}\right), \quad (3.83)$$

where $X_1' = \max\left(T_1', \frac{\in_2' d^m d_2^m}{C}\right)$.

The outage probability of U1 in cooperative TDMA with SWIPT with partial RS scheme is given as

$$P_1^{p-OMA} = 1 - \sum_{n=1}^{M} \binom{M}{n} (-1)^{n-1} \sum_{k=0}^{\infty} \frac{(-1)^k}{k!} \left(\frac{n\lambda_g b'}{\rho}\right)^k \Gamma\left(1 - k, \frac{n\lambda_g T'}{p}\right), \quad (3.84)$$

where $T' = \frac{\in_1' d^m}{(1-\xi)}$, $T_1' = \frac{\in_1' d^m d_2^m}{C}$, $T_2 = \frac{\in_2' d^m d_2^m}{C}$, and $b' = \lambda_{h,1} T_1' + \lambda_{h,2} T_2'$. Similarly for cooperative TDMA network with SWIPT, outage probability of U_2 is given by;

$$P_2^{p-OMA} = 1 - \sum_{n=1}^{M} \binom{M}{n} (-1)^{n-1} \sum_{k=0}^{\infty} \frac{(-1)^k}{k!} \left(\frac{n\lambda_g \lambda_{h,2} b_2'}{\rho}\right)^k \Gamma\left(1 - k, \frac{n b_1'}{p}\right), \quad (3.85)$$

where $b_1' = \frac{\in_2' d^m}{(1-\xi)}$ and $b_2' = \frac{\in_2' d^m d_2^m}{C}$.

3.4.7.2 Random Relay Selection:

Random relay selection (RRS) consider any randomly selected relay to help the source in transferring the information. RRS can be considered a good benchmark for comparison. It is obvious that the randomly selected relay node may not be the optimal one for proposed SWIPT cooperative NOMA network. For random selection of relay, the selection process becomes independent of total number of available relay node, and thus the RRS can be regarded as a special case of two-stage and partial RS schemes with M=1. For two-stage RS outage probability of RRS scheme for U_1 and U_2 can be obtained by putting M=1 in eqn. (3.70) and eqn. (3.72). Similarly, for partial RS outage probability of RRS scheme, for U_1 and U_2 can be obtained by putting M=1 in eqn. (3.75) and eqn. (3.79).

Partial RS scheme selects the relay node which has best channel condition from source node, and thus this selection scheme refers to a simple comparison of channel states between source and relay nodes. This is different from two-stage RS, where all channel state information of S-R and relay to end users are required to choose the best single relay node. For C-NOMA networks, the partial RS ensures less complexity and overheads. However, the performance gain of partial RS does not improve significantly when more than two relay nodes are available between source and the end users. To utilize the benefits of both RS schemes for all SNRs, a hybrid RS scheme, which switches between partial and two-stage RS is proposed. As U_1 is priority user, its outage probability is used as switching criteria to switch between the two RS schemes i.e., $P^{par} = P_1^{par}$ and $P^{TS-F} = P_1^{TS-F}$. To select the RS strategy, the outage probability difference ΔP_{out} is introduced a

$$\Delta P_{out} = P^{par} - P^{TS-F} \quad . \tag{3.86}$$

When probability difference$\Delta P_{out} > 0$, outage probability caused by partial RS is greater than TS –F, which makes TS-F preferable RS. On the other hand for$\Delta P_{out} < 0$, TS-F causes more outage and thus partial RS is optimal for this case. Further analytical analysis of the hybrid scheme is beyond the scope of this work. However, the performance of hybrid scheme is numerically evaluated in the next chapter.

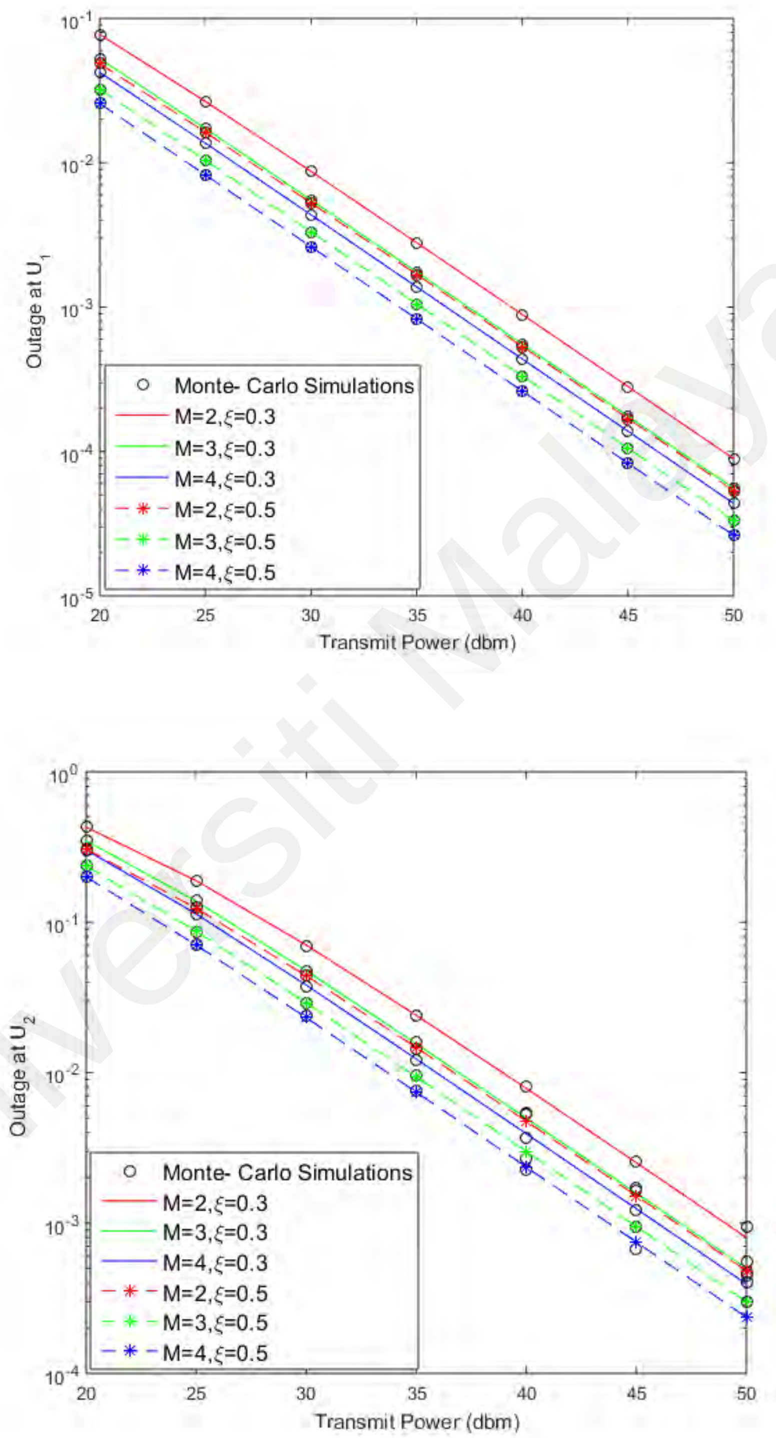
CHAPTER 4: RESULTS AND DISCUSSION

4.1 SWIPT Enabled Multiple Relay Cooperative NOMA Networks

In this section, the outage performance of NOMA end-users will be illustrated and analyzed. The impact of involved parameters on the performance of networks will be discussed. The analytical expression derived in chapter 3 will be used to plot analytical results. To verify the effectiveness of derived mathematical expression, a comprehensive analysis will be conducted. The analysis will show that the mathematical model is accurate and comprehensive. Based on derived expression and Monte-Carlo simulations, the impact of various network parameters, such as number of available relay nodes, power of interfering signals on the overall outage performance of system will be illustrated. The use of SWIPT introduces new challenges due to the randomness of harvested energy at relay node. The analysis related to SWIPT includes impact of energy harvesting, effect of conversion efficiency and power splitting ratios on the performance of SWIPT enabled C-NOMA networks.

4.1.1 Effect of Number of Relays on Outage Probability

The outage performance of SWIPT enabled C-NOMA network in the presence of interference is evaluated and analyzed by plotting theoretical results and Monte Carlo simulations. All the parameters have been listed in table 3.1. The outage probability of U_1 and U_2 are plotted in two different figures (Fig. 4.1 and Fig. 4.2) to avoid ambiguity. It is evident from Fig. 4.1, that outage performance is significantly improved by increasing transmit power, it is because of fact that achievable decoding rate and amount of harvested energy increases as transmit power growths. It can be also observed that outage performance is improved when number of relays increases. This behavior is obvious because when less relay node available to perform SWIPT and detection, there is less chance of successfully decoding the information and harvesting enough energy for successful transmission of information. Therefore, with more number of available relays, outage performance is improved.



(a)

(b)

Figure 4.1: Impact of Number of Relays 'M' on the Outage Performance of U_1 (a) and U_2 (b)

Considering, the two end users U_1 and U_2 for the proposed system model, Fig. 4.2 plots the sum throughput with increasing number of relays and power splitting factor (ξ=0.3,0.5). The Fig. demonstrates that overall system throughput improves with number of relays and transmit power. It can be seen that for PS relaying protocol, the increase in PS factor improves the system throughput. With increase in PS factor, the amount of harvested energy at relay increase, therefore with more transmission energy from relay, signal detection at end user becomes better.

