VŠB - Technical University of Ostrava Faculty of Electrical Engineering and Computer Science

# Study of IoT Networks Inspired by the Emerging NOMA Technique: Analysis, Simulations and Improvements 

PHD THESIS

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## Study of IoT Networks Inspired by the Emerging NOMA Technique: Analysis, Simulations and Improvements

Studium IoT sítí inspirovaných objevující se technikou NOMA: analýza, simulace a vylepšení

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#### Abstract

Abstrakt Disertační práce se zabývá studiem IoT sítí inspirovanými technikou neortogonálního vícenásobného přístupu NOMA (Non-Orthogonal Multiple Access), která je klíčovou technologií v bezdrátových komunikačních sítích nové generace. Neustále rostoucí počet zařízení IoT klade větší a větší nároky na množství současně připojených zařízení, nízkou latenci a požadavky na různá prostředí, která se vyskytují v ad hoc a oportunistických sítích.

Nejprve jsem navrhl nový MPCR (Multi-Point Cooperative Relay) NOMA model, ve kterém na základě informací o stavu kanálu (CSI) vybere základnová stanice BS nejbližší zařízení UE a pošle superponovaný signál k tomuto UE jako prvnímu relay uzlu. Počet UE v síti je $N$ a v této síti existuje $N$-té UE, které je nejdále od BS a má nejhorší CSI od BS ve srovnání s jinými UE. $N$-té UE přijímá signál přeposlaný z $N-1$ uzlů, které se skládají z UE s lepším CSI. V $i$-tém $(i \in N)$ relay uzlu detekuje svou vlastní zprávu pomocí SIC (Successive Interference Cancellation) a poté předává superponovaný signál do nejbližšího nejbližšího UE, konkrétně do $(i+1)$ UE zároveň s přebytkem energie, která je použita pro EH (Emergy Harvesting) na dalším UE. Prostřednictvím tohoto procesu lze výrazně zlepšit výkon nejvzdálenějš́ho UE v síti.

Dále jsem zkoumal různé relay protokoly, konkrétně typ DF (Decode-and-Forward) a AF (Amplify-and-Forward) s pevným ziskem FG (Fixed-Gain) nebo proměnným VG (Variable Gain). Navrhl jsem protokol vícenásobného způsobu přepínání PSS (Protocol Switching Selection) pro kooperativní sítě NOMA, abych minimalizoval OP (Outage Probability) a maximalizoval propustnost systému a energetickou účinnost (EE). Disertační práce zkoumá šest scénářů. Konkrétně se jedná o kooperativní systém NOMA s (i) HD (half-duplex) s DF režimem; (ii) FD (full-duplex) s DF; (iii) HD a AF s FG; (iv) HD a AF s VG; (v) FD a AF s FG; a nakonec (vi) FD a AF s VG v relay uzlu. Poté jsem navrhl rámec Pomocí PSS se dojedná způsob přenosu, který poskytuje nejlepší výkonnostní parametry systému.

Nakonec jsem navrhl energeticky nenáročnou IoT sít s velmi nízkou latencí inspirovanou vznikající technikou C-NOMA (Cooperative-NOMA). Její model se skládá ze zdroje ve středu sítě, blízkého zařízení uvnitř sítě a vzdáleného zařízení mimo sít. Blízké zařízení slouží jako relay uzel, který pomáhá vzdálenému. Navrhnul jsem sít IoT tak, aby používala techniku SWIPT (Simultaneous Wireless Information and Power Transfer), aby blízké zařízení mohlo získávat energii a využívat ji k přeposílání. Zkoumal jsem dva spolupracující režimy přeposílání : (i) HD a (ii) FD, každý s nebo bez odposlechu. Navržený způsob pro PS (Power Splitting) využívá faktory PS k dosažení spravedlivé úrovně kvality služby (QoS) pro zařízení. Rovněž jsem odvodil nové analytické výrazy pro přesné a přibližné stanovení OP a SOP (Secrecy OP), propustnosti a Jainova indexu spravedlnosti.


Klíčová slova: IoT sítě; NOMA; SWIPT; EH; PS; TAS.


#### Abstract

The dissertation deals with the study of Internet of Things (IoT) networks inspired by the nonorthogonal multiple access (NOMA) technique, which is a key technology in next-generation wireless communication networks. An ever growing number of IoT devices require large connections, low latency and locations which depend on variable environments such those found in ad hoc and opportunistic networks.

First, I designed a novel multi-points cooperative relay (MPCR) NOMA model, in which the base station (BS) selects the nearest user equipment (UE) and sends a superposed signal to this UE as the first relay node, the selection is performed on the basis of the channel state information (CSI). The network contains $N$ UE, and the $N$-th UE, which is farthest from the BS and has the poorest CSI from the BS compared other UE. The $N$-th UE receives a forwarded signal from $N-1$ relaying nodes which consist of UE with better CSI. At the $i$-th $(i \in N)$ relaying node, it detects its own message by using successive interference cancellation (SIC) and then forwards the superimposed signal to the next nearest UE, namely the $(i+1)$-th UE , and includes an excess power which will be used to energy harvesting (EH) at the next UE. Through this process, the performance of the farthest UE in a network can be significantly improved.

Next, I examined various forwarding protocols, i.e., decode-and-forward (DF), amplify-and-forward (AF) with fixed gain (FG) or variable gain (VG). Then, I designed a multiple protocol switching selection (PSS) framework over cooperative non-orthogonal multiple access (C-NOMA) networks to minimize the outage probability (OP) and maximize the system throughput and energy efficiency (EE). The dissertation investigates six scenarios, i.e., a C-NOMA system with paired (i) half-duplex (HD) and DF; (ii) full-duplex (FD) and DF; (iii) HD and AF with FG; (iv) HD and AF with VG; (v) FD and AF with FG; and (vi) FD and AF with VG protocols at the relay. The PSS framework selects the transmission scenario which provides the best system performance.

Finally, I designed an ultra-low latency and low energy IoT network inspired by the emerging C-NOMA technique. The IoT network model consists of a source at the center of the network, a near device inside the network, and a far device outside the network. I deployed the near device as a relay to assist the far device. The near device is assumed to be a low energy node. As a result, the near device cannot forward signals to the far device through its own power. I therefore design the IoT network to apply the simultaneous wireless information and power transfer (SWIPT) technique so that the near device can harvest energy and use it to forward signals. Two cooperative IoT network scenarios are examined: (i) HD and (ii) FD relaying, each with and without eavesdroppers. The designed power slitting (PS) framework exploits PS factors for fairness in the quality of service (QoS) for the devices. Novel analysis expressions were obtained for accurate and approximate closed-forms of OP, secrecy outage probability (SOP), system throughput and Jain's fairness index.


Keywords: IoT networks; NOMA; SWIPT; EH; PS; TAS.

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## List of Abbreviations

4G fourth-generation

5G fifth-generation
ACK acknowledgment
AF amplify-and-forward

AR augmented reality
AWGN additive white Gaussian noise

BER bit error rate

BCM best cooperative mechanism

BS base station

CDF cumulative distribution function

C-NOMA cooperative non-orthogonal multiple access
CR cognitive radio
CSI channel state information
DF decode-and-forward

DoF degree-of-freedom
Dir direct

DT data transmission

EE energy efficiency

EH energy harvesting
ESC ergodic sum capacity
ETB even transmission block

ESR ergodic sum rate

FD full-duplex

FG fixed gain
FIN finish

FP first phase
FTS first time slot
G-WNs green wireless networks
HD half-duplex
HPPPs homogeneous Poisson point processes
IoT Internet of Things
LI loop interference
MIMO multi-input multi-output
MISO multi-input single-output
MPCR multi-points cooperative relay
MRC maximum ratio combining
MUD multiple user detection
NOMA non-orthogonal multiple access
OAS optimal antenna selection
OMA orthogonal multiple access
OP outage probability
OTB odd transmission block
PA power allocation
PDF probability density function
PLC power line communication
PLS physical layer security
PS power slitting
PSS protocol switching selection
RF radio frequency
RS relay selection
SAS sub-optimal antenna selection
SC selection combining

SIC successive interference cancellation
SIMO single-input-multi-output
SINR signal to interference plus noise ratio
SISO single-input single-output
SNR signal to noise ratio
SOP secrecy outage probability
SP second phase
STS second time slot
STT space-time transmission
SWIPT simultaneous wireless information and power transfer
SYN synchronization
TAS transmit antenna selection
TS time switching
TSSRS two-stage secure relay selection
UE user equipment
VG variable gain
VR virtual reality
QoS quality of service

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## Chapter 1:

## Introduction

### 1.1 Motivation and goals

THE explosive growth of mobile devices and the IoT is facing a trend of increased wireless network traffic in future networks. Researchers have confirmed NOMA as the candidate for fifth-generation (5G) wireless communication technology [1-4]. Liu et al. [5] demonstrated that a NOMA system has a better ergodic sum rate (ESR) than an orthogonal multiple access (OMA) system. The key technologies of NOMA are lower latency, enhanced fairness between users and a better efficiency spectrum because all UE is served in the same time slot or frequency by sharing the spectrum with different power allocation (PA) coefficients according to the UE channel conditions in the same power domain. The BS sends a superimposed signal to all UE in the same time slot. For example, the down-link NOMA system consists of nearby UE with strong channel conditions and distant UE with poor channel conditions [6-10]. At the UE, the signals received are decoded by applying SIC until their own information is successfully detected [11, 12]. For example, the nearby UE decodes the data symbol of the distant UE first, then decodes its own data symbol after subtracting the decoded data symbol of the distant UE. Additionally, the distant UE only decodes its own data symbol by treating the nearby UE data symbol as noise. In [6], the authors studied the outage probability (OP) and ergodic sum capacity (ESC) of NOMA systems with randomly distributed UE in the neighbourhood of the BS and verified that the performance of a NOMA system considerably outperformed an OMA system when a PA scheme was deployed.

To improve system performance, researchers have proposed many different technologies. One of them is cooperative communications, which deploys relays as an effective solution to combat fading. The authors studied FD relays to avoid wasting time slot/frequency by replacing HD relays [13]. The authors indicated that system performance could be enhanced by increasing the $m$ coefficient of the Nakagami- $m$ fading channels compared to Rayleigh fading channels [TTNam08]. As expected, in accordance with capability and reality, some wireless technologies combined with NOMA were proposed to scale up system performance, for example, cooperative communication [14, 15], FD [16]-[TTNam01], cognitive radio (CR) [17]-[TTNam02], millimetre wave [18], visible light communication [19], etc. Based on previously studied results and as the first motivation, I propose deploying $N-1$ relay nodes to support the farthest $N$ th UE with the poorest channel conditions.

Other protocols such as HD, FD, DF and AF with FG or VG have also been studied to find a better protocol to implement with NOMA technology. In [TTNam04], the DF protocol was deployed. The advantage of the DF protocol was forwarded signals without including the data symbols of the previous UE and simplicity in analysis and simulations. The authors also
considered deploying the AF protocol with FG or VG, although they demonstrated that the DF protocol is better than the AF protocol with certain parameters, and conversely, that the AF protocol is better than DF with other parameters. Because each relaying protocol has its own advantages, I therefore propose investigating the following pairing protocols: $\mathrm{HD}, \mathrm{FD}, \mathrm{DF}, \mathrm{AF}$ with FG, and AF with VG. As the second motivation, I propose a mechanism for switching adaptive protocols to optimize system performance of the IoT networks.

Previous studies have commonly assumed that only a single antenna is equipped at the network nodes. Researchers have recently proposed multiple antenna technology as a powerful option for enhancing system performance [20-23]. The authors investigated the system performance of a NOMA network with multiple antennas and an EH relay on the OP performance [24]. Although system performance can be potentially improved by equipping more antennas, the improvement is limited by the cost of radio frequency (RF) technology at the UE. To avoid expensive hardware costs and maintaining the throughput profits from multiple antennas, a transmit antenna selection (TAS) protocol was verified and accepted as a powerful option [25]. In [5], the authors investigated OP in a dual-hop relay over a multi-input multi-output (MIMO)NOMA network with TAS and maximum ratio combining (MRC) protocols over Rayleigh fading channels. From the study's results, the authors determined that system performance could be improved by increasing the number of antennas.

The physical layer security (PLS) is also a topic popular in wireless communications and IoT networks. PLS is able to see secret communications by exploiting the entropy and confuse time of wireless channels without the use of an encoding algorithm [26]. Zhang et al. [27] investigated the secrecy system performance of a single-input single-output (SISO)-NOMA system and verified the secrecy sum rate of a NOMA system as superior to a traditional OMA system. The authors investigated the PLS of NOMA systems in massive networks where all UE and eavesdroppers were located at random positions [28] and obtained new, precise asymptotic expressions for SOP [29]. The authors in [30] assumed that the BS had full CSI in both the main channels of the trusted UE and the wiretap channels of non-trusted UE. They proposed optimal antenna selection (OAS) and sub-optimal antenna selection (SAS) protocol schemes to improve the SOP performance of a MIMO-NOMA system compared to an ordinary space-time transmission (STT) protocol. Precise asymptotic expressions in closed form for the SOP of a MIMO-NOMA system were obtained in [31]. The results indicated that both SAS and OAS protocols could considerably improve secrecy performance. Lei et al. [32] investigated the secrecy performance of two types of UE over down-link NOMA systems in which SISO and multi-input single-output (MISO) schemes were applied with different TAS methods. However, the authors assumed that the UE had only one receiver antenna. From previously studied results and as the final motivation, I propose investigating OP and SOP of IoT networks.

### 1.2 Dissertation structure

The dissertation is structured as follows: Chapter 2 introduces the background knowledge; Chapter 3 describes the State-of-the-Art; Chapter 4 states the aims of the dissertation; Chapter

5 specifies my first aims, explains how to achieve the aim and then presents the results of investigation; Chapter 6 details how I may achieve my second aim and explains the research process activities for the aims; Chapter 7 describes the third aim, new PS models and examines the PS models; Finally, a conclusion for my dissertation is included in Chapter 8.