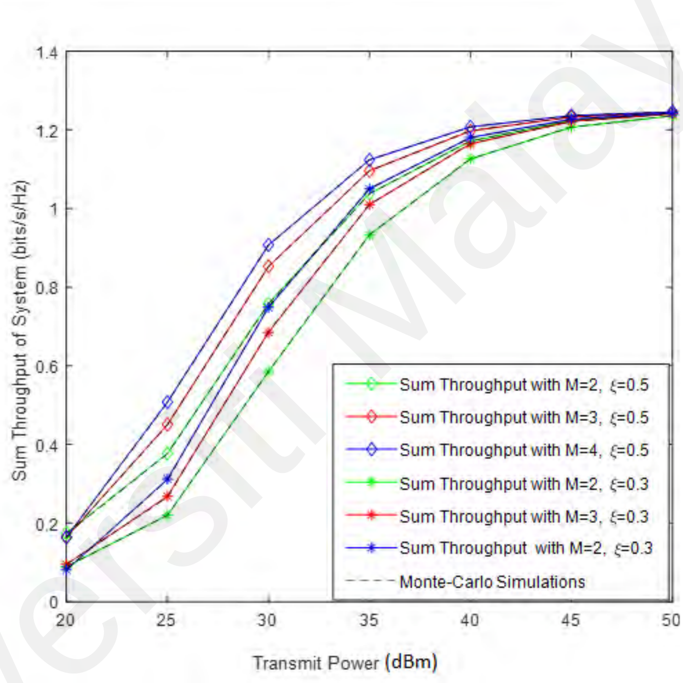


Figure 4.2: Impact of Number of Relays 'M' on System Throughput (bit/sec/Hz)

4.1.2 Effect of Power of Interfering Signal

The proposed model assumes that energy constrained relay node harvests energy from source signal and external interfering source. Fig. 4.3 shows the effect of power of interfering signal on the outage performance. Firstly the analytical values are in good agreement with Monte Carlo simulations. Additionally, when the power of interfering signals increases or interference power becomes stronger, the sum throughput of system is improved. This improvement is due to fact that relay is powered by interference in addition to source signal. So as interference power gets stronger, the amount of harvested energy is improved. The relay uses the harvested power for transmission, the greater transmission power promotes the detection process and thus performance is improved.

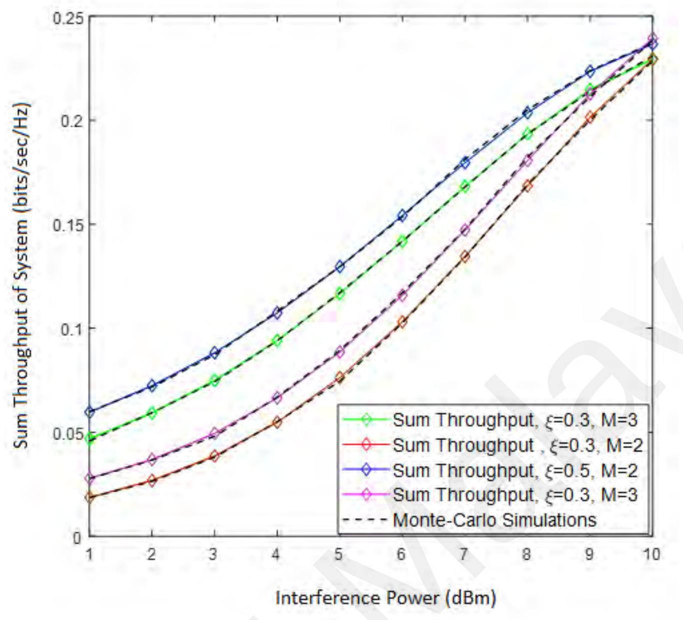


Figure 4.3: Impact of Interfering Signal on the Sum Throughput of System with N0=0.01, Ps=25 dBm

4.1.3 Effect of Conversion Efficiency

Fig. 4.4. Depicts the sum throughput versus energy conversion efficiency 'η'. Energy conversion efficiency depends upon the hardware design of energy receiver. In this work, a linear harvesting model is assumed, where this factor is assumed constant and the relationship between the energy received at input terminal and output is linear. Fig. 4.4 shows that with an increase in the conversion efficiency, outage probability decreases. This is obvious because an increase in conversion efficiency directly improves the power harvested at relay node. With higher transmit power, outage performance improves and it directly enhances the system throughput.

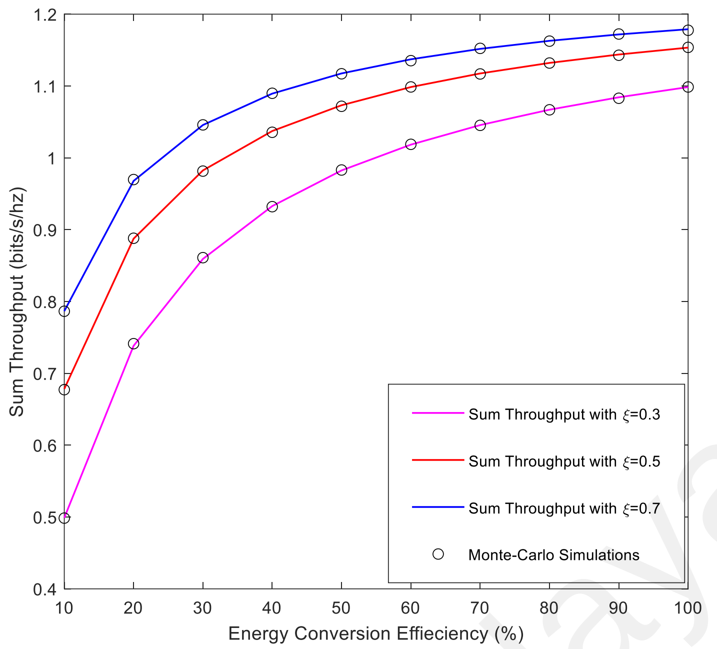


Figure 4.4: Impact of Energy Harvester Conversion Efficiency on the Sum Throughput of System with P_s=30 dBm, M=2, L=2

4.1.4 Effect of Power Splitting Ratio

Fig. 4.5 shows the sum throughput by varying the power splitting ratio, sum throughput increases as power splitting ratio 'ρ' increases from 0 to 0.9. This observation is different when C-OMA networks without interference. The outage probability of TDMA based networks without interference kept on decreasing until an optimal point. At this point probability is minimum and outage starts increasing when value of PS factor is further increased. On contradiction, when interference is involved in C-NOMA networks throughput is maximum when more power is used for energy harvesting. The reason for this behavior is that when more transmission power is available at relay node, the transmission is more reliable.

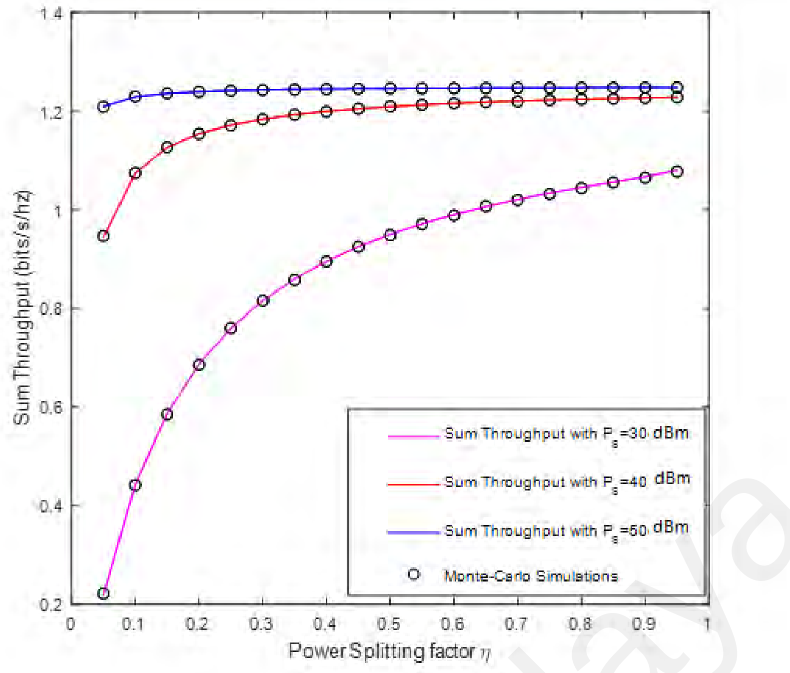


Figure 4.5: Impact of Power Splitting Parameter on the System Throughput with Varying Transmit SNR, M=2 and L=2

4.1.5 Effect of Distance

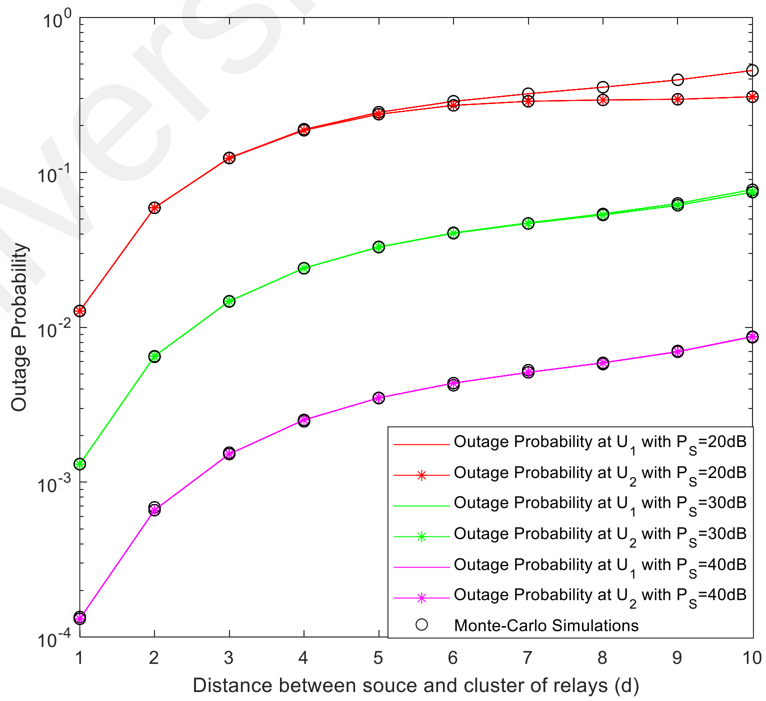


Figure 4.6: Impact of Varying Distance of Relay Cluster on Outage Performance of End Users

Fig. 4.6 plots the outage probability of end-users for delay-limited transmission mode, at different values of the BS to cluster of relays distance, d. The transmit power from BS, P_s and number of relays M=2, and noise variance N_0=0.01 are kept constant. It can be seen in the figure that throughput decreases with an increase in the distance of relays from BS. This behavior is due to the fact that with an increase in distance, both the strength of received signal and energy harvested at relay node decreases due to greater path loss. Consequently, the received signal strength at end users lessens and outage increases. It is also observed that outage doesn't increases much by increasing 'd' beyond 6m. As, the relay node comes closer to end users, lesser amount of harvested energy becomes sufficient for reliable communication. Another interesting finding is the optimal relay location, which minimizes the outage for EH NOMA networks is closer to source node. This observation is different from non EH network, where the minimal outage is achieved when relays are located mid-way between source and users.

4.1.6 Comparison with Single Relay EH-NOMA Network

Fig. 4.7 shows that when only one relay is available for cooperation, the system throughput is worst. System throughput improves with an increase in number of relays. Wireless networks are densely populated these days. Generally, multiple nodes are present between two communicating parties. The use of multiple relays can help to improve the system performance. Moreover, comparing the outage performance of both users it is observed that the outage of U_2 is slightly better than outage performance of U_1 at lower SNR, the reason of this behavior is that U_2 performs SIC to detect its own message, i.e., it eliminates interfering signal of U_1. On the other hand, U_1 does not remove interference from paired user U_2, and it results in its lesser success probability. However, as the transmit SNR improves the performance gap disappears. Another interesting fact is that the transmission data rate of U_2 is higher and more power was allocated to U_1, however, the outage performance of both users is nearly same. The outage performance at both users becomes nearly same because U_1 encounters interference from U_2, it also justifies the more power allocation to U_1. It also verifies the user fairness provided by NOMA.

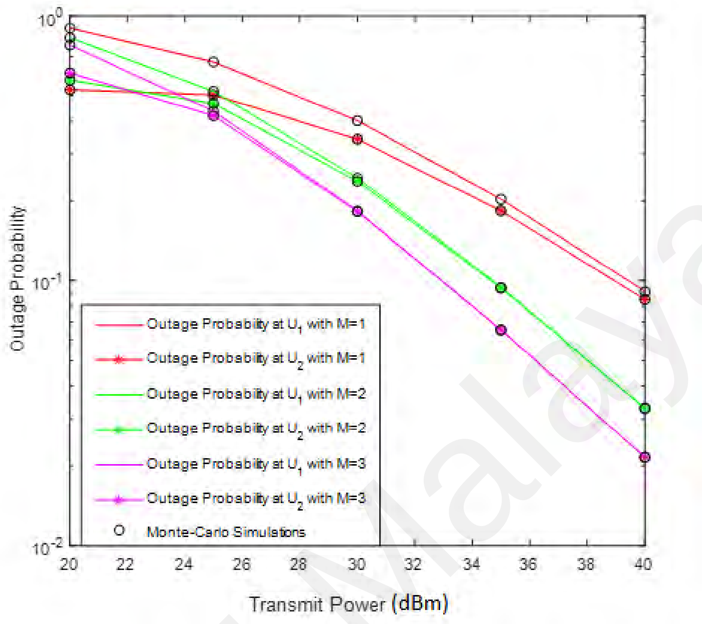


Figure 4.7: Comparative Outage Probability Analysis of Multi-Relay and Single Relay Network

4.2 Multiple Relay C-NOMA Networks with SWIPT in The Presence Of Interference and Spatially Distributed Users

In this section, the outage performance and sum throughput of near and far users with different choices of transmitting power, number of near users, power splitting ratio, path loss co-efficient, energy conversion efficiency and interference power are demonstrated and discussed.

4.2.1 Impact of Number of Relays

This section presents the outage performance of spatially distributed near and far users with increasing transmit power, different choices of number of relays and power splitting factor. Fig. 4.8 plots outage probability of near user 'P_1' and far user 'P_2' with increasing transmit power. In the figure, the black circles have been used to represent Monte Carlo simulations for each case. It is evident from figure that analytical and simulated results match well. Several conclusion can be drawn from the Fig. 4.8; comparing the outage performance of two users, it can be seen that performance of near user is better compared to far user. The path loss is less for near users which results in better performance gain. Considering the impact of power splitting factor, it is observed that by increasing ξ from 0.5 to 0.7, improves the outage performance of far user, however it causes a performance degradation at near/relay user. Since at lower PS factor, more power is left for signal detection of near user, and with increasing PS factor, more power is allocated for energy harvesting. With a decrease in available power for signal detection, outage at near user decrease, while at the same time, more power is harvested for the transmission of signal to far user. With more transmit power at near user, outage performance of end user improves. Fig. 4.8 also shows the impact of increasing number of available relaying devices in cooperative area, there is a significance improve in outage performance of near user, however this performance gap is comparatively lower in the far users. Performance improvement in near user is expected since partial relay selection considers the node with best channel conditions for relaying, the outage decreases when the best one is selected from a larger number of available nodes. The outage reduction in far user is less significant than near user. The observation is consistent to results in (Lee, Da Costa, Vien, Duong, & de Sousa Jr, 2016), where author demonstrated that for partial relay selection in AF NOMA networks, increasing number of nodes do not give significant performance gain for far users.

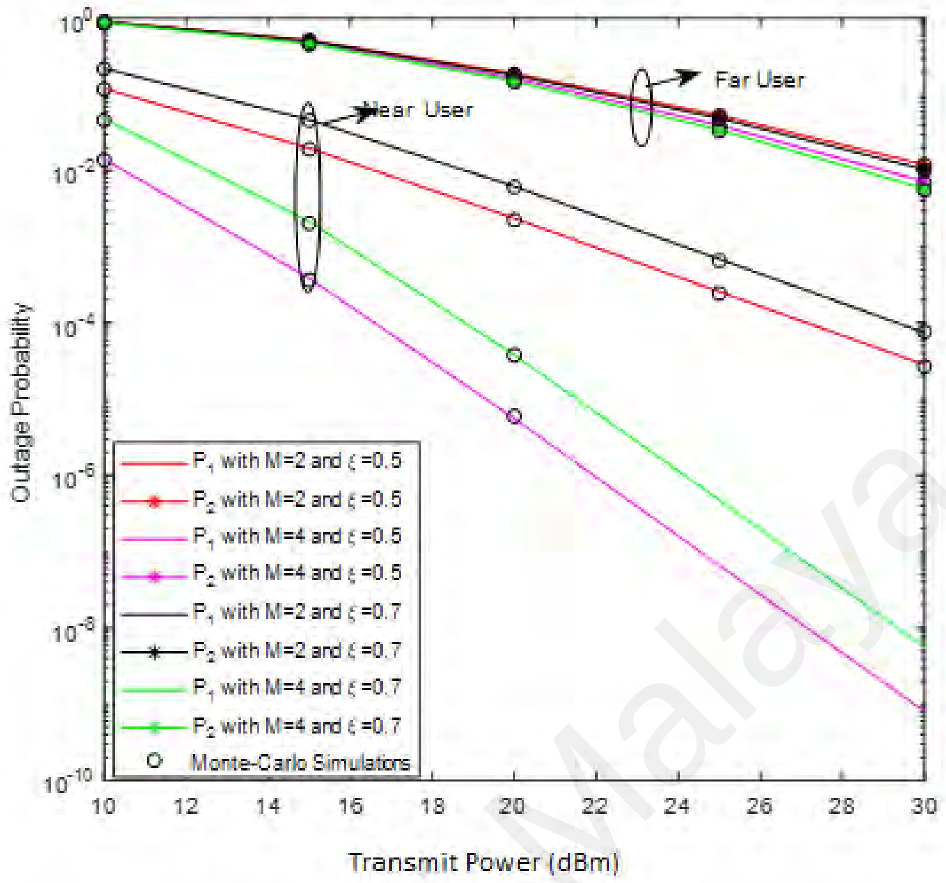


Figure 4.8: Impact of Number of Relays 'M' and Transmit Power on the Outage Performance of U_1 and U_2

Fig. 4.9 plots the sum-throughput for the considered system model taking into account the near/relay user and far user in the system. The sum throughput is plotted for varying power splitting factors and number of intermediate relay nodes 'M', while keeping the transmit power fixed to 20 dBm. It is observed that sum throughput improves with the increase in PS factor, ξ . It is deduced from the results that the sum-throughput is affected by ξ, however this effect become minimal with an increase in transmit power. When transmit power of source is greater, direct link between source and end user becomes stronger, since maximum of direct and relayed signal is selected, the effect of power splitting factor at far user becomes less significant.