## Chapter 2:

## Background

AS a developmental version of fourth-generation (4G) wireless networks, the epoch of 5 G wireless communication networks is rising. It has been widely believed that 5 G may face the increasing demands of a data traffic explosion and new networking services, i.e., IoT, big data, virtual reality (VR), augmented reality (AR), etc. These networking services require that the 5 G wireless communication networks contain much higher bit-rates $(100 \times \sim 1000 \times$ than 4 G networks), lower latency ( 1 ms for a transmission block) and massive connections ( 106 devices $/ \mathrm{Km}^{2}$ with diverse QoS requirements) [33]. From a technical perspective, to meet the aforementioned challenges, I study some potential technologies, i.e., NOMA, cooperative networks, massive MIMO networks, EH protocol, etc., in my dissertation.

### 2.1 Overview of NOMA Networks

In comparing the benefits of the OMA technique, the NOMA technique is designed to share degree-of-freedom (DoF) among UE via superposition and consequently needs to employ multiple user detection (MUD) to separate interfered UE which shares the same DoF, as plotted in Figure 2.1.


Figure 2.1: Evolution from 4G-OMA to 5G-NOMA wireless communication networks [33].

The NOMA technique is beneficial to a large number of connections by allocating PA factors in the same DoF. Therefore, the NOMA technique may provide higher overloading transmission and further improve network capacity, wherein multiple UE with different traffic requirements may be multiplexed to transmit on the same DoF to improve latency and fairness. A comparison of OMA and NOMA is outlined in Table 1.

NOMA has therefore been confirmed as a potential multi-access technique for 5G wireless communication networks and beyond because of its higher spectral efficiency, greater number of connections, lower latency, and better fairness in QoS.

Table 1: Comparison of the OMA and NOMA techniques [33].

|  | Advantages | Disadvantages |
| :--- | :--- | :--- |
| OMA | - Simpler UE detection | - Lower spectral efficiency |
|  |  | - Lower number of UE |
|  | - Unfairness for UE |  |
|  | - Higher fairness for UE | - Higher UE complexity |
|  | - Lower latency |  |
|  | - Providing diverse QoS |  |

### 2.2 Overview of Cooperative Networks

The cooperative technique has recently raised much attention for adopting NOMA in wireless communication networks as an emerging solution to combat channel fading. In a cooperative IoT network, UE with better CSI is operated as a relaying node to receive and forward the superimposed signals to other UE with poorer CSI. The coverage of the NOMA network is thereby extended [TTNam05].


Figure 2.2: Design of a cooperative IoT network [TTNam05].

Figure 2.2 illustrates the cooperative IoT network for emerging 5 G wireless networks with a BS, a near user $U_{1}$, and a far user $U_{2}$ which is far from the BS. Since there is no direct down-link from the BS to user $U_{2}$, user $U_{1}$ is therefore deployed as a relay. In this case, user $U_{1}$ receives the superimposed signals from the BS and then forwards them to user $U_{2}$. As a result, the QoS of user $U_{2}$ is ensured.

### 2.3 Overview of MIMO-NOMA Networks

In [TTNam05], I adopted the MIMO technique for a C-NOMA network to improve networking capacity. Although the system performance, i.e., OP and system throughput, may potentially be enhanced by equipping multiple antennas, it would increase hardware costs. In studies [TTNam05, TTNam06, TTNam07], the authors deployed a TAS protocol to avoid the high hardware costs while preserving the benefits of multiple antennas.

Figure 2.3 illustrates the design of a massive MIMO-NOMA network in which all network nodes equip multiple antennas. The authors designed the pre-coding channel matrices to select


Figure 2.3: Design of massive MIMO-NOMA network [TTNam07].
the best channel from the transmitter to the receiver. As a result, the system performance of the massive MIMO-NOMA network is optimized.

### 2.4 Overview of Energy Harvesting Protocols

Another potential technology for 5G networks and beyond is the simultaneous transmission of information with RF-EH. A study [34] on wireless EH offers a deep survey of the advantages of SWIPT. The authors surveyed several SWIPT technologies, including SWIPT enabled multicarrier systems, FD SWIPT systems, etc. Given the explosion in the number of networked devices, for example IoT devices, the energy issue is especially important.


Figure 2.4: Designs of (a) TS and (b) PS architectures [34].
Two EH techniques, i.e., time switching (TS) [35] and PS [TTNam05, TTNam06, TTNam07], represent solutions for simultaneous data and energy transmission as you can see in Figure 2.4. Adoption of the SWIPT protocol is promising as a potential solution in extending a network's lifespan.

## Chapter 3:

## State-of-the-Art

In [36], the authors applied dual-hop relay systems with DF and AF protocols. The authors in [37] investigated the performance of an FD relay model over Rayleigh fading channels using the DF protocol and by optimizing the PA factors. The study in [38] inspected the effect of relay selection (RS) in C-NOMA on system performance. The authors in [39] proposed a novel best cooperative mechanism (BCM) for wireless EH and spectrum sharing for 5G networks. The studies [40-42] included AF and DF relaying. In [42], the results showed that a dual-hop power line communication (PLC) system can improve system capacity compared to direct-link transmission. Rabie et al. [43] proposed the use of multi-hop relays instead of single-hop or dualhop relays and investigated EE over PLC channels assuming log-normal fading. The studies [44, 45] analyzed the system performance of multi-hop AF/DF relaying over PLC channels in terms of average bit error rate (BER) and ESC. These studies showed that system performance can be improved by increasing the number of relays. The authors in [38] also studied the effect of RS on system performance. The results of a comparison between two-stage and max-min RS showed that a C-NOMA system over Rayleigh fading channels with two-stage RS was better than max-min RS. I hypothesized the presence of $N$ users, with the $N$-th user being farthest away from the BS and possessing the worst CSI. The QoS of the $N$-th user can be improved with the cooperation of $N-1$ users instead of adopting only single relay cooperation. At each node, best neighbor selection must be determined to forward the signal to the next neighbor. Selection of the best neighbor is repeated until the signal reaches the destination.

Relaying technology has recently gained much research interest as an effective solution to fading resistance. In the C-NOMA model, a user with the strongest CSI is selected as a relaying device which forwards the superimposed signals to users with poorer CSI. Therefore, the scope/distance of the network is expanded and the reliability of the network is enhanced by the improvement of QoS for users [46-49]. In [50], the authors investigated the OP of the AF and DF relaying schemes. The authors also proposed the use of an FD protocol instead of the HD protocol to avoid wasting time slots [13]. Although a C-NOMA network improves QoS for remote users, it also increases bandwidth costs. This problem can be solved by applying the FD relay technique. The FD relay receives and forwards a signal simultaneously in the same frequency band [51]. A disadvantage of FD relaying is the effect of the loop interference (LI) channel from its own transmitter antenna modeled as a fading channel. The LI channels are the main challenge in implementing FD relays [52]. In [52], the authors proposed interference cancellation techniques, including passive cancellation, active analog cancellation and active digital cancellation. The studies in $[53,54]$ discussed two main types of FD relay techniques, namely FD-AF relaying and FD-DF relaying. A mechanism of random switching between HD/FD relays was examined in transmit power adaptation [55]. Another full study of HD/FD relay and DF
protocol is given in [56]. Adapting previous research results, the question arises whether HD or FD protocol is more suitable. A disadvantage of the FD protocol is that it is affected by the LI channel, while HD protocol does not have any LI channel. The FD protocol, however, has a better frequency efficiency than the HD protocol. The present study proposes a protocol switching mechanism to effectively use the advantages of each protocol. This mechanism can be deployed as a sensor for relaying in future IoT networks. The authors in [57] also investigated the HD/FD relay and AF protocol with FG. Through their results, the authors demonstrated that the NOMA system outperformed an OMA system over Nakagami- $m$ fading channels. AF-VG is less interesting in research because of its complexity. Finally, this dissertation also investigates HD/FD relays which use the AF protocol with FG or VG.

Some important and recent studies similar to this research are found in [58-65]. In an excellent work [58], the authors investigated SOP for C-NOMA in CR networks and took into account the effect of a user's distance from the BS on secrecy performance. Although the authors investigated CR-NOMA with multiple users and multiple eavesdroppers, the PA coefficients for users were fixed. My objective is to implement a PA strategy to ensure QoS for users. Using SWIPT, Zhou et al. [59] improved the secrecy performance of a NOMA system based on CR networks. Another work [60] investigated the popular PLS topic to find a method to minimize power over MISO-NOMA systems. In their work in [61], the authors fully surveyed the special issues in PLS, such as PLS fundamentals, C-NOMA for PLS, cooperative jamming for PLS and hybrid C-NOMA for PLS. In another work [62], the authors investigated the secrecy performance of random MIMO-NOMA with homogeneous Poisson point processes (HPPPs) at both the BS and users over $\alpha-\mu$ fading channels. The authors obtained analysis results and verified them with Monte Carlo simulations. From the obtained results, the author indicated that SOP performance was affected by the number of users, the path-loss exponent and the number of antennas. In [63], the authors investigated a MIMO-NOMA system based on a TAS protocol for two users over Nakagami- $m$ fading channels. Although the work was interesting, the authors did not consider the PA issue, for example, in [58]. Feng et al. [64] considered the PA issue to maximize QoS for strong users while guaranteeing QoS for weak users. In another work [65], the authors investigated two source-destination pairs through two-stage secure relay selection (TSSRS) to maximize the SOP of a single source-destination pair while guaranteeing the SOP of the other pair. However, the author only equipped a single antenna for the source, relay, destination and eavesdropper. Some issues exist which demand investigation. I discuss these in the following chapters, which examine the aims of this dissertation.

The PLS in wireless communications is used especially to combat eavesdroppers. The risk of eavesdroppers is due to opportunistic broadcasting in wireless signals. Many security solutions have been proposed to improve security while information passes over a network: multi-relaying and best RS[66-68], equipped multi-antennas [69] combined multi-antennas and TAS protocol [30, 32, 70, 71], signals distributed over Nakagami- $m$ fading channels [72], optimized PA factors [73], secrecy performance in combination with SWIPT [74, 75], etc. To the best of our knowledge, no studies have investigated how to improve secrecy performance based on the PS factor. Rabie et al. [76] examined the dual-hop relay network with a source, a relay and a destination. both

TS and PS protocols were deployed and obtained OP and ergodic capacity in closed-forms. The authors confirmed that the good selection of the EH time in TS protocol and PS factor in PS protocol was the primary key to reach the best system performance. In another similarly work, it is interesting that the authors clearly analyzed TS and PS protocols in EH over cooperative wireless systems, where multiple relays assist a single destination [77]. Chen et al. [35] proposed the use of harvested power at the source to forward signals to the destination. However, the dissertation applies some "extended" issues:

- I consider how the network may simultaneously serve while the network contains multiple devices.
- I consider how the EH may be used to transmit signal.
- And, I consider how PS factors may be used to combat eavesdroppers.


## Chapter 4:

## The Aims of the Dissertation

THE dissertation has three main aims based on Chapter 3 (Sate-of-the-Art) and contributes to improving the efficiency of wireless communications in IoT networks inspired by the emerging NOMA technique.

### 4.1 Aim 1: Design of a Novel Multi-Points Cooperative Relay Model

I propose a new MPCR NOMA model to aid IoT networks instead of simply using a relay, as in previous studies. Based on the CSI, the BS selects the nearest UE with the strongest CSI and sends superimposed signals to this UE as the first relaying node. I have assumed the presence of $N$ UE in the IoT network and the $N$-th UE, which is farthest from the BS, has the poorest CSI compared to the other UE. The $N$-th UE receives a forwarded signal from $N-1$ relaying nodes, which are UE with better CSI. At the $i$-th relaying node, it detects its own symbol by using SIC and forwards the superimposed signal to the next nearest UE, denoted by the $(i+1)$-th UE. The superimposed signal also includes excess power which is used for EH purposes at the next UE. Through these, OP performance at the farthest UE in an IoT network can be significantly improved. In addition, I will derive the closed form expressions of OP at the UE over both the Rayleigh and Nakagami- $m$ fading channels. Analysis and simulation results will be investigated through the use of a suitable simulation method to verify that the effectiveness of the proposed model is consistent for IoT wireless networks.

### 4.2 Aim 2: System Performance Optimization of an IoT-NOMA Network

This aim is to analyze the effect of the forwarding protocols over IoT networks assisted by C-NOMA networks, minimize OP performance and maximize system throughput and EE performance. The proposal analyzes six scenarios: ( $i$ ) C-NOMA system with HD and DF protocols at the relay; (ii) C-NOMA system with FD and DF protocols at the relay; (iii) C-NOMA system with HD and AF with FG protocols at the relay; (iv) C-NOMA system with HD and AF with VG protocols at the relay; $(v)$ C-NOMA system with FD and AF with FG protocols at the relay; (vi) C-NOMA system with FD and AF with VG protocols at the relay. From on these six scenarios, I aim to determine which one demonstrates optimal transmission for best system performance. I will propose a mechanism for switching between HD/FD and DF/AF with FG/VG protocols to improve the QoS for UE with poor CSI. This mechanism can be deployed in future wireless sensor networks. EE will also be assessed in relation to future green wireless networks (G-WNs).

I will also adopt the MIMO technique to improve the system performance of IoT-NOMA networks. However, the third aim is to optimize the system performance of IoT-NOMA networks.

I will therefore consider a TAS protocol to select the best signal at the receivers (relays and terminal devices). Then, I will exploit the instantaneous AF factor maximization for the AF protocol which gives the best system performance.