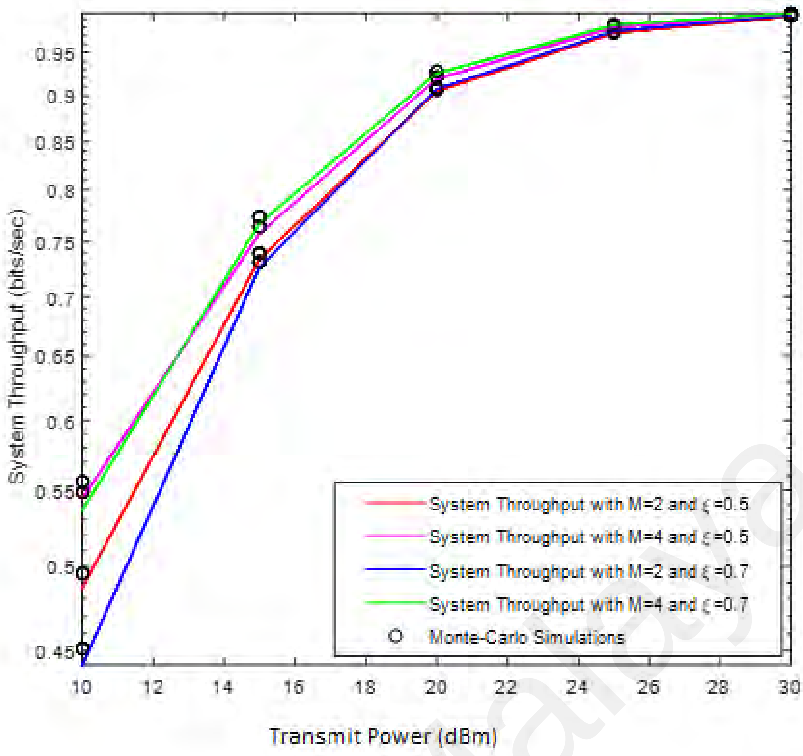


Figure 4.9: Impact of Number of Relays 'M' and Transmit Power on the System Throughput (bits/s/Hz)

4.2.2 Effect of Conversion Efficiency

Fig. 4.10. depicts the sum throughput for near/relay user and far users versus energy conversion efficiency 'η'. Energy conversion efficiency is determined by the circuitry of the energy harvester. As the conversion efficiency improves the amount of harvested energy at relay users enhances. In Fig. 4.10, sum throughput is plotted at fixed transmit power '25 dBm' for different choices of power splitting ratio. It is evident that with an increase in conversion efficiency, the system throughput for a given PS factor improves, which is obvious due to the fact that better efficiency improves the harvested power and overall transmission capacity. Comparing the result for different PSR factors, it is shown that sum throughput for higher PS factor is lesser when conversion efficiency is lower. The PS factor relates to the amount of received signal dedicated for the energy harvester, when the overall conversion efficiency of energy harvesting circuitry is lower, more

power allocation to harvest energy cause an overall greater loss in system throughput. However, as the efficiency gets improved, the system throughput is maximum for higher PS factor. It can be deduced that less PS factor is optimum for the devices with lower conversion efficiency, while higher PS factor should be used for efficient energy converting systems.

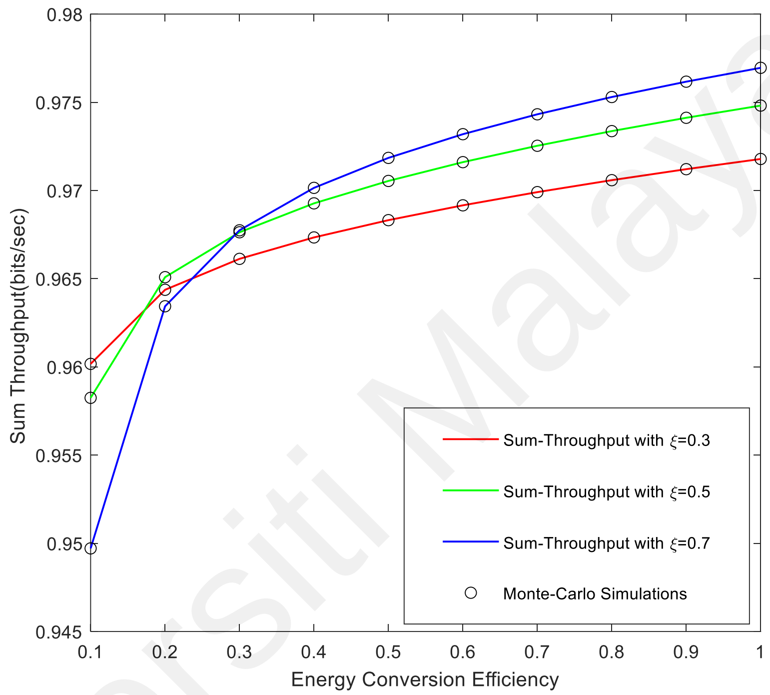


Figure 4.10: Impact of Energy Conversion Efficiency on the Outage Performance, when M=2; L=2, and Transmit Power P_s=25 dBm

4.2.3 Impact of Radius of Cooperative Disk

Fig. 4.11 shows the effect on outage performance when the radius of the cooperative area is increased. Outage performance of selected near-user is reduced when the radius of cooperative area is increased. It can be explained as when the relay user is located at a greater distance, the possibility of successful detection of its message becomes lower. It is obvious that greater path loss will effect performance adversely. On the other hand the outage probability of far user depicts a different behavior. With the increase in area outage performance at far users is degraded in the start and after a certain radius, it nearly becomes constant. Outage performance degrades quickly in the starts, as the relay node gets away from the source, the amount of harvested energy and signal detection at relay becomes less. However after a certain distance the amount of harvested energy at relay decreases, but also the relay user becomes closer to the far-user, and thus the reduced amount of energy is enough for successful transmission at far-user. Secondly, when transmission power at relay node decrease, the direct end user link is always better than the relayed transmission. Fig. 4.12 shows an overall degradation in system throughput with an increase in the radius of cooperating area.

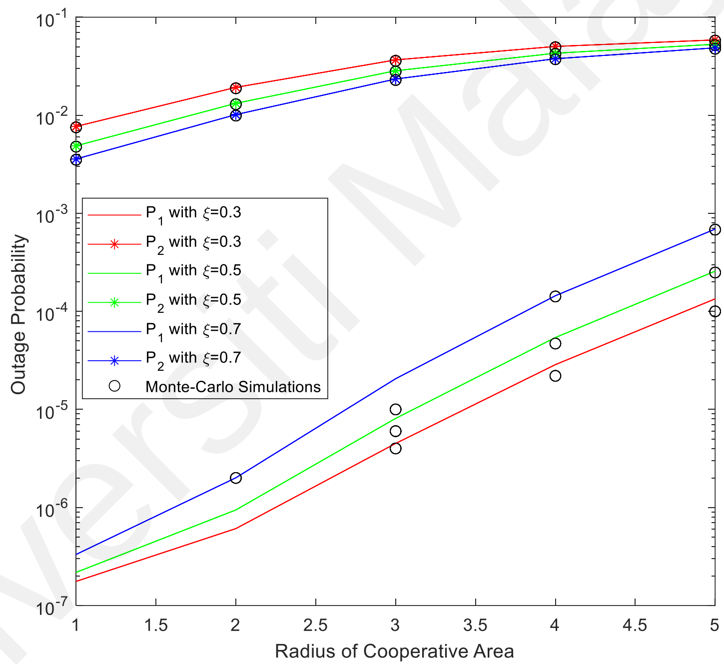


Figure 4.11: Outage Probability with an Increase in the Radius of Cooperative Area with Transmit Power =25 dBm, R_{U1}=7m, R_{U2} =8m, M=2 and L=2

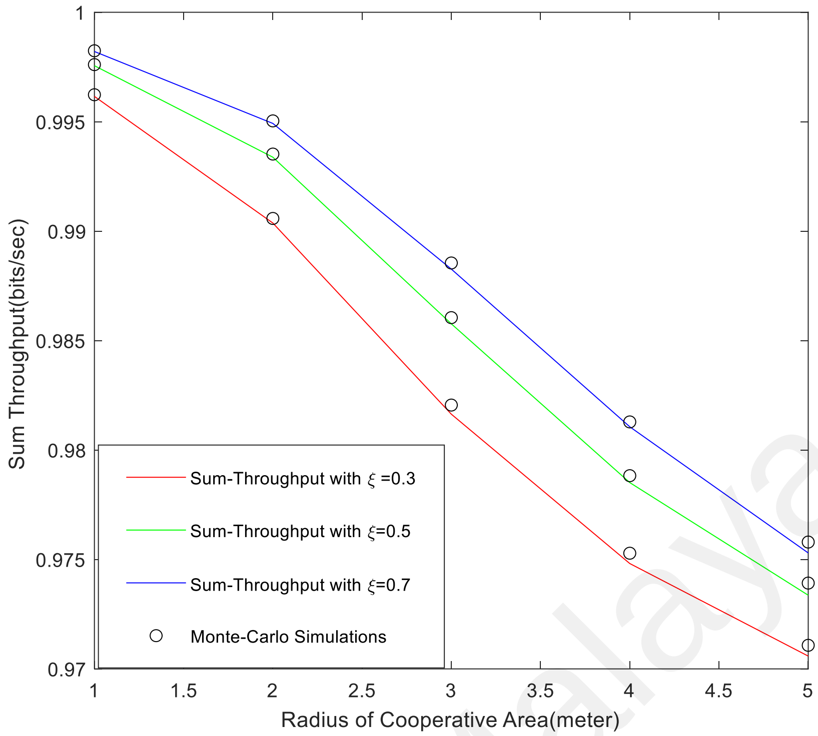


Figure 4.12: Sum-Throughput with an Increase in the Radius of Cooperative Area when Transmit Power = 25 dBm, R_{U1}=7m, R_{U2} =8m, M=2, L=2.

4.2.4 Impact of Targeted Data Rates of Users

Fig 4.13 shows the outage performance of both near/relay and far users for different data rates. The result depicts that for any value of targeted data rates outage decreases with an increase in transmit power (P_s). When the target rates for delay-limited transmission mode increase, the outage performance decreases. This is because when more data bits are expected to be transmitted over given spectral resources, the possibility of wrong detection improves.

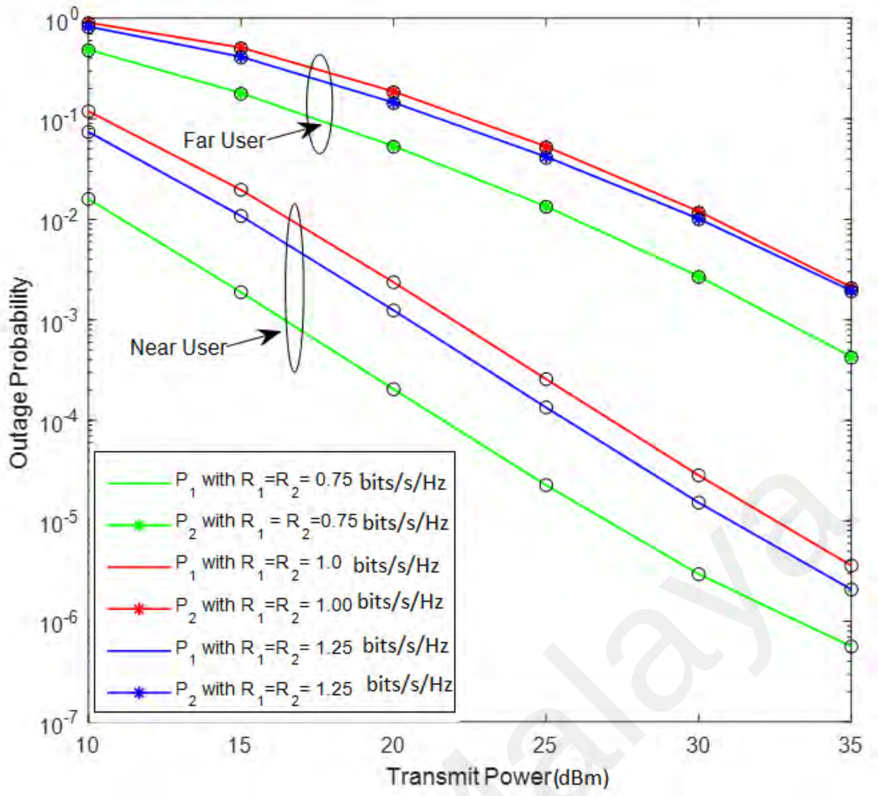


Figure 4.13: Impact of Users' Target Rate on the Outage Performance with M=2 and L=2

4.2.5 Effect of Power of Interfering Signals

Fig. 4.14 shows the impact of interference power on the outage probability of both near and far users, while transmitting power, Ps=15 dBm, noise variance, N0=0.01, and the number of relays, M=2, are kept constant. It is observed that outage performance of near user is degraded as interference power increases, this behavior is justified as the interference power increases, the SINR at near user is reduced, which in turns causes a decrease in successful detection of near user. For far-user, a slight improvement in the outage of far user with an increase in the interference power is observed. As interference power increases from 1 to 10 dBm, the outage decays from 0.5002 to 0.4999. This slight improvement is due to the fact that relay is powered by interference in addition to source signal. As interference power gets stronger, the amount of harvested energy is improved. The relay uses the harvested power for transmission, the greater transmission power ease the detection process and thus performance is improved. However, performance improvement is not very significant. With an increase in interference power at relay, the signal detection of far user also becomes challenging. According to the proposed model, the maximum of direct and relayed links is selected for transmission. Due to interference, detection at relay user becomes difficult and direct link becomes significant. Due to this reason, the impact of interference on far user doesn't appear. It can be concluded that relaying in the presence of interference does not provide any significant performance gain.

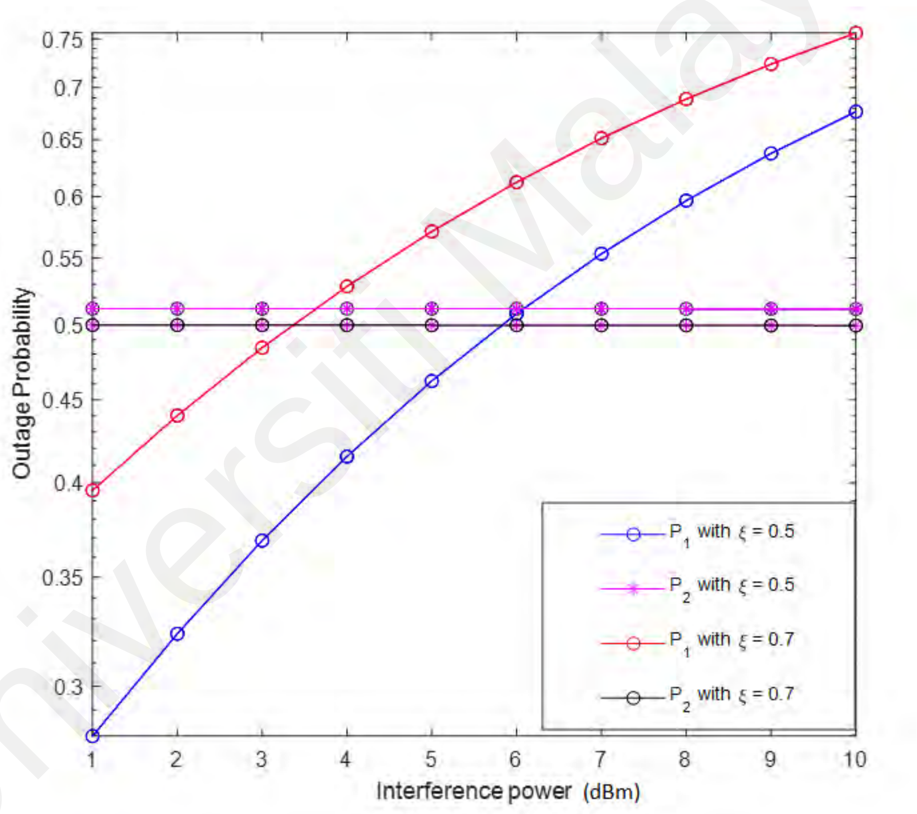


Figure 4.14: Impact of Interfering Signal on the Outage Performance of Near and Far User

4.3 Relay Selection Schemes for Cooperative NOMA (C-NOMA) with Simultaneous Wireless Information and Power Transfer (SWIPT)

This Section provides the performance analysis of the proposed two-stage relay selection scheme for C-NOMA with SWIPT in section 3.4. Outage performance of the proposed relay selection scheme is compared with partial relay selection scheme, random relay selection and C-OMA network. Unless stated, the system parameters that have been selected for all the numerical examples are as follows: channel averages $\lambda_g = \lambda_{h,1} = \lambda_{h,2} = 1$, noise variance N_0 = 0.01, energy harvesting efficiency η=0.9, path loss exponent $m=2$, PA factors for fixed NOMA α_1=3/4, α_2=1/4, PS factor ξ=0.60. In 2D space coordinates of source, cluster of relays, users U_1 and U_2 are set as (0,0), (0,x_R), (2,0.3), and (2,-0.3) respectively. Simulations results have been obtained by using 10^6 realizations of exponential channels $|g_n|^2$, $|h_{n,1}|^2$ and $|h_{n,2}|^2$. Analytical results of outage probability for two-stage relay selection and partial relay selection have been evaluated using MAPLE software.

4.3.1 Comparison of Different Relay Selection Schemes

Fig. 4.15 compares the outage probability of priority user U_1 with TS-F, TS-D, partial RS, TS-F with OMA, partial RS with OMA and RRS schemes with C-NOMA SWIPT networks by varying transmitted SNR. It is evident from Fig. that outage for both TS schemes is nearly same, since the successful detection of U_1 was targeted in both schemes. For TS-F, only relays capable to decode message of U_1 were selected, whereas for TS-D, PA factors were set to meet the QoS requirement of U_1. On comparing C-NOMA SWIPT with C- OMA SWIPT, it can be seen for all RS schemes NOMA offers a prominent performance gain over OMA. This is due to fact that using NOMA multiple users can be simultaneously served over shared resources. The outage performance is worst for case of RRS scheme, since only one relay node is available for cooperation.