### 4.3 Aim 3: OP and SOP Improvement in IoT-NOMA Networks by Adopting SWIPT

I will examine a low energy IoT network, inspired by the use of the emerging C-NOMA wireless communication technique. The IoT network model consists of a source at the center of the network, a nearby device inside the network and a distant device outside the network. The distant device, however, is in the proximity of the nearer device. I will deploy the nearby device as a relay to assist the distant device. The experiment assumes that the energy of the nearby device is low. As a result, the nearby device cannot forward signals to the distant device. The IoT network therefore applies the SWIPT technique on the nearby device to harvest energy and uses the harvested energy to forward the signals. Two cooperative IoT network scenarios will be examined: HD/FD relaying with an eavesdropper and HD/FD relaying without an eavesdropper. This proposal will also exploit PS factors for QoS fairness within the devices and examine how system performance may be improved. Accurate and approximate closed form expressions will be obtained in this novel analysis for OP, SOP, system throughput and Jain's index fairness.

## Chapter 5:

## Novel Multi-Points Cooperative Relay Model

In the dissertation, I focus on MPCR in NOMA networks to improve the QoS for UE which is far from the BS and has poor CSI. The main contributions of the dissertation in this work are:

- A proposed down-link NOMA network with random $N$ UE.
- An MPCR model to improve QoS for the $N$-th UE farthest from the BS by using $N-1$ UE as DF relaying nodes in HD/FD mode. Each $U E_{i}$ relaying node receives and forwards a superimposed signal to next hop, i.e., $U E_{i+1}$, which is the nearest to $U E_{i}$. This process repeats until the superimposed signal is sent to the farthest UE, i.e., $U E_{N}$.
- A clearly presented algorithm for OP investigations of UE in MPCR.
- At $U E_{i}$ for $\forall i>1$, the received signal has excess power which is used for EH to charge the battery, assuming unlimited battery capacity.
- Investigated OP and system throughput for each UE, written in closed form expressions.
- Clearly presented analysis and simulation results, with Monte Carlo simulations ( $10^{6}$ samples of channels) produced in the Matlab ${ }^{1}$ software to verify my propositions.

Note that the outcomes in the Chapter 5 have been published in the paper [TTNam03] entitled "Multi-points cooperative relay in NOMA system with N-1 DF relaying nodes in HD/FD mode for N user equipment with energy harvesting", in (MDPI) Electronics, 8 (2), art. no. 167 (2019). DOI: 10.3390/electronics8020167. IF 1.764

### 5.1 System Models

Previous studies of NOMA considered a direct (Dir) down-link scenario which served a number of users in the same time slot. These studies, however, generally applied a fixed number of users and therefore have not shown the generality of the model. To ensure generality, I have upgraded the model to a random and unpredictable number of users.

### 5.1.1 Direct Link Scenario

The authors analyzed different NOMA techniques, including power domain and code domain [10]. The role of the power domain has been proved important in determining the performance of the system through the availability of CSI [78].

[^0]The BS sends a superimposed signal $S$ to all UE in the same power domain and same time slot according to the equation:

$$
\begin{equation*}
S=\sqrt{P_{0}} \sum_{j=1}^{N} \sqrt{\alpha_{j}} x_{j} . \tag{5.1}
\end{equation*}
$$



Figure 5.1: An IoT NOMA system with $N$ UE.
Thus, the received signal at the $i$-th UE, $\forall i \in\{1, \ldots, N\}$, can be expressed as:

$$
\begin{equation*}
y_{i}^{D i r}=h_{0, i} \sqrt{P_{0}} \sum_{j=1}^{N} \sqrt{\alpha_{j}} x_{j}+n_{i}, \tag{5.2}
\end{equation*}
$$

where $h_{0, i}$ denotes the channels from the BS to each $i$-th UE over a Rayleigh or Nakagami- $m$ fading channel. Furthermore, $N$ is a random number of UE linked to the network, $\alpha_{j}$ in the rule such that $\sum_{j=1}^{N} \alpha_{j}=1$ is a PA factor for each UE and $P_{0}$ is the transmission power of the BS. $n_{i}$ denotes the additive white Gaussian noise (AWGN) of the $i$-th UE, where $n_{i} \sim C N\left(0, N_{0}\right)$ with zero mean, variance $N_{0}$ and $i \in\{1, \ldots, N\}$.

It is important to highlight that the channel coefficient from the BS to each UE is expressed as $h_{0, i}$ in our expressions.

In a Dir link scenario, the first user with the strongest CSI at the nearest distance from the BS was ranked first in the channel gain list. The list is in decreasing order according to:

$$
\begin{equation*}
\left|h_{0,1}\right|>\left|h_{0,2}\right|>\ldots>\left|h_{0, i}\right|>\ldots>\left|h_{0, N-1}\right|>\left|h_{0, N}\right| . \tag{5.3}
\end{equation*}
$$

According to NOMA theory, users with the worst signal quality should be given priority to allocate the highest PA factor. In terms of NOMA characteristics, I have also assumed that the BS already owns the CSI of all UE fully. In a previous study [79], the authors considered that CSI is available to the system and used to determine the decoding order of user data. The authors in [7] studied how NOMA performance depends on PA techniques to ensure fairness for users under instantaneous CSI and average CSI. The superimposed signals are sent to the UE in the same power domain with different PA factors, in the purpose of ensuring system performance and service quality fairness for all users. Therefore, the list of PA factors is arranged in descending
order for each UE in the network according to:

$$
\begin{equation*}
\alpha_{1}<\alpha_{2}<\ldots<\alpha_{i}<\ldots<\alpha_{N-1}<\alpha_{N} . \tag{5.4}
\end{equation*}
$$

In Figure 5.1, $U E_{N}$ is farthest from the BS. The $x_{N}$ symbol is therefore allocated the strongest PA factor and will be first decoded at all UE in the network by applying SIC [80]. The order of decoding is done sequentially according to the reversed list of PA factors presented in equation (5.4). The signal to interference plus noise ratio (SINR) of all UE are expressed as:

$$
\begin{equation*}
\gamma_{i \rightarrow x_{j}}^{D i r}=\frac{\left|h_{0, i}\right|^{2} \rho_{0} \alpha_{j}}{\left|h_{0, i}\right|^{2} \rho_{0} \sum_{k=1}^{j-1} \alpha_{k}+1}, \tag{5.5}
\end{equation*}
$$

where $i \in\{1, \ldots, N\}$ and $j \in\{N, \ldots, i\}$.
In a special case at the $U E_{1}$, after it decodes the $x_{j}$ symbols, where $j \in\{N, \ldots, 2\}$, by using (5.5), $U E_{1}$ decodes its own symbol $x_{1}$ with only AWGN $n_{1}$ according to:

$$
\begin{equation*}
\gamma_{1 \rightarrow x_{1}}^{D i r}=\left|h_{0,1}\right|^{2} \rho_{0} \alpha_{1} . \tag{5.6}
\end{equation*}
$$

Furthermore, $\rho_{0}$ in (5.5) or (5.6) is the signal to noise ratio (SNR), which is be given by:

$$
\begin{equation*}
\rho_{i}=\frac{P_{i}}{N_{0}}, \tag{5.7}
\end{equation*}
$$

where $i \in\{0, \ldots, N-1\}$, e.g., $\rho_{0}=P_{0} / N_{0}$, where $P_{0}$ is the transmitting power of the BS.
The achievable instantaneous bit rate of the $i$-th UE when it decodes the $x_{j}$ symbol, where $x_{j} \in\left\{x_{N}, \ldots, x_{i}\right\}$, is given by:

$$
\begin{equation*}
R_{i \rightarrow x_{j}}^{D i r}=\log _{2}\left(1+\gamma_{i \rightarrow x_{j}}^{D i r}\right), \tag{5.8}
\end{equation*}
$$

where $i \in\{1, \ldots, N\}$ and $j \in\{N, \ldots, i\}$. If $i \neq j \neq 1, \gamma_{i \rightarrow x_{j}}^{D i r}$ is then given by (5.5). If $i=j=1$, $\gamma_{i \rightarrow x_{j}}^{D i r}$ is then given by: (5.6).

### 5.1.2 $N-1$ DF Relaying Nodes Scenario

The system model in [43] has only one relay to improve the QoS of UE which is far from the BS. I propose an improved model which uses MPCR instead of only one user as a relay device. In Figure 5.1, we can see $N$ users in the network with descending order channel conditions where the $N$-th UE has the poorest signal compared to other UE. Figures 5.2 a and 5.2 b show the $N-1$ HD relaying nodes model and $N-1$ FD relaying nodes model, respectively. In FD mode, the relays are affected by the LI channels, which themselves affect system performance. This dissertation investigates the system performance on MPCR in HD or FD mode for $N$ users over Rayleigh or Nakagami- $m$ fading channels. Previous studies on the NOMA system used a cooperative relay to improve system performance rather than a direct transmission system. The
contributions of previous studies $[7,79,81]$ are the motivation for this dissertation to continue creating improvements in system performance.
Z. Ding et al. [38] proposed a RS method to select the best relay with the best channel conditions by using a two-stage relay RS which outperformed the max-min RS protocol. In [38], the authors selected the best relay in $N$ relays to serve two other users [38]. In my proposed models as shown in Figures 5.2 a and 5.2 b , all the $N-1$ UE can be selected as relaying nodes. The selected relaying node set is initialized empty $\varpi=\emptyset$, and the first relaying node can be selected according to:

$$
\begin{equation*}
\varpi_{1}=\max \left\{R_{i \rightarrow x_{1}}^{\Omega}>R_{1}^{*}\right\} \tag{5.9}
\end{equation*}
$$

where $R_{i \rightarrow x_{1}}^{\Omega}$ is given by (5.22), and $\varpi_{1}$ has been added into $\varpi=\varpi \cup \varpi_{1}$.


Figure 5.2: The NOMA system with $N-1$ relaying nodes in HD/FD mode.

The BS sends a superimposed signal to the nearest distance user with the strongest channel conditions, i.e., $U E_{1}$ in Figures 5.2a and 5.2b, after the BS successfully selects $U E_{1}$ as a relay. It is important to point out the difference. In this dissertation, each relay node has either a single or twin antenna which works in HD or FD mode.

The received signals at $U E_{1}$ in HD or FD mode are the same as (5.2) or (5.10), respectively, as follows:

$$
\begin{equation*}
y_{1}^{F D}=h_{0,1} \sqrt{P_{0}} \sum_{j=1}^{N} \sqrt{\alpha_{j}} x_{j}+h_{L I, 1} \sqrt{P_{0}} \tilde{x}_{1}+n_{1} \tag{5.10}
\end{equation*}
$$

where $h_{L I, 1}$ is the LI channel generated by the transmitter antenna itself and $n_{1}$ is the AWGN noise of the device $U E_{1}$.

If the $U E_{1}$ works in HD relaying mode, $U E_{1}$ decodes its own symbol by applying (5.5) or (5.6). If $U E_{1}$ works in FD relaying mode, $U E_{1}$ decodes the $x_{j}$ symbol, where $j \in\{N, \ldots, 2\}$ or $j=1$, by applying the SINR in (5.11a) or (5.11b):

$$
\begin{align*}
\gamma_{1 \rightarrow x_{j}}^{F D} & \triangleq \frac{\left|h_{0,1}\right|^{2} \rho_{0} \alpha_{j}}{\left|h_{0,1}\right|^{2} \rho_{0} \sum_{k=1}^{j-1} \alpha_{k}+\left|h_{L I, 1}\right|^{2} \rho_{1}+1}  \tag{5.11a}\\
& \triangleq \frac{\left|h_{0,1}\right|^{2} \rho_{0} \alpha_{1}}{\left|h_{L I, 1}\right|^{2} \rho_{1}+1} \tag{5.11b}
\end{align*}
$$

The $U E_{1}$ then sends a superimposed signal, i.e., $S_{1}$ given by (5.13), to the UE which is the next nearest relay node, i.e., $U E_{2}$. The second relay node can be selected by applying the equation:

$$
\begin{equation*}
\varpi_{2}=\max \left\{R_{i \rightarrow x_{2}}^{\Omega}>R_{2}^{*}, i=\{1, \ldots, N\}, i \notin \varpi\right\} \tag{5.12}
\end{equation*}
$$

where $R_{i}^{\Omega}$ is also given by (5.22), not being contained in the $\varpi$ set, which is a selected relay nodes set. I removed $U E_{i}$ where $i \in \varpi$ from relay selection because the signal could be sent back to the previous relay node and the superimposed signal is unable to send to $U E_{N}$. Furthermore, $\varpi_{2}$ is also then added to $\varpi$. Note that the nearest neighbor represented in $[82,83]$ are the neighbors closest to the BS. However, the authors in [84] extended the definition of the nearest neighbor as a device which can set up the transmission channel in the best conditions compared to other devices.

A superimposed signal is sent to the next relay node, expressed by:

$$
\begin{equation*}
S_{1}=\sqrt{P_{1}}\left(\sqrt{\alpha_{1}} x_{\emptyset}+\sum_{j=2}^{N} \sqrt{\alpha_{j}} x_{j}\right) \tag{5.13}
\end{equation*}
$$

where $x_{\emptyset}$ is an empty information symbol which was also $x_{1}$ decoded at $U E_{1}$.
The received signals at $U E_{2}$ in both HD and FD relaying modes are expressed, respectively, as:

$$
\begin{equation*}
y_{2}^{H D}=h_{1,2} \sqrt{P_{1}}\left(\sqrt{\alpha_{1}} x_{\emptyset}+\sum_{j=2}^{N} \sqrt{\alpha_{j}} x_{j}\right)+n_{2} \tag{5.14}
\end{equation*}
$$

and

$$
\begin{equation*}
y_{2}^{F D}=h_{1,2} \sqrt{P_{1}}\left(\sqrt{\alpha_{1}} x_{\emptyset}+\sum_{j=2}^{N} \sqrt{\alpha_{j}} x_{j}\right)+h_{L I, 2} \sqrt{P_{2}} \tilde{x}_{2}+n_{2} \tag{5.15}
\end{equation*}
$$

where $h_{1,2}$ is the channel from $U E_{1}$ to $U E_{2}, P_{1}$ denotes the transmitting power at $U E_{1}$, and $h_{L I, 2}$ is the LI channel from the transmitting antenna to the receiving antenna at $U E_{2}$. Specifically, the $x_{1}$ symbol existed in (5.2) and (5.10) but was replaced by the $x_{\emptyset}$ symbol in (5.14) and (5.15) because $x_{1}$ was previously decoded and removed from the superimposed signal by $U E_{1}$. Therefore, the $x_{\emptyset}$ symbol does not contain information and becomes redundant in the superimposed signal. The dissertation proposes using the excess power from the $x_{\emptyset}$ symbol for EH purposes. This is described in the next section.

The SINR to decode $x_{j}$ symbol and its own $x_{2}$ symbol at $U E_{2}$ in HD relaying mode can be expressed, respectively, as:

$$
\begin{align*}
\gamma_{2 \rightarrow x_{j}}^{H D} & \triangleq \frac{\left|h_{1,2}\right|^{2} \rho_{1} \alpha_{j}}{\left|h_{1,2}\right|^{2} \rho_{1} \sum_{k=2}^{j-1} \alpha_{k}+1}  \tag{5.16a}\\
& \triangleq\left|h_{1,2}\right|^{2} \rho_{1} \alpha_{2} . \tag{5.16b}
\end{align*}
$$

Similarly, the SINR to decode $x_{j}$ symbol and its own $x_{2}$ symbol at $U E_{2}$ in FD relaying mode can be expressed, respectively, as:

$$
\begin{align*}
\gamma_{2 \rightarrow x_{j}}^{F D} & \triangleq \frac{\left|h_{1,2}\right|^{2} \rho_{1} \alpha_{j}}{\left|h_{1,2}\right|^{2} \rho_{1} \sum_{k=2}^{j-1} \alpha_{k}+\left|h_{L I, 2}\right|^{2} \rho_{2}+1}  \tag{5.17a}\\
& \triangleq \frac{\left|h_{1,2}\right|^{2} \rho_{1} \alpha_{2}}{\left|h_{L I, 2}\right|^{2} \rho_{2}+1} \tag{5.17b}
\end{align*}
$$

where $j \in\{N, \ldots, 3\}$ in expressions (5.16a) and (5.17a) or $j=2$ in (5.16b) and (5.17b).
After $U E_{2}$ decodes its own symbol, it selects the next relay node and sends a new superimposed signal to the nearest UE, i.e., $U E_{3}$. This process loops until a superimposed signal is sent to the farthest UE, i.e., $U E_{N}$ in Figure 5.2.

Proposition 1: In the dissertation, I propose an EH model which uses the excess power in superimposed signals for the purposes of EH, as depicted in Figure 5.3. As expressed in (5.18) and (5.19), the received signals at the $i$-th UE, where $i \in\{2, \ldots, N\}$, have an empty $x_{\emptyset}$ symbol with no information. Thus, the PA factors of each empty symbol can be harvested. In previous studies, the power for EH was transmitted to users via different time slots or different antennas on the receivers. However, in my research, I use only one antenna and same time slot for receiving both signals and energy from the transmitter.


Figure 5.3: DF protocol and EH protocol at the i-th $U E$ node.

In general, the received signals at $U E_{i}$ in both the HD and FD relaying nodes can be rewritten, respectively, as:

$$
\begin{equation*}
y_{i}^{H D}=h_{i-1, i} \sqrt{P_{i-1}}\left(\sum_{l=1}^{i-1} \sqrt{\alpha_{l}} x_{\emptyset}+\sum_{k=i}^{N} \sqrt{\alpha_{k}} x_{k}\right)+n_{i} \tag{5.18}
\end{equation*}
$$

and

$$
\begin{equation*}
y_{i}^{F D}=h_{i-1, i} \sqrt{P_{i-1}}\left(\sum_{l=1}^{i-1} \sqrt{\alpha_{l}} x_{\emptyset}+\sum_{k=i}^{N} \sqrt{\alpha_{k}} x_{k}\right)+h_{L I, i} \sqrt{P_{i}} \tilde{x}_{i}+n_{i}, \tag{5.19}
\end{equation*}
$$

where $y_{i}^{H D}$ and $y_{i}^{F D}$ denote the received signals at the $U E_{i}$ node, $h_{i-1, i}$ is the channel from the previous node to the current node, and $P_{i-1}$ and $P_{i}$ are the transmitting power of the previous UE and current UE, respectively. It is important to notice that $\sum_{l=1}^{i-1} \alpha_{l}+\sum_{k=i}^{N} \alpha_{k}=1$.

The SINR of each $i$-th UE relaying node for detecting the $x_{j}$ symbol in HD and FD modes are expressed, respectively, as:

$$
\begin{align*}
\gamma_{i \rightarrow x_{j}}^{H D} & \triangleq \frac{\left|h_{i-1, i}\right|^{2} \rho_{i-1} \alpha_{j}}{\left|h_{i-1, i}\right|^{2} \rho_{i-1} \sum_{k=i}^{j-1} \alpha_{k}+1},  \tag{5.20a}\\
& \triangleq\left|h_{i-1, i}\right|^{2} \rho_{i-1} \alpha_{i}, \tag{5.20b}
\end{align*}
$$

and

$$
\begin{align*}
\gamma_{i \rightarrow x_{j}}^{F D} & \triangleq \frac{\left|h_{i-1, i}\right|^{2} \rho_{i-1} \alpha_{j}}{\left|h_{i-1, i}\right|^{2} \rho_{i-1}^{j-1} \sum_{k=i}^{j-1} \alpha_{k}+\left|h_{L I, i}\right|^{2} \rho_{i}+1},  \tag{5.21a}\\
& \wedge \frac{\left|h_{i-1, i}\right|^{2} \rho_{i-1} \alpha_{i}}{\left|h_{L I, i}\right|^{2} \rho_{i}+1}, \tag{5.21b}
\end{align*}
$$

where $i \in\{1, \ldots, N\}$ and $j \in\{N, \ldots, i+1\}$ in (5.20a) and (5.21a), and $i=j$ in (5.20b) and (5.21b).

In NOMA theory, the attainable instantaneous bit rate can be calculated according to:

$$
\begin{equation*}
R_{i \rightarrow x_{j}}^{\Omega}=\Delta \log _{2}\left(1+\gamma_{i \rightarrow x_{j}}^{\Omega}\right), \tag{5.22}
\end{equation*}
$$

where $\Omega=\{H D, F D\}, \Delta=1 / 2$ for $\Omega=H D$ or $\Delta=1$ for $\Omega=F D, i \in\{1, \ldots, N\}$, and $j \in\{N, \ldots, i\}$. If $i \neq j$, then $\gamma_{i \rightarrow x_{j}}^{\Omega}$ is given by (5.20a) or (5.21a). If $i=j$, then $\gamma_{i \rightarrow x_{j}}^{\Omega}$ is given by ( 5.20 b ) or ( 5.21 b ).

A selected relay node can be expressed by:

$$
\begin{equation*}
\varpi_{i}=\max \left\{R_{i \rightarrow x_{j}}^{\Omega}>R_{j}^{*}, i \in\{1, \ldots, N\}, i \notin \varpi\right\} . \tag{5.23}
\end{equation*}
$$

Furthermore, a selected relay node set $\varpi$ after the signal has been sent to the $U E_{N}$ includes:

$$
\begin{equation*}
\varpi=\varpi_{1} \cup \varpi_{2} \cup \ldots \cup \varpi_{N-1} . \tag{5.24}
\end{equation*}
$$

### 5.2 System Performance Analysis

In this section, I evaluate the performance of the proposed system, first in terms of OP and then system throughput.

### 5.2.1 Outage Probability

For the analysis, OP is defined as the occurrence of the transmitting event ceasing if any instantaneous bit rate in (5.8) or (5.22) cannot reach the minimum bit rate thresholds.

The probability density function (PDF) and cumulative distribution function (CDF) of Rayleigh distribution are described, respectively, as:

$$
\begin{equation*}
f_{\left|h_{a, b}\right|^{2}}(x)=\frac{1}{\sigma_{a, b}^{2}} e^{-\frac{x}{\sigma_{a, b}^{2}}}, \tag{5.25}
\end{equation*}
$$

and

$$
\begin{equation*}
F_{\left|h_{a, b}\right|^{2}}(x)=1-e^{-\frac{x}{\sigma_{a, b}^{2}}} \tag{5.26}
\end{equation*}
$$

where $\left|h_{a, b}\right|^{2}$ are random independent variables, i.e., $x$ in PDF and CDF, $a$ and $b$ are the source and destination, respectively, and $\sigma_{a, b}^{2}$ is the mean of the channel where $\sigma_{a, b}^{2}=E\left[\left|h_{a, b}\right|^{2}\right]$.

In general, the PDF and CDF over Nakagami- $m$ fading channels can be expressed, respectively, as:

$$
\begin{equation*}
f_{\left|h_{a, b}\right|^{2}}(x)=\left(\frac{m}{\sigma_{a, b}^{2}}\right)^{m} \frac{x^{m-1}}{\Gamma(m)} e^{-\frac{m x}{\sigma_{a, b}}}, \tag{5.27}
\end{equation*}
$$

and

$$
\begin{align*}
F_{\left|h_{a, b}\right|^{2}}(x) & =\frac{\gamma\left(m, \frac{m x}{\sigma_{a, b}^{2}}\right)}{\Gamma(m)} \\
& =1-e^{-\frac{m x}{\sigma_{a, b}^{2}} \sum_{j=0}^{m-1}\left(\frac{m x}{\sigma_{a, b}^{2}}\right)^{j} \frac{1}{j!}} . \tag{5.28}
\end{align*}
$$

In a Dir link scenario, an outage event occurs if $U E_{i}$, where $i \in\{1, \ldots, N\}$, cannot decode the $x_{j}$ symbol, where $j \in\{N, \ldots, i\}$. The OP for each UE joining the NOMA system is expressed as:

$$
\begin{equation*}
\Theta_{i}^{D i r}=1-\prod_{j=N}^{i} \operatorname{Pr}\left(R_{i \rightarrow x_{j}}^{D i r}>R_{j}^{*}\right) . \tag{5.29}
\end{equation*}
$$

where $R_{i \rightarrow x_{j}}^{D i r}$ is given by (5.8) and $R_{j}^{*}$ is the bit rate threshold of $U E_{j}$.
By applying the PDF in (5.25) and (5.27), equation (5.29) is solved and can be rewritten in closed form as:

$$
\begin{equation*}
\Re \Theta_{i}^{D i r}=1-\prod_{j=N}^{i} e^{-\frac{R_{j}^{* *}}{\chi_{j} \rho_{0} \sigma_{0, i}^{2}}} \tag{5.30}
\end{equation*}
$$

and

$$
\begin{align*}
& \aleph \Theta_{i}^{D i r} \\
& =1-\prod_{j=N}^{i}\left[\frac{\left(\frac{m}{\sigma_{0, i}^{2,}}\right)^{m}\left(\left(\frac{m}{\sigma_{0, i}^{2}}\right)^{-m} \Gamma(m)+\left(\frac{R_{j}^{* *}}{\chi_{j} \rho_{0}}\right)^{m}\left(\frac{m R_{j}^{* *}}{\chi_{j} \rho_{0} \sigma_{0, i}^{2}}\right)^{-m}\left(\Gamma\left(m, \frac{m R_{j}^{* *}}{\chi_{j} \rho_{0} \sigma_{0, i}^{2}}\right)-\Gamma(m)\right)\right)}{\Gamma(m)}\right], \tag{5.31}
\end{align*}
$$

where $\Gamma$ (.) and $\Gamma(.,$.$) are the gamma function and gamma incomplete function, respectively.$ Furthermore, $R_{j}^{* *}=2^{2 R_{j}^{*}}-1$. It is important to notice that (5.30) and (5.31) have users over Rayleigh and Nakagami- $m$ fading channels, respectively. In addition, $\chi_{j}$ in (5.30) and (5.31) is given by:

$$
\begin{align*}
& \chi_{j} \triangleq \alpha_{j}-R_{j}^{* *} \sum_{k=1}^{j-1} \alpha_{k}  \tag{5.32a}\\
& \chi_{j} \triangleq \alpha_{1} \tag{5.32b}
\end{align*}
$$

where $\forall i$, and $j \in\{N, \ldots, 2\}$ in (5.32a). Furthermore, $i=j=1$ in Equation (5.32b).
Remark 1: Based on the proposed model with $N-1$ relaying nodes as illustrated in Figure 5.2 , the present study investigates the OP of $N$ UE nodes in both HD and FD modes, expressed by:

$$
\begin{equation*}
\Theta_{i}^{\Omega}=(1-\underbrace{\prod_{l=1}^{i-1} \operatorname{Pr}\left(R_{l \rightarrow x_{i}}^{\Omega}>R_{i}^{*}\right)}_{\eta})(1-\underbrace{\prod_{j=N}^{i} \operatorname{Pr}\left(R_{i \rightarrow x_{j}}^{\Omega}>R_{j}^{*}\right)}_{\mu}) \tag{5.33}
\end{equation*}
$$

where $\eta$ is the successful probability of detecting the $x_{i}$ symbol at previous UE and $\mu$ is the successful probability of detecting the $x_{j}$ symbol at the $i$-th UE. In a special case of the $i$-th UE where $i=1$, it is important to notice that $\eta$ in (5.33) is equal to zero and (5.33) becomes identical to (5.29). In (5.33), $\eta$ and $\mu$ are also solved by applying the CDF and obtained OP of each UE node in closed form over a Rayleigh fading channel on both HD and FD modes, respectively, according to:

$$
\begin{equation*}
\Re \Theta_{i}^{H D}=\underbrace{(1-\underbrace{\prod_{l=1}^{i-1} e^{-\frac{R_{i}^{* *}}{\psi_{i} \rho_{l-1} \sigma_{l-1, l}^{2}}}}_{\eta})}_{A_{1}} \underbrace{(1-\underbrace{\prod_{j=N}^{i} e^{-\frac{R_{j}^{* *}}{\chi_{j} \rho_{i} \sigma_{i-1, i}^{2}}}}_{\mu})}_{A_{2}} \tag{5.34}
\end{equation*}
$$

and

$$
\begin{align*}
\Re \Theta_{i}^{F D} & =\underbrace{(1-\underbrace{\prod_{l=1}^{i-1}\left(e^{-\frac{R_{i}^{* *}}{\psi_{i} \rho_{l-1} \sigma_{l-1, l}^{2}}} \frac{\psi_{i} \rho_{l-1} \sigma_{l-1, l}^{2}}{\psi_{i} \rho_{l-1} \sigma_{l-1, l}^{2}+R_{i}^{* *} \rho_{l} \sigma_{h_{L I, l}}^{2}}\right)}_{l})}_{B_{1}} \\
& \times \underbrace{(1-\underbrace{\prod_{j=N}^{i}\left(e^{-\frac{R_{j}^{* *}}{\chi_{j} \rho_{i-1} \sigma_{i-1, i}^{2}}} \frac{\chi_{j} \rho_{i-1} \sigma_{i-1, i}^{2}}{\chi_{j} \rho_{i-1} \sigma_{i-1, i}^{2}+R_{j}^{* *} \rho_{i} \sigma_{L I, i}^{2}}\right.}_{\mu})}_{B_{2}}) \tag{5.35}
\end{align*}
$$