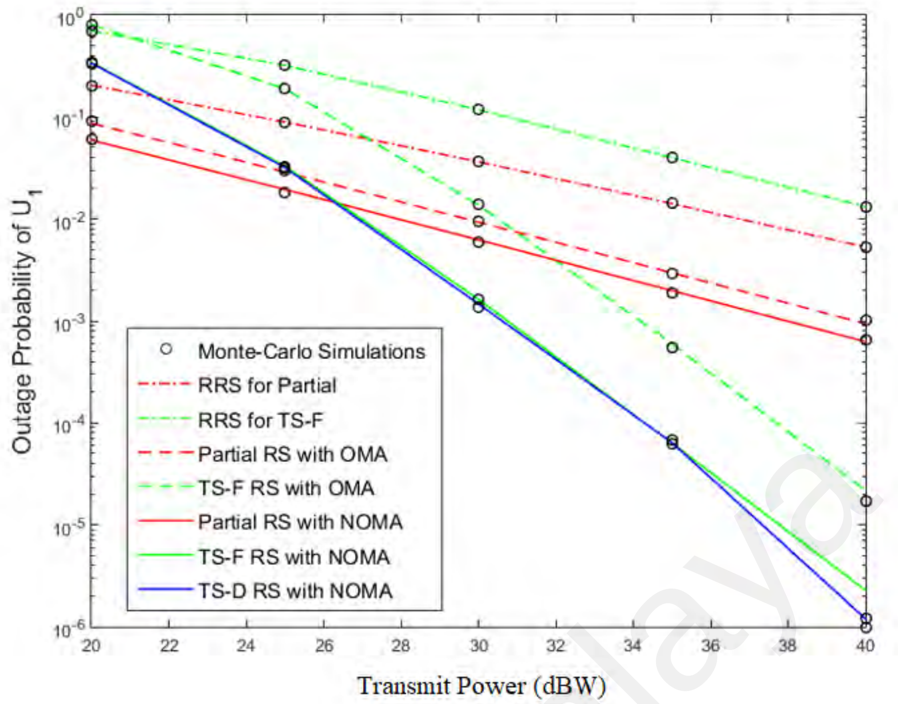


Figure 4.15: -Outage Probability of U_1 with M=3, R_1 = 0.5 bits/s/Hz, R_2 = 1.5 bits/s/Hz and the normalized distances between source and relays is $d = |x_R| = 1.3\text{m}$

Fig 4.16 plots outage probability of U_2 with TS-F, TS-D, partial RS, TS-RS with OMA, partial RS with OMA and RRS. On comparing performance of the relay selection schemes, it can be observed that for high data rate user U_2, TS-D achieves the best performance for all values of SNR. Furthermore, Fig. 4.16 manifests that C-NOMA can significantly improve the outage performance over C-OMA. The worst outage performance for RRS is understandable because when only one random relay node is available, the probability of successful detection and harvesting enough energy for transmission reduces.

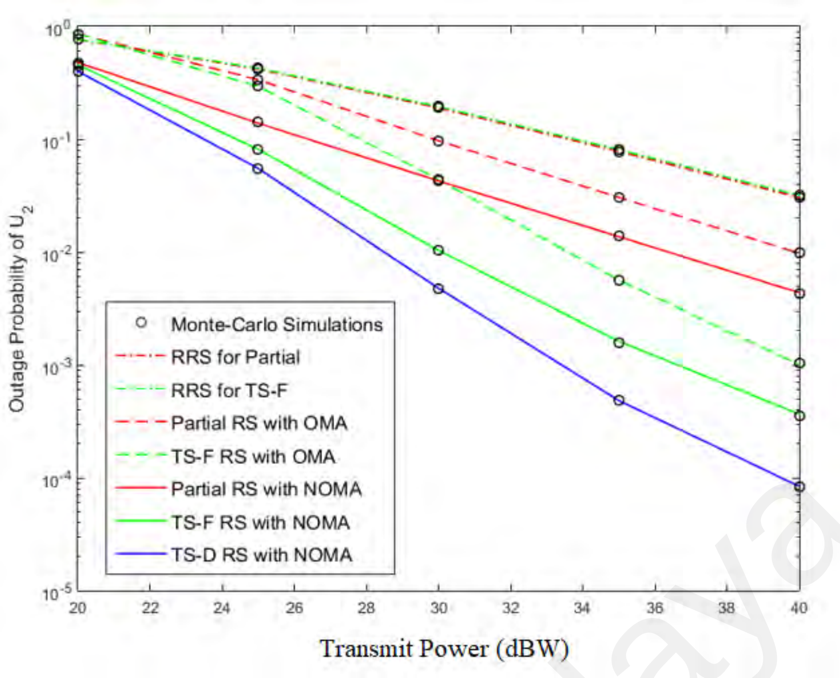


Figure 4.16: Outage Probability of U_2 with M=3, R_1 = 0.5 bits/s/Hz, R_2 = 1.5 bits/s/Hz and normalized distance $d = |x_R| = 1.3m$.

4.3.2 Effect of Increasing Number of Relay Nodes

In Fig. 4.17 outage probability of U_1 and U_2 is plotted against transmit SNR for both partial and TS-F RS schemes. It is evident from figure that outage performance is significantly improved by increasing transmitting power because of fact that achievable decoding rate and amount of harvested energy increases as transmit SNR rises. It can be also observed that performance gets improved when the number of relays increased. As the number of relays increase, the probability of selecting relays at first stage of relay selection scheme also increases, and outage is improved. Moreover, outage performance of U_1 is better than outage performance of U_2 because of two reason: (1) U_1 is the priority user, and greater power has been assigned to U_1 i.e., $\alpha_1 > \alpha_2$, (2) data rate requirement of U_1 is set lower than U_2, i.e., user 1 requires quick services with low data rate requirement.

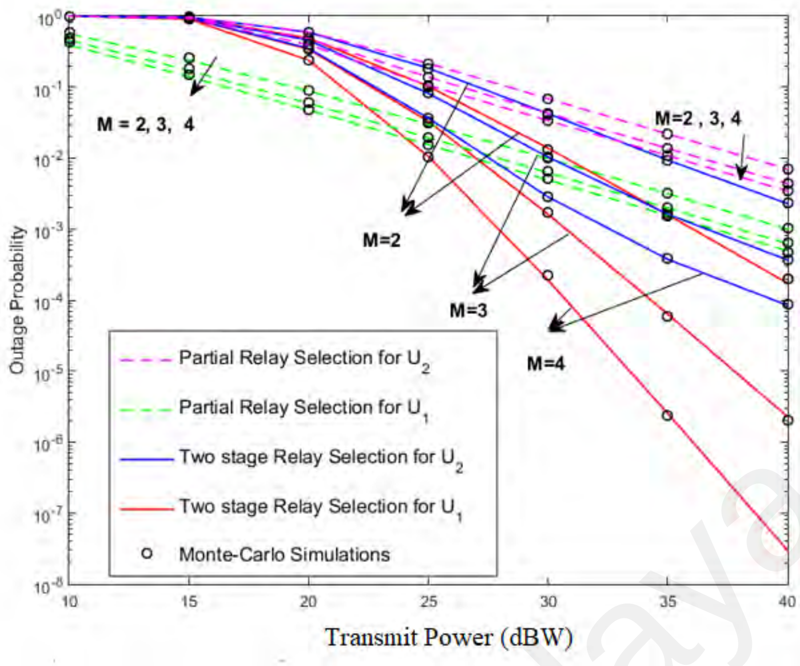


Figure 4.17: Outage Probability of TS-F and Partial RS with Increasing Number of Relays, where R_1 = 0.5 bits/s/Hz, R_2 = 1.5 bits/s/Hz and the Normalized Distances $d = |x_R| = 1.3m$

On comparing the performance of the two relay RS, it can be observed that for high data rate user U_2, two-stage relay selection performs better. For less transmitting power, for U_1, partial relay selection performs better than two-stage relay selection scheme. However, with an increase in transmitted power, outage performance of two-stage method improves substantially. Interestingly, with an increase in transmit power and number of relays, performance gain of partial relay selection does not improve considerably, whereas, for two-stage relay selection this performance gap is very significant. It can be concluded that partial relay selection does not take advantage of the network's density. The similar observation holds for AF relay network (Lee, Da Costa, Vien, Duong, & de Sousa Jr, 2016). The authors showed that partial relay selection illustrates no significant gain when number of relay nodes are increased from two to ten. So, it is safe to suggest that when more than two intermediate relays nodes are present, two-stage partial relay selection is optimal selection scheme for both end users.

4.3.3 Effect of Varying Distance of Relay

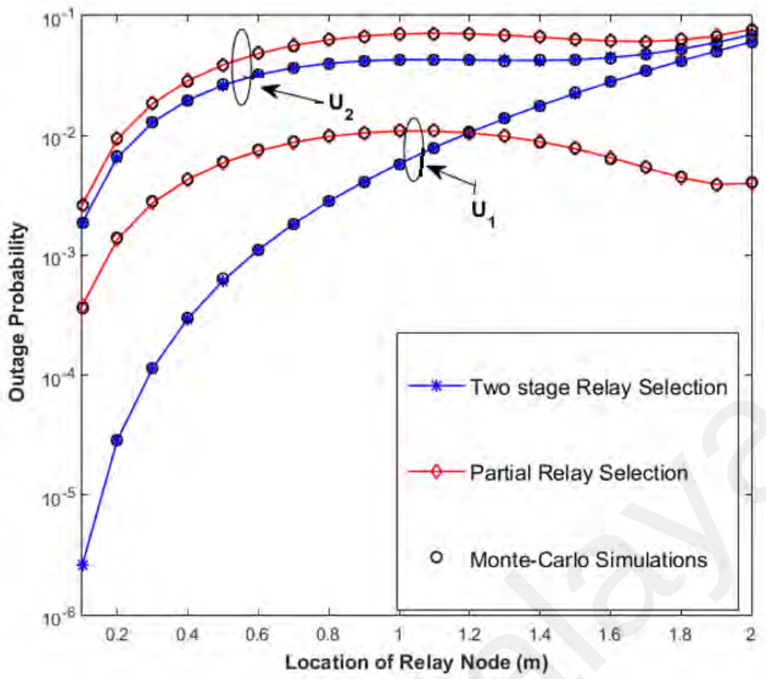


Figure 4.18: Outage probability by Varying Location of Relay Nodes, where M=2, Transmit SNR=25 dBW, R_1 = 0.5 bits/s/Hz, R_2 = 1.5 bits/s/Hz, U_1 and U_2 Fixed at distance (2, 0.3) and (2, -0.3)

Fig. 4.18 plots the outage probability of users by varying location of relay node between source and end users, while U_1 and U_2 are considered to be fixed. It is evident that for both partial and two-stage relay selection, outage probability becomes worst as the distance between source and relay node increases. This is because of the fact that the energy harvested using SWIPT decreases with an increase in distance due to higher path loss, which consequently affects the signal strength at destination node and outage performance. It can be seen that by increasing distance beyond mid-way, outage probability does not increase much. The reason for this phenomenon is that when relay node gets closer to end users, less amount of harvested energy becomes sufficient for successful communication.