The following information clarifies: $\Re \Theta_{i}^{\Omega}$, where $i \in\{1, \ldots, N\}$ and $\Omega=\{H D, F D\}$, denotes the OP of $U E_{i}$ over Rayleigh fading channels. The $\eta$ symbol in both (5.34) and (5.35) is the successfully detected $x_{i}$ symbol at $U E_{l}$ probability, where $l \in\{1, \ldots, i-1\}$. Similarly, the $\mu$ symbol in both (5.34) and (5.35) is the successfully detected $x_{j}$ symbol, where $j \in\{N, \ldots, i\}$ at the $U E_{i}$. The two cases are as follows:

- In the first case, $i=1, \eta=0$ in both (5.34) and (5.35). The OP of the $U E_{1}$ in HD/FD mode is $\Re \Theta_{i}^{\Omega}=\left\{A_{2}, B_{2}\right\}$.
- In the second case, $\forall i>1$ and $\Re \Theta_{i}^{\Omega}=\left\{A_{1} A_{2}, B_{1} B_{2}\right\}$ in (5.34) and (5.35).

In the second case only: $\psi_{i}$ in both (5.34) and (5.35) is given by

$$
\begin{equation*}
\Psi_{i}=\left(\alpha_{i}-R_{i}^{* *} \sum_{k=l}^{i-1} \alpha_{k}\right) . \tag{5.36}
\end{equation*}
$$

In both cases: $\chi_{j}$ is given by (5.32a) or (5.32b) after it has been rewritten, respectively, as:

$$
\left[\begin{array}{l}
\chi_{j} \triangleq \alpha_{j}-R_{j}^{* *} \sum_{k=i}^{j-1} \alpha_{k}  \tag{5.37}\\
\chi_{j} \triangleq \alpha_{i}
\end{array}\right.
$$

Remark 2: The results presented in the studies [85] have firmly contributed to the role of the NOMA over Rayleigh fading channels. However, studies of NOMA over the Nakagami- $m$ fading channels have received little attention because of the system's complexity. I therefore investigate the OP of each UE over Nakagami- $m$ fading channels with $m=2$ on both $N-1$ HD/FD relaying nodes. Furthermore, (5.33) can be solved by applying the PDF in (5.27), which is expressed in closed form, as this dissertation's contribution.

$$
\left.\left.\begin{array}{rl}
\aleph \Theta_{i}^{H D, m=2}= & \underbrace{(1-\underbrace{\prod_{l=1}^{i-1}\left[e^{-\frac{2 R_{i}^{* *}}{\psi_{i} \rho_{l-1} \sigma_{l-1, l}^{2}}} 2 R_{i}^{* *}+\psi_{i} \rho_{l-1} \sigma_{l-1, l}^{2}\right.}_{\eta}}_{C_{1}} \psi_{i} \rho_{l-1} \sigma_{l-1, l}^{2} \tag{5.38}
\end{array}\right]\right), ~(\underbrace{(1-\underbrace{\prod_{j=N}^{i}\left[e^{-\frac{2 R_{j}^{* *}}{\chi_{j} \rho_{i-1} \sigma_{i-1, i}^{2}}} \frac{2 R_{j}^{* *}+\chi_{j} \rho_{i-1} \sigma_{i-1, i}^{2}}{\chi_{j} \rho_{i-1} \sigma_{i-1, i}^{2}}\right]}_{\mu})}_{C_{2}},
$$

and

Two cases have been described above. It is not necessary to present these cases again. The analysis results are presented in the next section. See the Appendix for proofs of the remarks.

$$
\begin{aligned}
& \aleph \Theta_{i}^{F D, m=2}
\end{aligned}
$$

### 5.2.2 System Throughput

The total achievable received data rate at $U E_{i}$, which is denoted as the system throughput $P_{\text {sum }}^{\Omega}$, is the sum of the throughput results of all UE in the system, given by:

$$
\begin{equation*}
P_{\text {sum }}^{\Omega}=\sum_{i=1}^{N} P_{i}^{\Omega}=\sum_{i=1}^{N}\left(1-\Theta_{i}^{\Omega}\right) R_{i}^{*} \tag{5.40}
\end{equation*}
$$

### 5.2.3 A Proposal for Energy Harvesting

Proposition 2: In (5.18) and (5.19), the received signals at $U E_{i}$, where $\forall i>1$, include two parts which are the $x_{k}$ data symbol and $x_{\emptyset}$ empty symbol, where $k \in\{i, \ldots, N\}$ and $l \in\{1, \ldots, i-1\}$. The $x_{\emptyset}$ symbol does not contain any information. I therefore propose collecting the energy of the PA factors of the $x_{\emptyset}$ symbols for charging the battery. Another assumption is that the battery is not limited by capacity. Thus, the EH for each UE in both HD and FD scenarios is expressed by:

$$
\begin{equation*}
E H_{i}=\xi \sqrt{\sum_{l=1}^{i-1} \alpha_{l} \rho_{i-1}\left|h_{i-1, i}\right|^{2}} \tag{5.41}
\end{equation*}
$$

where $i \in\{2, \ldots, N\}$ and $\xi$ is the collection coefficient.

### 5.3 A Proposed Algorithm for N-1 Relaying Nodes

Proposition 3: In this section, a proposed algorithm for processing with $N-1$ relaying nodes is shown in Figure 5.2. The treatment flow is executed in a waterfall pattern in the order shown in Figure 5.3.

1. Generate random $N$ UE in the network with $N$ channels from the BS to UE.
2. Create a list of channels in descending order, the best channel being at the top of the list. Upon completion of the list, the BS will know which user is best to select for use as the first hop relaying node.
3. From the results of analysis [79], the authors found that the performance of a NOMA system depends on the efficiency of the PA factors and appropriate selection of the bit rate threshold. Lack of CSI may affect the performance of the NOMA system. I have assumed that at the BS and each UE, full CSI of the UE is available. According to the order of CSI as shown in (5.3), the allocated PA factors and the selected bit rate thresholds for the UE are calculated according to:

$$
\begin{equation*}
\alpha_{i}=\frac{\min \left(\sigma_{0, j}^{2}\right)}{\sum_{k=i}^{N} \sigma_{0, k}^{2}} \tag{5.42}
\end{equation*}
$$

and

$$
\begin{equation*}
R_{i}^{*}=\frac{\max \left(\sigma_{0, i}^{2}\right)}{\sum_{k=i}^{N} \sigma_{0, k}^{2}} \tag{5.43}
\end{equation*}
$$

where in ordering and pairing $i \in\{1, \ldots, N\}$ and $j \in\{N, \ldots, 1\}$. After the BS allocates the PA factors to the UE, logically, a superimposed signal is sent to the nearest UE which has has been selected as the first hop relaying node, i.e., $U E_{1}$.
4. The $U E_{1}$ receives and decodes the $x_{j}$ symbol, where $j \in\{N, \ldots, i\}$, according to (5.20a)(5.21b), and excess power is collected by the UE for recharging. $U E_{1}$ selects the next relay node according to (5.23) and sends a superimposed signal according to (5.18) or (5.19) to the next hop relaying node after $U E_{1}$ successfully detects its own symbol, i.e., $x_{1}$. This process (step 4) is repeated until the superimposed signal is transmitted to the last UE, i.e., $U E_{N}$ in the model. The OP occurs when $x_{j}$, where $j \in\{N, \ldots, i\}$, cannot be detected successfully at $U E_{i}$, where $i \in\{1, \ldots, N\}$.

### 5.4 Numerical Results and Discussions

### 5.4.1 Numerical Results and Discussion for OP Performance

It is important to note that the OP results of the Dir, HD and FD scenarios are represented in Figure $5.4 \mathrm{a}, \mathrm{b}$ by black dashed lines, red dash-dot lines, and blue solid lines, respectively. In the first case, I assumed only three connected users in the network at the t-th time slot. I analyzed the performance of the system based on the OP of each user in the three different above-mentioned scenarios. Some of the simulation parameters, e.g., the channel coefficients $h_{0,1}=1, h_{0,2}=1 / 2$, and $h_{0,3}=1 / 3$, adopt the earlier presented assumptions. Based on the transmission channel coefficients of the users, I allocated the following respective PA factors for users $U E_{1}, U E_{2}$, and $U E_{3}: \alpha_{1}=0.1818, \alpha_{2}=0.2727, \alpha_{3}=0.5455$, respectively, where $\sum_{i=1}^{3} \alpha_{i}=1$ by applying (5.42). Because the third user $U E_{3}$ has the poorest signal quality, it is prioritized for allocation of the largest PA factor. My analysis results showed that the users who are far from the BS and have poor signal quality have better results, e.g., the OP results for $U E_{2}$ and $U E_{3}$ are better than the OP results for $U E_{1}$, although their signal qualities are weaker than the first. Figure 5.4 a indicates the OP results for $U E_{3}$ has with a diamond marker. These are the best results compared to the other users, even though $U E_{3}$ has the weakest signal quality $h_{0,3}=1 / 3$. Because $U E_{3}$ cooperates with the other UE, the QoS of $U E_{3}$ is improved and is better than the other UE. These results demonstrate the effectiveness of the proposed MPCR model. The OP results of the first user $U E_{1}$ are the worst and approximate each other in all three scenarios. $U E_{1}$ had the strongest channel coefficient $h_{0,1}=1$ compared to the other UE and was allocated the smallest PA factor $\alpha_{1}=0.1818$. A previous study of FD relaying [TTNam01,TTNam02] and the results of comparison between FD and HD [86] showed that the OP results of relaying in FD mode were worse than in the HD scenario. These research results have similarities. The system performance efficiency of the MPCR model with $N-1$

FD relaying nodes produces an approximation with $N-1 \mathrm{HD}$ relaying nodes in the low SNR. However, as the SNR ascends, the performance of the MPCR system with $N-1$ HD relaying nodes improves, indicated by the red dash-dot lines in Figure 5.4a. Specifically, the first user's OP results in the FD scenario are the worst. However, not much difference from the Dir and HD scenarios is evident, the reason being that the first relaying node in FD mode is affected by its own antenna channel noise whereas the Dir and HD transmission scenarios with one antenna have no LI channels.

Table 2: 3 UE in a NOMA system at the $t$-th time slot.

| UE | Channels | PA Coefficients | Bit Rate Thresholds |
| :---: | :---: | :---: | :---: |
| $U E_{1}$ | $h_{0,1}=1$ | $\alpha_{1}=0.1818$ | $R_{1}^{*}=0.5455$ |
| $U E_{2}$ | $h_{0,2}=0.5$ | $\alpha_{2}=0.2727$ | $R_{2}^{*}=0.2727$ |
| $U E_{3}$ | $h_{0,3}=0.3333$ | $\alpha_{3}=0.5455$ | $R_{3}^{*}=0.1818$ |

To be clearer, I increased the number of users in the network to $N=4$ users with a channel coefficient for $U E_{4}$ of $h_{0,4}=1 / 4$ at the ( $\mathrm{t}+1$ )-th time slot. The OP of the users are presented in Figure 5.4b. This is because the system has a new joined user, i.e., $U E_{4}$, involved in the network with very weak signal quality. I therefore reapplied (5.42) to reallocate the PA factors to the users, where $\alpha_{1}=0.12, \alpha_{2}=0.16, \alpha_{3}=0.24$, and $\alpha_{4}=0.48$, as shown in Table 3. Because the PA coefficients have changed, the instantaneous bit rate thresholds of users have also changed accordingly. The instantaneous bit rate thresholds of the users are $R_{i}^{*}=$ $\{0.48,0.24,0.16,0.12\} \mathrm{bps} / H z$, where $i \in\{1, \ldots, 4\}$. In this case, to ensure QoS to the fourth user with the poorest signal quality, we allocate this user with the largest PA factor and the lowest threshold, i.e., $\alpha_{4}=0.48$ and $R_{4}^{*}=0.12 \mathrm{bps} / \mathrm{Hz}$, compared to the other users in the network. The other users must also share the PA factors with $U E_{4}$ in the same power domain. Comparing the corresponding rows in Tables 2 and 3, both $\alpha_{i}$ and $R_{i}^{*}$, where $i=\{1,2,3\}$, are reduced to share power and the bit rate with $U E_{4}$. As shown in Figure 5.4b, although $U E_{4}$ has the poorest signal quality, it has the best OP results. This demonstrates that MPCR combines with the PA factor and instantaneous bit rate threshold selection effectively. In particular, the OP results in both HD and FD scenarios using $N-1$ relaying nodes always outperform the schemes with no relaying.

Table 3: 4 UE in a NOMA system at the $(\mathrm{t}+1)$ th time slot.

| UE | Channels | PA Coefficients | Bit Rate Thresholds |
| :---: | :---: | :---: | :---: |
| $U E_{1}$ | $h_{0,1}=1$ | $\alpha_{1}=0.1200$ | $R_{1}^{*}=0.4800$ |
| $U E_{2}$ | $h_{0,2}=0.5$ | $\alpha_{2}=01600$ | $R_{2}^{*}=0.2400$ |
| $U E_{3}$ | $h_{0,3}=0.3333$ | $\alpha_{3}=0.2400$ | $R_{3}^{*}=0.1600$ |
| $U E_{4}$ | $h_{0,4}=0.2500$ | $\alpha_{4}=0.4800$ | $R_{4}^{*}=0.1200$ |

The dissertation investigates the effect of the PA factor and SNR on a user's service quality, especially weak users. In Figure 5.4b, the weakest user, i.e., $U E_{4}$, has a fixed PA factor $\alpha_{4}=0.48$. The dissertation considers whether the PA coefficient for $U E_{4}$ increases or decreases and the

QoS for $U E_{4}$ varies over the corresponding SNR. For simplicity, I assume that user $U E_{4}$ and the other users are over Rayleigh fading channels. $U E_{4}$ and the other users over Nakagami- $m$ fading channels will be analyzed later. The dissertation assumes that the fourth user can be allocated a variable power factor $\alpha_{4} \in\{0.1, \ldots, 0.9\}$. Figure 5.5 presents the OP of $U E_{4}$ with a variable PA factor and the results for Dir, HD or FD relaying scenarios as a solid grid, dashed grid and dash-dot grid, respectively. Figure 5.5 shows that the OP results of $U E_{4}$ with the cooperation of three HD relaying nodes and three FD relaying nodes in MPCR scenarios are better than the results in the Dir scenario. In particular, the OP results of $U E_{4}$ in the MPCR system with $N-1 \mathrm{HD} / \mathrm{FD}$ relaying nodes are also approximations at all SNR. These results are consistent with the results for $U E_{4}$ presented in Figure 5.4b.


Figure 5.4: The OP results of $N=\{3,4\}$ UE over Rayleigh fading channels.

The dissertation also investigates the OP of the users over Nakagami- $m$ fading channels versus the users over Rayleigh fading channels as shown in Figure 5.5. To ensure a fair comparison, the simulation parameters in the Nakagami- $m$ fading channels scenario are the same as the simulation parameters shown in Table 2. It is therefore unnecessary to present these simulation parameters again. At low SNR, the OP results of the users over Rayleigh fading channels and Nakagami- $m$ fading channels are approximated. However, when the SNR increases, the OP results of the users over the Nakagami- $m$ scenario show significant improvement.


Figure 5.5: The OP results of the 4 th UE, where $\alpha_{4}=\{0.1, \ldots, 0.9\}$ and $S N R=\{-10, \ldots, 30\}$.

### 5.4.2 Numerical Results and Discussion for System Throughput

For system performance evaluation, system throughput is an important criterion measured as the sum of the instantaneous achievable bit rates of all users in the system. I reuse the simulation parameters as described in the evaluation of the OP shown in Tables 2 and 3 and therefore do not restate them. The system throughput for each user, where $N=3 \mathrm{UE}$ or $N=4 \mathrm{UE}$, are presented in Figures 5.7a and 5.7b. The solid lines, dash-dot lines and dashed lines are the system throughput of the users in Dir, HD and FD scenarios, respectively. The OP results of the users in the HD and FD scenarios are approximately equal, and consequently, the throughput results of these users are also approximately equal. The dash-dot lines and dashed lines overlap in both Figures 5.7a and 5.7b. The analysis results showed that the system throughput of users in the $N-1 \mathrm{HD} / \mathrm{FD}$ relaying node scenarios are always better than the system throughput of users in the non-relay scenarios. Specifically, system throughput of the first UE is approximate in all three scenarios. At a SNR of 30 dB , all users in all three scenarios reach their bit rate thresholds $R_{i}^{*}$.

The dissertation also analyzes the effect of the PA factor $\alpha_{4}$ on the fourth user's throughput with variable $\alpha_{4} \in\{0.1, \ldots, 0.9\}$ values instead a fixed $\alpha_{4}=0.48$. The higher grid lines in Figure 5.8 show better results than elsewhere in the chart. In this case, the instantaneous bit rate
threshold of $U E_{4}$ is $R_{4}^{*}=0.12 \mathrm{bps} / \mathrm{Hz}$. At low SNR , e.g., $S N R=0 \mathrm{~dB}$, the system throughput results in all scenarios are approximately zero. Although the SNR has increased, e.g., $S N R=10$ dB , the system throughput results are still approximately zero if the PA factor, i.e., $\alpha_{4}$, is still low, e.g., $\alpha_{4}=0.1$. However, where $\alpha_{4}=0.4$ and $S N R$ maintains 10 dB , the system throughput results of $U E_{4}$ for all three HD relaying nodes and all three FD relaying nodes in the MPCR scenario improve and reach their bit rate threshold. Figure 5.7 b shows that at a SNR of 10 dB and $\alpha_{4}=0.48, U E_{4}$ reaches its approximate bit rate threshold. In another example with the paired $\alpha_{4}=0.5$ and $S N R=0 \mathrm{~dB}, U E_{4}$ also reaches its bit rate threshold, shown in Figure 5.8. From this analysis, we can detect pairs of values $\alpha_{4}$ and $S N R$ where $U E_{4}$ reaches the threshold $R_{4}^{*}=0.12 \mathrm{bps} / \mathrm{Hz}$.


Figure 5.6: The OP results of three UE over Rayleigh fading channels versus Nakagami- $m$ fading channels, where $m=2$.

The system throughput of the users in $N-1$ HD relaying nodes over both Rayleigh and Nakagami- $m$ scenarios were analyzed and compared and are presented in Figure 5.9a. $N=3$ UE over Rayleigh fading channels and Nakagami- $m$ fading channels are indicated with solid lines and dashed lines, respectively, from the results of $\Theta_{1}^{H D}>\Theta_{2}^{H D}>\Theta_{3}^{H D}$, as shown in Figure 5.6a. By applying (5.40), we obtain $P_{1}^{H D}<P_{2}^{H D}<P_{3}^{H D}$ with low SNR. As the SNR increases, the system throughput of each UE changes, e.g., $S N R=30 \mathrm{~dB}, P_{1}^{H D}>P_{2}^{H D}>P_{3}^{H D}$, and reaches the bit rate thresholds $R_{i}^{*}$.


Figure 5.7: The system throughput results of the users over Rayleigh fading channels.

The results for the $N-1$ FD relaying node scheme as shown in Figure 5.9b are similar. Specifically, the users over Nakagami- $m$ fading channels have better OP results than the users
over Rayleigh fading channels at a certain SNR, e.g., $S N R=10 \mathrm{~dB}$ and $\aleph \Theta_{i}^{F D}<\Re \Theta_{i}^{F D}$, shown in Figure 5.6b. Therefore, $\aleph P_{i}^{F D}>\Re P_{i}^{F D}$, where $\aleph$ and $\Re$ denote Nakagami- $m$ and Rayleigh fading channels, respectively, after applying (5.40). These results prove that the Nakagami- $m$ channel is better than the Rayleigh channel. However, when the SNR increases, the users reach approximate throughput results near the thresholds $\aleph P_{i}^{H D} \approx \Re P_{i}^{H D} \approx R_{i}^{*}$.

### 5.4.3 $N$ UE with $N-1$ HD/FD Relaying Nodes

The dissertation investigates the system performance for $N$ UE, where $N$ is a random and large number, according to the model in Figure 5.2. Because of the limited power of my personal computers, the dissertation investigates and presents cases with only three or four users, $N=$ $\{3,4\}$, in the system. However, the presented results do not highlight all the advantages of the proposed algorithm. I therefore increased the limit of the number of users to a larger $N$. Figure 5.10 shows 9 UE in the network. I investigated the OP of the UE in the network over both Rayleigh and Nakagami- $m$ fading channels. For example, in the $N-1$ HD relaying node scenario, the OP of the first UE, i.e., $U E_{1}$, is calculated according to (5.34) and (5.38) for Rayleigh or Nakagami- $m$ fading channels, respectively, where $m=2$ and $\eta=0$. In another example, in the FD scenario, the OP of last UE, i.e., $U E_{9}$, over Rayleigh or Nakagami- $m$ fading channels is computed from (5.35) and (5.39), respectively. When the number of users is greater than nine UE, $N>9$, the results of the analysis are difficult to inspect from the figure and require more time for simulation. I therefore concluded this investigation for up to nine users in the network.


Figure 5.8: Throughput of the 4 th UE over Rayleigh fading channels, where $\alpha_{4}=\{0.1, \ldots, 0.9\}$ and $S N R=\{-10, \ldots, 30\} \mathrm{dB}$.


Figure 5.9: Comparison of the system throughput results of Rayleigh versus Nakagami- $m$, where $m=2$.


Figure 5.10: Comparison of the OP results of Rayleigh versus Nakagami- $m$ fading channels.

### 5.5 Conclusion

In the first aim of the dissertation, I proposed a novel NOMA network model with $N-1$ relaying nodes instead of the use of only one relay, as in previous studies. A superimposed signal would be sent through $N-1$ relaying nodes before it reaches the farthest UE, denoted as $U E_{N}$, which is at the extent of the network coverage. The closed form expressions of $N-1 \mathrm{HD} / \mathrm{FD}$ relaying node scenarios over Rayleigh/Nakagami- $m$ fading channels were also presented, along with an explanation for corresponding processing. Note that the wireless networks may significantly improve by deploying adaptive Nakagami- $m$ factor [TTNam08]. The results presented in the figures show that my proposed models with $N-1 \mathrm{HD} / \mathrm{FD}$ relaying nodes are more effective in serving the far user in the next generation of IoT networks, attaining the first aim of the dissertation.

### 5.6 Appendix

### 5.6.1 Proof of $N-1$ HD relaying node scenario

The condition for the occurrence of outage events is given by (5.33). By substituting (5.22), where $\Omega=H D$, into (5.33), we obtain an expression for computing the OP of each UE in the $N-1$ HD relaying node scenario:

$$
\begin{equation*}
\Theta_{i}^{H D}=\left(1-\prod_{l=1}^{i-1} \operatorname{Pr}\left(\left|h_{l-1, l}\right|^{2}>\frac{R_{i}^{* *}}{\chi_{i} \rho_{l-1}}\right)\right)\left(1-\prod_{j=N}^{i} \operatorname{Pr}\left(\left|h_{i-1, i}\right|^{2}>\frac{R_{j}^{* *}}{\chi_{j} \rho_{i-1}}\right)\right) . \tag{5.44}
\end{equation*}
$$

By applying the PDF (5.25) of Rayleigh distributions, Equation (5.44) can be rewritten as an experimental integral:

$$
\begin{equation*}
\Re \Theta_{i}^{H D}=\left(1-\prod_{l=1}^{i-1} \int_{\frac{R_{i}^{* *}}{\chi_{i} \rho_{l-1}}}^{\infty} \frac{1}{\sigma_{l-1, l}^{2}} e^{-\frac{x}{\sigma_{l-1, l}^{2}}} d x\right)\left(1-\prod_{j=N}^{i} \int_{\frac{R_{j}^{* *}}{\chi_{j} \rho_{i-1}}}^{\infty} \frac{1}{\sigma_{i-1, i}^{2}} e^{-\frac{x}{\sigma_{i-1, i}^{2}}} d x\right) \tag{5.45}
\end{equation*}
$$

Equation (5.45) can be solved and expressed as (5.34).
However, Equation (5.45) can be rewritten with the PDF (5.27) of Nakagami- $m$ fading channels as:

$$
\begin{align*}
\aleph \Theta_{i}^{H D} & =\left(1-\prod_{l=1}^{i-1} \int_{\frac{R_{i}^{* *}}{\lambda_{i} \rho_{l-1}}}^{\infty}\left(\frac{m}{\sigma_{l-1, l}^{2}}\right)^{m} \frac{x^{m-1}}{\Gamma(m)} e^{-\frac{m x}{\sigma_{l-1, l}^{2}}} d x\right. \\
& \times\left(1-\prod_{j=N}^{i} \int_{\frac{R_{j}^{* *}}{\chi_{j} \rho_{i-1}}}^{\infty}\left(\frac{1}{\sigma_{i-1, i}^{2}}\right)^{m} \frac{x^{m-1}}{\Gamma(m)} e^{-\frac{m x}{\sigma_{i-1, i}^{2}}} d x\right), \tag{5.46}
\end{align*}
$$

and after the solution of (5.46), it can be expressed as (5.38).