4.3.4 Effect of Circuit Power Consumption

Fig. 4.19 shows the effect of circuit power on the outage performance. This effect is visible at low SNR; however, it becomes negligible when SNR increases. It can also be observed that this effect is more prominent for partial relay selection whereas for two-stage relay selection this effect is absent. The reason for this behavior is that, for two-stage relay selection, only those relays have been selected which can successfully harvest energy greater than energy required to maintain circuitry.

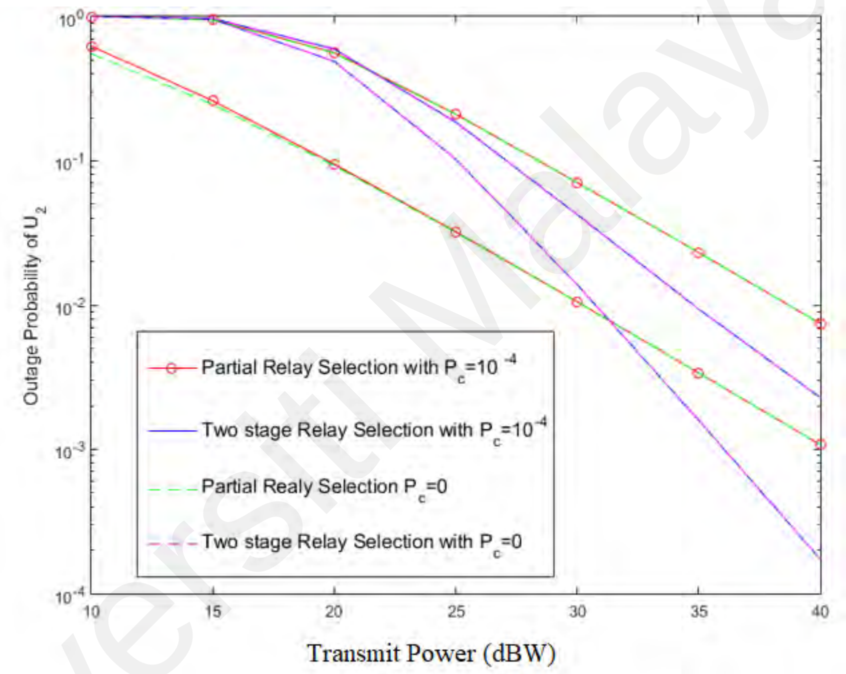
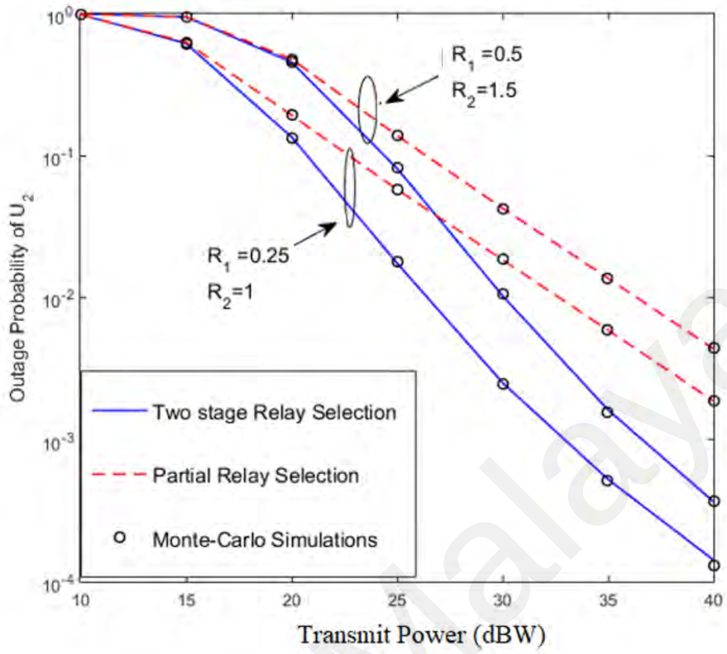


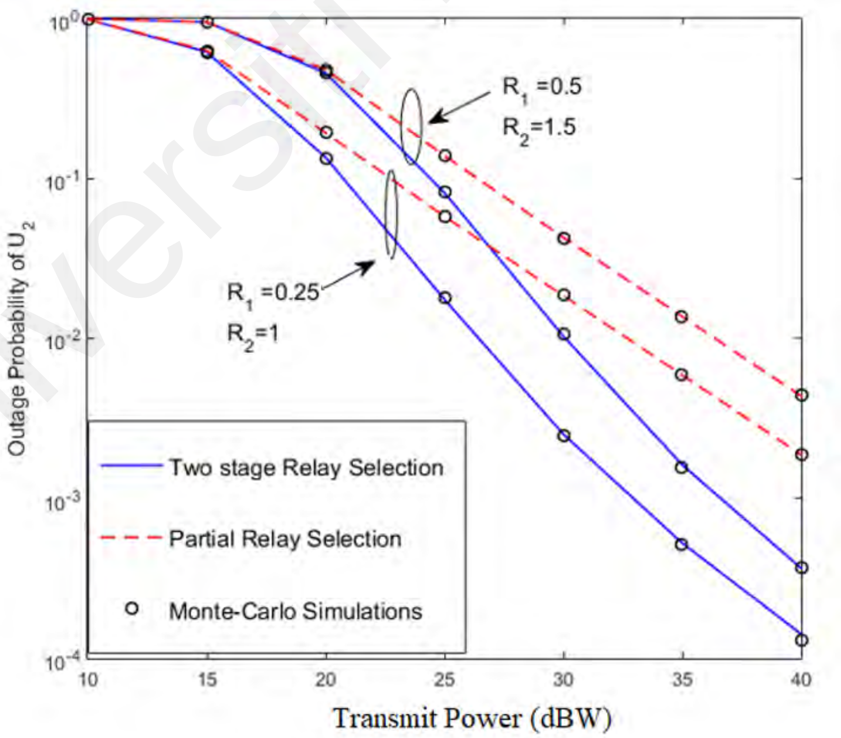
Figure 4.19: Effect of Circuit Power Consumption at Outage probability of Two-Stage and Partial RS Schemes with M=2, R_1 = 0.5 bits/s/Hz, R_2 = 1.5 bits/s/Hz

4.3.5 Effect of Users Target Data Rates

Fig. 4.20 shows how outage probability of U_1 and U_2 is affected by user's targeted data rates, respectively. It can be seen that by increasing the rates, outage probability also increases, which is general behavior for delay constraint networks. The performance difference of partial relay selection and two-stage relay selection is explained as follows: for U_1, when transmit power value is low, the partial relay selection scheme outperforms the two-stage scheme. As transmitting power increases, the outage performance of two-stage relay selection becomes minimal.



(a)



(b)

Figure 4.20: Effect of Users' Target Rates on Outage Performance of U$_1$ (a) and U$_2$ (b) with Two-Stage and Partial Relay Selection when M = 2 and $d = |x_R| = 1.3$m

The higher performance gain of partial relay selection at lower SNR is due to the reason that partial relay selection does not define any criteria for the selection of relay nodes. The best node among all available intermediate nodes is selected straightforwardly. On the other hand, for two-stage relay selection, those relays which fulfill certain conditions are selected as potential relays. At lower SNR, less number of relay meet the required conditions and hence the number of available relay nodes becomes less. For U_2, two-stage relay selection outperforms for the whole range of SNR. It is also evident that with an increase in transmit SNR, the performance gap of relay selection schemes also increases.

4.3.6 Impact of Using SWIPT on the Performance

In Fig. 4.21, the effect of using SWIPT on outage performance of U_1 and U_2 is studied by investigating the outage probability with and without SWIPT respectively. Figures show that the use of energy harvesting method at relay node results in outage loss, and the outage performance is worst when there is only one relay node. However, the performance improves when more than one relays are available for cooperation. the slope of the graph shows that the use of SWIPT does not affect the diversity gain, and diversity achieved by cooperative NOMA with energy harvesting remains the same as that of C-NOMA without SWIPT given that the number of relays is the same. This loss of outage is anticipated, using SWIPT energy is harvested from the source signal and the amount of harvested energy is much smaller compared to the case without SWIPT.