### 5.6.2 Proof of $N-1$ FD relaying node scenario

By substituting (5.22), where $\Omega=F D$, into (5.33), we obtain an expression for computing the OP of each UE in the $N-1$ FD relaying node scenario:

$$
\begin{align*}
\Theta_{i}^{F D}= & \left(1-\prod_{l=1}^{i-1} \operatorname{Pr}\left(\left|h_{l-1, l}\right|^{2}>\frac{R_{i}^{* *}\left(\left|h_{L i, l}\right|^{2} \rho_{l}+1\right.}{\chi_{i} \rho_{l-1}},\left|h_{L i, l}\right|^{2}>0\right)\right)  \tag{5.47}\\
& \times\left(1-\prod_{j=N}^{i} \operatorname{Pr}\left(\left|h_{i-1, i}\right|^{2}>\frac{R_{j}^{* *}\left(\left|h_{L i, i}\right|^{2} \rho_{i}+1\right.}{\chi_{j} \rho_{i-1}},\left|h_{L i, i}\right|^{2}>0\right)\right)
\end{align*}
$$

By applying the PDF of Rayleigh or Nakagami- $m$ fading, which are (5.25) and (5.27), respectively, Equation (5.47) can be rewritten as experimental integrals:

$$
\begin{align*}
\Re \Theta_{i}^{H D}= & \left(1-\prod_{l=1}^{i-1} \int_{0}^{\infty} \int_{\frac{R_{i}^{* *}\left(y \rho_{l}+1\right)}{\chi_{i} \rho_{l-1}}}^{\infty} \frac{1}{\sigma_{l-1, l}^{2} \sigma_{L I, l}^{2}} e^{-\left(\frac{x}{\sigma_{l-1, l}^{2}}+\frac{y}{\sigma_{L I, l}^{2}}\right)} d x d y\right) \\
& \times\left(1-\prod_{j=N}^{i} \int_{0}^{\infty} \int_{\frac{R_{-}^{* *}\left(y_{i}+1\right)}{\chi_{j} \rho_{i-1}}}^{\infty} \frac{1}{\sigma_{i-1, i}^{2} \sigma_{L I, i}^{2}} e^{-\left(\frac{x}{\sigma_{i-1, i}^{2}}+\frac{y}{\sigma_{L I, i}^{2}}\right)} d x d y\right), \tag{5.48}
\end{align*}
$$

and

$$
\begin{align*}
\aleph \Theta_{i}^{F D}= & \left(1-\prod_{l=1}^{i-1} \int_{0}^{\infty} \int_{\frac{R_{i}^{* *}\left(y_{l}+1\right)}{\chi_{i} \rho_{l-1}}}^{\infty}\left(\frac{m^{2}}{\sigma_{l-1, l}^{2} \sigma_{L I, l}^{2}}\right)^{m} \frac{(x y)^{m-1}}{(\Gamma(m))^{2}} e^{\left.-m\left(\frac{x}{\sigma_{l-1, l}^{2}}+\frac{y}{\sigma_{L I, l}^{2}}\right) d x d y\right)}\right. \\
& \times\left(1-\prod_{j=N}^{i} \int_{0}^{\infty} \int_{\frac{R_{j}^{* *}\left(\rho_{i}+1\right)}{\chi_{j} \rho_{i-1}}}^{\infty}\left(\frac{m^{2}}{\sigma_{i-1, i}^{2} \sigma_{L I, i}^{2}}\right)^{m} \frac{(x y)^{m-1}}{(\Gamma(m))^{2}} e^{\left.-m\left(\frac{x}{\sigma_{i-1, i}^{2}}+\frac{y}{\sigma_{L I, i}^{2}}\right) d x d y\right) .} .\right. \tag{5.49}
\end{align*}
$$

Expressions (5.48) and (5.49) are solved and expressed as (5.35) and (5.39), respectively, where $m=2$.

## Chapter 6:

## System Performance Optimization of IoT NOMA Networks

## Part I - Protocol Switching Selection

FOR the second aim of the dissertation, I examine some forwarding protocols at the relay and propose the PSS mechanism for optimizing system performance. I briefly describe the work and research which satisfies the second aim:

- An investigation into the system performance of C-NOMA under six different scenarios: (i) HD and DF relaying; (ii) FD and DF relaying; (iii) HD and AF with FG relaying; (iv) FD and AF with FG relaying; (v) HD and AF with VG relaying; (vi) FD and AF with VG relaying. The OP expression of each scenario is presented in closed form.
- A proposed mechanism for switching protocols and optimizing system performance by selecting the best protocol for forwarding signals to the next user.
- An investigation of system performance with different SNR to find a suitable means of transmitting power to avoid wasting energy. Energy saving is required in G-WNs.
- An analysis and simulation of OP, system throughput and EE using Matlab software. An algorithm used for Monte Carlo simulations is also proposed for computing the OP of individual scenarios. The simulation results were used to verify the analysis results. The figures are presented clearly and accurately to demonstrate my propositions.

Note that the outcomes in the Chapter 6 (Part I) have been published in the paper [TTNam04] entitled "HD/FD and DF/AF with a fixed-gain or variable-gain protocol switching mechanism over cooperative NOMA for green-wireless networks", in (MDPI) Sensors, 19 (8), art. no. 1845 (2019). DOI: 10.3390/s19081845. IF 3.031

### 6.1 System Models

In the system model (Figure 6.1), two users wait to receive the signals with the assumption that the channel at user $U_{1}$ is in a better condition than that at user $U_{2}$. Both users are over Rayleigh fading channels. Because $U_{2}$ has poor channel conditions, and instead of receiving the down-link signals directly from the BS , it requires cooperation from a relay. The dissertation assumes that $U_{1}$ can be used as a cooperative relay. Another assumption is that $U_{1}$ can work in all six scenarios: HD and DF, FD and DF, HD and AF with FG, FD and AF with FG, HD
and AF with VG, FD and AF with VG. The dissertation analyzes all six scenarios to determine the best protocol. Based on these facilities, the dissertation proposes using a wireless sensor to switch between protocols and select suitable protocols for forwarding signals to optimize the system performance.


Figure 6.1: HD/FD and DF/AF with FG/VG relay over a cooperative NOMA system.
In Figure 6.1, although the FD protocol can send and receive data simultaneously, an initial superimposed signal is sent from the BS to the relay in the first time slot (FTS). The relay decodes the $x_{2}$ symbol and removes $x_{2}$ from the superimposed signal before decoding its own $x_{1}$ symbol. The information in the $x_{2}$ symbol is then restored and forwarded to $U_{2}$ in the second time slot (STS). However, the forwarded signal from the transmitter antenna generates an LI channel to the receiver antenna while $U_{2}$ receives another signal from the BS. Thus, the C-NOMA system requires two time slots for the HD scenario or two phases in one time slot for the FD scenario to transmit a superimposed signal from the BS to the second user $U_{2}$.

### 6.1.1 First Time Slot for the HD scenario or first phase for the FD scenario

According to the NOMA theory, the BS sends a superimposed signal to $U_{1}$ in the FTS, expressed by:

$$
\begin{equation*}
S=\left(\sqrt{\alpha_{1} P_{0}} x_{1}+\sqrt{\alpha_{2} P_{0}} x_{2}\right) \tag{6.1}
\end{equation*}
$$

where $\alpha_{1}<\alpha_{2}$ and $\alpha_{1}+\alpha_{2}=1$ are in accordance with the condition $\left|h_{0,1}\right|>\left|h_{0,2}\right|, P_{0}$ is the transmission power of the BS , and $x_{i}$ for $i=\{1,2\}$ is the information symbol of each user, sequentially.

Therefore, the received signal at $U_{1}$ can be expressed as:

$$
\begin{equation*}
y_{1}^{\Omega}=h_{0,1} \sqrt{P_{0}} \sum_{k=1}^{2} \sqrt{\alpha_{k}} x_{k}+\varepsilon h_{1,1} \sqrt{P_{1}} \tilde{x}+n_{1}, \tag{6.2}
\end{equation*}
$$

where $h_{0,1}$ denotes the transmission channel from the BS to $U_{1}, h_{1,1}$ is the LI channel from the transmitter antenna to the receiver antenna at $U_{1}$, and $n_{1}$ is the AWGN at $U_{1}$ for $n_{1} \sim$ $C N\left(0, N_{0}\right)$ with zero mean and variance $N_{0} . \Omega=\{H D, F D\}$ is the HD/FD switching mode
with $\varepsilon$ state factor. If $\varepsilon=0$, the relay operates in the HD mode. If $\varepsilon=1$, the relay operates in the FD mode.
$U_{1}$ needs two phases to decode its own information symbol. In the first phase (FP), $U_{1}$ decodes the $x_{2}$ symbol by dealing with the $x_{1}$ symbol, the LI channel $h_{1,1}$ and AWGN $n_{1}$. The SINR can then be expressed as:

$$
\begin{equation*}
\gamma_{1 \rightarrow 2}^{\Omega}=\frac{\left|h_{0,1}\right|^{2} \alpha_{2} P_{0}}{\left|h_{0,1}\right|^{2} \alpha_{1} P_{0}+\varepsilon\left|h_{1,1}\right|^{2} P_{1}+N_{0}}=\frac{\left|h_{0,1}\right|^{2} \alpha_{2} \rho_{0}}{\left|h_{0,1}\right|^{2} \alpha_{1} \rho_{0}+\varepsilon\left|h_{1,1}\right|^{2} \rho_{1}+1}, \tag{6.3}
\end{equation*}
$$

where $\rho_{0}=P_{0} / N_{0}$.
In the second phase (SP), after $U_{1}$ has decoded the $x_{2}$ symbol, $x_{2}$ is removed from the superimposed signal as noise. $U_{1}$ decodes its own symbol $x_{1}$ after removing $x_{2}$ by dealing with AWGN $n_{1}$ and the LI channel $h_{1,1}$. The SINR can then be expressed as:

$$
\begin{equation*}
\gamma_{1 \rightarrow 1}^{\Omega}=\frac{\left|h_{0,1}\right|^{2} \alpha_{1} P_{0}}{\varepsilon\left|h_{1,1}\right|^{2} P_{1}+N_{0}}=\frac{\left|h_{0,1}\right|^{2} \alpha_{1} \rho_{0}}{\varepsilon\left|h_{1,1}\right|^{2} \rho_{1}+1} . \tag{6.4}
\end{equation*}
$$

The instantaneous achievable bit rate of $U_{1}$ when $U_{1}$ decodes the $x_{j}$ symbol can therefore be expressed as:

$$
\begin{equation*}
R_{1 \rightarrow j}^{\Omega}=\Delta \log _{2}\left(1+\gamma_{1 \rightarrow j}^{\Omega}\right) \tag{6.5}
\end{equation*}
$$

where $j=\{2,1\}, \Delta=1 / 2$ for $\Omega=H D$ or $\Delta=1$ for $\Omega=F D$.
6.1.2 Second Time Slot for the HD scenario or second phase for the FD scenario In $\mathrm{STS} / \mathrm{SP}, U_{1}$ will forward a recovered signal to $U_{2}$ using either the DF protocol or the AF protocol with FG or VG by the PSS.
6.1.2.1 DF Protocols at the Relay Once the $x_{2}$ symbol is decoded and removed from the superimposed signal, $x_{2}$ is restored and sent to $U_{2}$. Therefore, $U_{2}$ will receive a signal expressed as:

$$
\begin{equation*}
y_{2}^{D F}=h_{1,2} \sqrt{P_{1}} x_{2}+n_{2}, \tag{6.6}
\end{equation*}
$$

where $h_{1,2}$ is the transmission channel from $U_{1}$ to $U_{2}, P_{1}$ is the transmission power of $U_{1}$ and $n_{2}$ is the AWGN of $U_{2}$.
$U_{2}$ decodes its own $x_{2}$ symbol by removing AWGN $n_{2}$ from the received signal. Meanwhile, SINR can be expressed by:

$$
\begin{equation*}
\gamma_{2 \rightarrow 2}^{D F}=\frac{\left|h_{1,2}\right|^{2} P_{1}}{N_{0}}=\left|h_{1,2}\right|^{2} \rho_{1} . \tag{6.7}
\end{equation*}
$$

The instantaneous achievable bit rate of $U_{2}$ in the DF protocol is expressed as:

$$
\begin{equation*}
R_{2 \rightarrow 2}^{D F}=\Delta \log _{2}\left(1+\gamma_{2 \rightarrow 2}^{D F}\right) \tag{6.8}
\end{equation*}
$$

6.1.2.2 AF with FG/VG Protocols at the Relay Where the $U_{1}$ relay uses the AF protocol, $U_{1}$ will amplify the received signal according to the amplification factor $\kappa_{\omega}$, for $\omega=$ $\{F G, V G\}$, before forwarding the superimposed signal to $U_{2}$.

The $\kappa_{\omega}$ amplification coefficient for FG and VG, respectively, are given as:

$$
\begin{align*}
\kappa_{\omega} & \triangleq \sqrt{\frac{P_{1}}{P_{0} E\left[\left|h_{1,2}\right|^{2}\right]+N_{0}}}=\sqrt{\frac{\rho_{1}}{\rho_{0} \sigma_{1,2}^{2}+1}}  \tag{6.9a}\\
& \triangleq \sqrt{\frac{P_{1}}{P_{0}\left|h_{1,2}\right|^{2}+N_{0}}}=\sqrt{\frac{\rho_{1}}{\rho_{0}\left|h_{1,2}\right|^{2}+1}} \tag{6.9b}
\end{align*}
$$

where $\omega \triangleq F G$ or $\omega \triangleq \triangleq \xlongequal{\wedge}$.
Therefore, the received signal at $U_{2}$ is expressed as:

$$
\begin{equation*}
y_{2}^{\Omega, \omega}=\kappa_{\omega} h_{1,2} \sqrt{P_{1}} y_{1}^{\Omega}+n_{2} \tag{6.10}
\end{equation*}
$$

where $\kappa_{\omega}$ is given by (6.9a) or (6.9b) and $y_{1}^{\Omega}$ is given by (6.2).
By substituting (6.2) and (6.9a) or (6.9b) into (6.10), $U_{2}$ decodes its own $x_{2}$ symbol by removing the $x_{1}$ symbol, removing the LI channel if $U_{1}$ functions in $\Omega=F D$ mode, removing AWGN $n_{1}$ of $U_{1}$ and removing its own AWGN $n_{2}$. Therefore, the SINR can be expressed as:

$$
\begin{equation*}
\gamma_{2 \rightarrow 2}^{\Omega, \omega}=\frac{\left|h_{0,1}\right|^{2} \alpha_{2} \rho_{0}}{\left|h_{0,1}\right|^{2} \alpha_{1} \rho_{0}+\varepsilon\left|h_{1,1}\right|^{2} \rho_{1}+1+\psi_{\omega}} \tag{6.11}
\end{equation*}
$$

where $\psi_{\omega}$ is given by:

$$
\begin{equation*}
\psi_{\omega}=\frac{1}{\kappa_{\omega}^{2}\left|h_{1,2}\right|^{2} \rho_{1}} \tag{6.12}
\end{equation*}
$$

for $\omega \triangleq F G$ or $\omega \triangleq V G$.
As with (6.8), the instantaneous bit rate threshold of $U_{2}$ in the AF protocol with FG/VG can be rewritten as:

$$
\begin{equation*}
R_{2 \rightarrow 2}^{\Omega, \omega}=\Delta \log _{2}\left(1+\gamma_{2 \rightarrow 2}^{\Omega, \omega}\right) \tag{6.13}
\end{equation*}
$$

### 6.2 System Performance Analysis

Previous research results showed the feasibility of deploying a cooperative relay with HD/FD and DF protocols to resist fading. A superimposed signal was transmitted through the network with the support of the $N-1 \mathrm{HD} / \mathrm{FD}$ relay before reaching the $N$-th user [TTNam03]. However, the AF protocol is less studied than the DF protocol because of its complexity in SIC. By contrast, the authors fully studied the AF protocol with FG [57]. Even so, it lacks a comparison to the AF protocol with VG. These research results were my motivation to seek a complete analysis and evaluation of the advantages of each protocol.