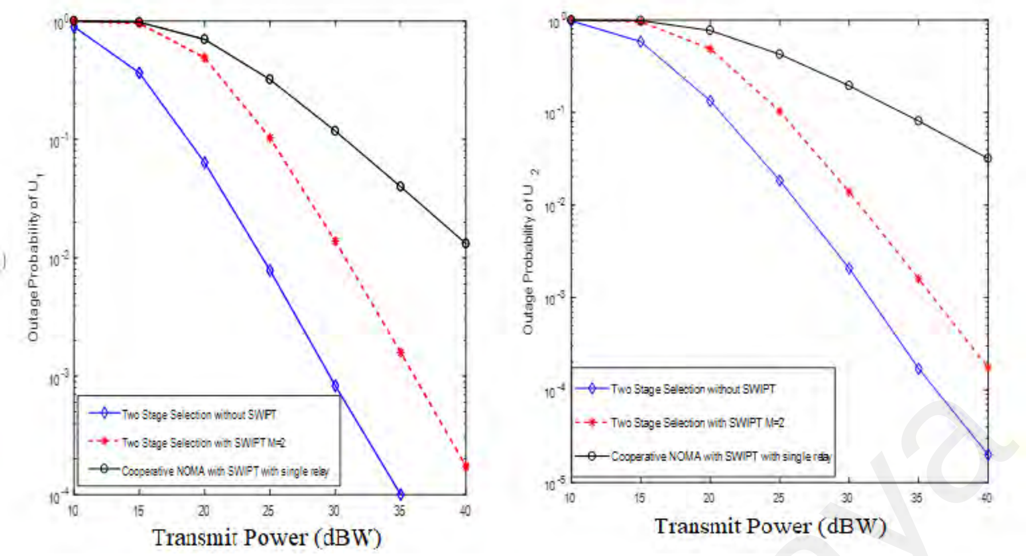


Figure 4.21: Impact of Using SWIPT with C-NOMA on the Outage Performance of U_1 (a) and U_2 (b), R_1 = 0.5 bits/s/Hz, R_2 = 2 bits/s/Hz and M=2

4.3.7 Hybrid Relay Selection Schemes

Fig. 4.22 plots TS and partial RS and hybrid relay selection scheme, with different number of relay nodes. It can be seen that hybrid relay schemes switches between TS and partial RS and avails their benefits over all SNR values. In the figure the red lines show the partial relay selection and black lines represent the two-stage relay selection, while dotted lines are representing the curves 'M=4'.This selection comes at the expense of complexity, as it requires to select the optimal relay selection scheme by comparing at given transmit SNR.

On comparing the performance of two-stage relay selection and partial relay selection in above figures, it can be concluded that two-stage relay selection is better for higher transmit SNR. Two-stage relay selection also depicts better outage performance when greater number of intermediate nodes are available for relaying the information. In existing wireless networks, the number of devices has grown enormously. There is a possibility that multiple intermediate node relay may exist between transmitter and receiver. Two-stage relay selection scheme can take advantage of network density. For denser network, two-stage relay selection is optimal relay selection criteria. On the other hand, for less dense and less complex networks, partial relay selection should be chosen.

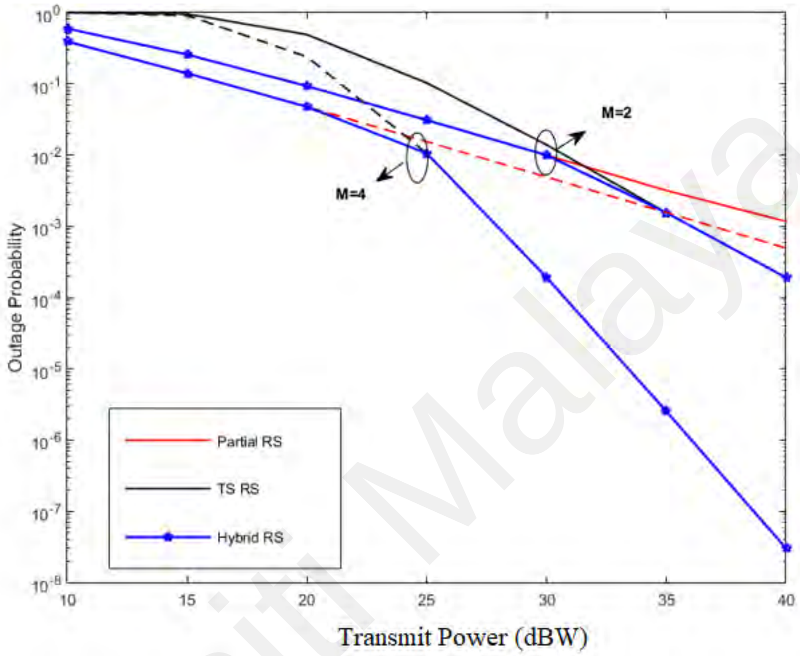


Figure 4.22: Hybrid Relay Selection for C-NOMA SWIPT Network when R_1 = 0.5 bits/s/Hz, R_2 = 1.5 bits/s/Hz

CHAPTER 5: CONCLUSION

5.1 Conclusion

To fulfill the increasing demands of future generation wireless networks, spectral efficiency, energy-saving, and cooperation among nodes are desirable. The proficient utilization of resources can help to design efficient networks for ultra-dense environments. NOMA is a new multiple access scheme that serves multiple users on shared spectral resources. SWIPT enables the devices to harvest energy from RF signals. Incorporating SWIPT in C-NOMA networks can help to design spectrally efficient networks with the capability to harvest energy from ambient resources. This study focused to design energy-efficient cooperative networks with non-orthogonal multiple accessing schemes.

The use of EH to enable devices is a major advancement to prolong the lifetime of devices and save energy. However, it is not a straightforward modification, since the harvested energy becomes random while propagating through the wireless propagation channel. Cooperative relaying has been adapted in wireless environments over decades. Cooperation provides multiple benefits including, reliability and performance improvement. In ultra-dense areas, multiple devices/nodes exist in close proximities, which can be used for cooperation. When multiple nodes are available, the selection of the best node/relay for cooperation can help to improve the energy harvesting capacity and system performance.

The presence of external interference and its adverse effect on wireless networks cannot be avoided. The mitigation of interference has been the biggest challenge for researchers and the telecommunication industry. Nevertheless, interference can be beneficial it is properly utilized as a source of energy harvesting to operate wireless nodes. Therefore, it is important to investigate the impact of interference on SWIPT enabled cooperative NOMA networks. In the first part of the study, energy harvesting communication networks are developed by exploiting interference as a source of energy harvesting. Outage performance of SWIPT enable cooperative NOMA networks with relays selection in multiple dedicated DF relaying was evaluated. The theoretical and simulations results revealed that by harvesting energy from the interference signal at the relay node, the overall sum-throughput of the system is improved. Additionally, the following results were observed during the investigation of the system; the outage performance improves by increasing transmit power, number of available relay nodes, and energy harvesting efficiency of energy harvesting receivers.

NOMA-assisted D2D enabled cooperative networks can be a beneficial solution as it exploits the direct communication links between users. The cost of dedicated relays can be avoided by cooperation among users. However, wireless nodes are spatially distributed, and it is challenging to design EH cooperative networks considering the spatial distribution of users. The second part of this work investigated SWIPT enabled multiple relay C-NOMA networks with spatially distributed users in the presence of interference. A mathematical framework to analyze the outage performance of the proposed system was provided. The numerical and simulation analysis showed that higher transmit power, number of available relaying devices, energy conversion efficiency help to reduce the outage. It was also identified that in the presence of direct link and external interference, the cooperative relaying does not provides significant performance gain. Additionally, it was observed that the optimal location of the relay node is nearest to the source.

The use of SWIPT demands some changes in the protocols and designs of wireless networks. The relay selection schemes need to be designed carefully considering the amount of harvested energy and quality of all involved wireless links. In the third part of the research, novel relay selection schemes termed two-stage relay selection scheme for C-NOMA with SWIPT networks has been proposed. The exact and asymptotic analytical expressions of the outage probability of two NOWA users of proposed schemes have been derived. The analytical and comparative analysis of two-stage relay selection showed that proposed relay selection schemes for NOMA yield better overall outage performance than C-OMA with SWIPT networks. It has been observed that with an increase in the number of relays, outage performance is improved, whereas this performance improvement is more significant for the new scheme than partial RS. For high data rate NOMA users, the outage performance of two-stage RS is always superior to partial relay RS, and the performance gap between the two schemes increases with an increase in transmitting power and number of relays. For low data rate NOMA users, partial relay selection works better only at low power regime, while two RS dominates as transmitting power increases. For SWIPT enable C-NOMA networks, the optimal location of the relay node which minimizes the outage probability is closer to the source node.

5.2 Future Directions

The amount of energy harvested from interference depends on the availability of an external source. The availability and constant power supply from external interferers are not guaranteed. During off-peak times, e.g., midnight or less populated areas, the amount of harvested energy can become insufficient. A more practical design that we intend to investigate in the future is to equip the relay nodes with energy storage. Such that the energy can be stored when ample sources are available and that stored energy can be utilized when an external source is unavailable.

Channel state information (CSI) is important in the successful detection of the work. In this work, it has been assumed that channel conditions are perfectly known at source and relay, however, a certain amount of error exists in channel estimation. A straightforward extension of this work is to investigate the impact of imperfect CSI on the overall performance of SWIPT enable C-NOMA networks. Another important point to highlight is that NOMA users can be ordered according to CSI, but it requires the knowledge of all relay to end-users channel at the relay node, which increases system overhead. This issue becomes more significant with an increase in the number of relays or NOMA users. In this work, the decoding order based on QoS requirement is adapted which means NOMA can be implemented when channel conditions between relay and users are statistically similar and relays do not need to gather CSI for links between relays and end-users. However, more general efficient decoding order schemes can be developed by considering both service priorities and ICSI. The scope of this study is limited to fixed decoding order. In our future work, a general decoding order scheme with imperfect CSI will be investigated.

Investing the SWIPT enabled C-NOMA networks in multiple antennas might give some useful results. Since, multiple antennas can boost the amount of harvested energy, also different transmitting and receiving antennas can be used for transmission and reception. Shortly, diversity gain and an increased amount of harvested power can be attained by MIMO networks. Another straightforward extension of this research is to investigate the proposed networks for the more generalized fading channels. In this work, the Rayleigh fading model has been considered, which assumes the absence of line-of-sight link between transmitter and receiver. If there is a good propagation link for the line -of-sight communication, the Rician fading channel model is an appropriate choice. More versatile fading models, for example, Nakagami-*m* and generalized K fading channel can also help to realize vast channel conditions.

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