In this section, I analyze OP, system throughput and EE to evaluate the system performance of a C-NOMA system in six proposed scenarios: (i) HD and DF protocols at the relay; (ii) FD
and DF protocols at the relay; (iii) HD and AF with FG protocols at the relay; (iv) FD and AF with FG protocols at the relay; $(v)$ HD and AF with VG protocols at the relay; (vi) FD and AF with VG protocols at the relay. The dissertation then proposes a mechanism for switching protocols to optimize the system's performance.

### 6.2.1 Outage Probability

The PDF and CDF over Rayleigh distributions are expressed, respectively, as:

$$
\begin{equation*}
f_{\left|h_{a, b}\right|^{2}}(x)=\frac{1}{\sigma_{a, b}^{2}} e^{-\frac{x}{\sigma_{a, b}^{2}}} \tag{6.14}
\end{equation*}
$$

and

$$
\begin{equation*}
F_{\left|h_{a, b}\right|^{2}}(x)=1-e^{-\frac{x}{\sigma_{a, b}^{2}}} \tag{6.15}
\end{equation*}
$$

where the random independent variable $x \geq 0$
Theorem 1: Outage of the signal transmission of $U_{1}$ will occur when $U_{1}$ cannot successfully decode the $x_{1}$ or $x_{2}$ symbol. Specifically, this outage will occur in either one of the following cases:

- Case 1: The instantaneous bit rate $R_{1 \rightarrow 2}^{\Omega}$ cannot reach the bit rate threshold $R_{2}^{*}$, i.e., $R_{1 \rightarrow 2}^{\Omega}<R_{2}^{*}$.
- Case 2: The instantaneous bit rate $R_{1 \rightarrow 2}^{\Omega}$ is able to reach the bit rate threshold $R_{2}^{*}$, but the instantaneous bit rate $R_{1 \rightarrow 1}^{\Omega}$ cannot reach the bit rate threshold $R_{1}^{*}$, i.e., $R_{1 \rightarrow 2}^{\Omega}>R_{2}^{*}$, and $R_{1 \rightarrow 1}^{\Omega}<R_{1}^{*}$.

Ultimately, the OP of $U_{1}$ can be expressed as:

$$
\begin{equation*}
\Theta_{1}^{\Omega}=1-\prod_{j=1}^{2} \operatorname{Pr}\left(R_{1 \rightarrow j}^{\Omega}>R_{j}^{*}\right)=1-\operatorname{Pr}\left(R_{1 \rightarrow 2}^{\Omega}>R_{2}^{*}, R_{1 \rightarrow 1}^{\Omega}>R_{1}^{*}\right) \tag{6.16}
\end{equation*}
$$

where $R_{j}^{*}$ is the minimum bit rate threshold of $U_{j}$ which is required.
The expression (6.16) can be solved and presented in closed form as:

$$
\begin{equation*}
\Theta_{1}^{\Omega}=1-e^{-\left(\frac{R_{1}^{* *}}{\alpha_{1} \rho_{0} \sigma_{0,1}^{2}}\right)} \frac{\alpha_{1} \rho_{0} \sigma_{0,1}^{2}}{\alpha_{1} \rho_{0} \sigma_{0,1}^{2}+\varepsilon R_{1}^{* *} \rho_{1} \sigma_{1,1}^{2}} e^{-\frac{R_{2}^{* *}}{\left(\alpha_{2}-\alpha_{1} R_{2}^{* *}\right) \rho_{0} \sigma_{0,1}^{2}} \frac{\left(\alpha_{2}-\alpha_{1} R_{2}^{* *}\right) \rho_{0} \sigma_{0,1}^{2}}{\left(\alpha_{2}-\alpha_{1} R_{2}^{* *}\right) \rho_{0} \sigma_{0,1}^{2}+\varepsilon R_{2}^{* *} \rho_{1} \sigma_{1,1}^{2}}}, \tag{6.17}
\end{equation*}
$$

where $R_{i}^{* *}=2^{2 R_{i}^{*}}-1$ for $i=\{1,2\}$ and $\Omega=H D, R_{i}^{* *}=2^{R_{i}^{*}}-1$ for $i=\{1,2\}$ and $\Omega=F D$, $\varepsilon=0$ for $\Omega=H D$ or $\varepsilon=1$ for $\Omega=F D$, respectively.

For the proof of Theorem 1, see the Appendix 6.6.1.
Theorem 2: Outage of the signal transmission of $U_{2}$ will occur when either $U_{1}$ or $U_{2}$ cannot successfully decode the $x_{2}$ symbol. Specifically, this outage will occur in either one of the following cases:

- Case 1: The instantaneous bit rate $R_{1 \rightarrow 2}^{\Omega}$ cannot reach the bit rate threshold $R_{2}^{*}$, i.e., $R_{1 \rightarrow 2}^{\Omega}<R_{2}^{*}$.
- Case 2: The instantaneous bit rate $R_{1 \rightarrow 2}^{\Omega}$ is able to reach the bit rate threshold $R_{2}^{*}$, but the instantaneous bit rate $R_{2 \rightarrow 2}^{\Omega}$ cannot reach the bit rate threshold $R_{2}^{*}$, i.e., $R_{1 \rightarrow 2}^{\Omega}>R_{2}^{*}$, and $R_{2 \rightarrow 2}^{\Omega}<R_{2}^{*}$.

Ultimately, the OP of $U_{2}$ can be expressed as:

$$
\begin{equation*}
\Theta_{2}^{\Omega, \omega}=1-\prod_{i=1}^{2} \operatorname{Pr}\left(R_{i \rightarrow 2}^{\Omega, \omega}>R_{2}^{*}\right)=\operatorname{Pr}\left(R_{1 \rightarrow 2}^{\Omega}<R_{2}^{*}\right)+\operatorname{Pr}\left(R_{1 \rightarrow 2}^{\Omega}>R_{2}^{*}, R_{2 \rightarrow 2}^{\Omega, \omega}<R_{2}^{*}\right) . \tag{6.18}
\end{equation*}
$$

The expression (6.18) can be obtained in a similar manner as expression (6.17). Hence, it is not necessary to demonstrate the proof again.
6.2.1.1 HD and DF Protocols at the Relay ( $\Omega=H D, \omega=D F$ )

Remark 1: In this scenario, $U_{1}$ operates under the HD and DF protocols. Therefore, Theorem 2 demonstrated as (6.18) can be rewritten and solved in closed form as:

$$
\begin{align*}
\Theta_{2}^{H D, D F} & =\prod_{i=1}^{2} \operatorname{Pr}\left(R_{i \rightarrow 2}^{H D, D F}<R_{2}^{*}\right)=\operatorname{Pr}\left(R_{1 \rightarrow 2}^{H D}<R_{2}^{*}\right)+\operatorname{Pr}\left(R_{1 \rightarrow 2}^{H D}>R_{2}^{*}, R_{2 \rightarrow 2}^{H D, D F}<R_{2}^{*}\right) \\
& =\left(1-\lambda_{1}\right)+\lambda_{1}(1-\underbrace{-\frac{R_{2}^{* *}}{\rho_{1} \sigma_{1,2}^{2}}}_{\lambda_{2}})=1-\lambda_{1} \lambda_{2}, \tag{6.19}
\end{align*}
$$

where $\lambda_{1}$ is given by (6.17) for $\varepsilon=0$.
For the proof of Remark 1, see the Appendix 6.6.2.

### 6.2.1.2 FD and DF Protocols at the Relay ( $\Omega=F D, \omega=D F$ )

Remark 2: In this scenario, $U_{1}$ operates under the FD and DF protocols. Therefore, Theorem 2 demonstrated as (6.18) can be rewritten and solved in closed form as:

$$
\begin{align*}
\Theta_{2}^{F D, D F} & =\prod_{i=1}^{2} \operatorname{Pr}\left(R_{i \rightarrow 2}^{F D, D F}<R_{2}^{*}\right)=\operatorname{Pr}\left(R_{1 \rightarrow 2}^{F D}<R_{2}^{*}\right)+\operatorname{Pr}\left(R_{1 \rightarrow 2}^{F D}>R_{2}^{*}, R_{2 \rightarrow 2}^{F D, D F}<R_{2}^{*}\right) \\
& =\left(1-\lambda_{1}\right)+\left(\lambda_{1}\left(1-\lambda_{2}\right)\right)=1-\lambda_{1} \lambda_{2}, \tag{6.20}
\end{align*}
$$

where $\lambda_{1}$ and $\lambda_{2}$ are given by (6.17) and (6.19) for $\varepsilon=1$, respectively. If $\varepsilon$ in (6.20) equals zero, (6.20) becomes (6.19).

For the proof of Remark 2, see the Appendix 6.6.2.
6.2.1.3 HD and AF with FG Protocols at the Relay ( $\Omega=H D, \omega \triangleq F G$ )

Remark 3: In this scenario, $U_{1}$ operates under the HD and AF with FG protocols. Before forwarding a signal to $U_{2}, U_{1}$ amplifies the received signal shown as (6.2), where $\varepsilon=0$, by the
amplification coefficient $\kappa_{F G}$ given by (6.9a). The OP of $U_{2}$ is then expressed in closed form as:

$$
\left.\begin{array}{rl}
\Theta_{2}{ }^{H D, F G} & =1-\prod_{i=1}^{2} \operatorname{Pr}\left(R_{i \rightarrow 2}^{H D, F G}>R_{2}^{*}\right)=\operatorname{Pr}\left(R_{1 \rightarrow 2}^{H D}<R_{2}^{*}\right)+\operatorname{Pr}\left(R_{1 \rightarrow 2}^{H D}>R_{2}^{*}, R_{2 \rightarrow 2}^{H D, F G}<R_{2}^{*}\right) \\
& =\left(1-\lambda_{1}\right)+\lambda_{1}\left(1-\frac{2 e^{-\frac{R_{2}^{* *}}{\left(\alpha_{2}-\alpha_{1} R_{2}^{* *}\right) \rho_{0} \sigma_{0,1}^{2}}} \sqrt{\frac{1}{\sigma_{1,2}^{2}}} K_{1}\left(\frac{2 \sqrt{\frac{1}{\sigma_{1,2}^{2}}}}{\sqrt{\frac{\left(\alpha_{2}-\alpha_{1} R_{2}^{*}\right) \rho_{0} \rho_{1}^{2} \sigma_{0,1}^{2}}{R_{2}^{* *}\left(1+\rho_{0} \sigma_{1,2}^{2}\right)}}}\right)}{\sqrt{\frac{\left(\alpha_{2}-\alpha_{1} R_{2}^{*}\right) \rho_{0} \rho_{1}^{2} \sigma_{0,1}^{2}}{R_{2}^{* *}\left(1+\rho_{0} \sigma_{1,2}^{2}\right.}}}\right), \tag{6.21}
\end{array}\right), \quad, \quad,
$$

where $\lambda_{1}$ is given by (6.17) for $\varepsilon=0$ and $K_{n}($.$) denotes a modified BesselK function.$
For the proof of Remark 3, see the Appendix 6.6.3.
6.2.1.4 FD and AF with FG Protocols at the Relay ( $\Omega=F D, \omega \triangleq F G$ )

Remark 4: In this scenario, $U_{1}$ operates under the FD and AF with FG protocols. Before forwarding a signal to $U_{2}, U_{1}$ amplifies the received signal shown as (6.2), where $\varepsilon=1$, by the amplification coefficient $\kappa_{F G}$ given by (6.9a). The OP of $U_{2}$ is then expressed in closed form as:

$$
\begin{align*}
& \Theta_{2}^{F D, F G}=1-\prod_{i=1}^{2} \operatorname{Pr}\left(R_{i \rightarrow 2}^{F D, F G}>R_{2}^{*}\right)=\operatorname{Pr}\left(R_{1 \rightarrow 2}^{F D}<R_{2}^{*}\right)+\operatorname{Pr}\left(R_{1 \rightarrow 2}^{F D}>R_{2}^{*}, R_{2 \rightarrow 2}^{F D, F G}<R_{2}^{*}\right) \\
& =\left(1-\lambda_{1}\right)+\lambda_{1}\binom{2 e^{-\frac{R_{2}^{* *}}{\left(\alpha_{2}-\alpha_{1} R_{2}^{* *}\right) \rho_{0} \sigma_{0,1}^{2}}} \sqrt{\frac{1}{\sigma_{1,2}^{2}}}\left(\alpha_{2}-\alpha_{1} R_{2}^{* *}\right) \rho_{0} \sigma_{0,1}^{2} K_{1}\left(\frac{2 \sqrt{\frac{1}{\sigma_{1,2}^{2}}}}{\sqrt{\frac{\left(\alpha_{2}-\alpha_{1} R_{2}^{* *}\right) \rho_{\rho} \rho_{1}^{2} \sigma_{0,1}^{2}}{R_{2}^{* *}\left(1+\rho_{0} \sigma_{1,2}\right)}}}\right)}{\left.1-\frac{\left(\left(\alpha_{2}-\alpha_{1} R_{2}^{* *}\right) \rho_{0} \sigma_{0,1}^{2}+\varepsilon R_{2}^{* *} \rho_{1} \sigma_{1,1}^{2}\right) \sqrt{\frac{\left(\alpha_{2}-\alpha_{1} R_{2}^{* *}\right) \rho_{\rho} \rho_{0}^{2} \sigma_{0,1}^{2}}{R_{2}^{* *}\left(1+\rho_{0} \sigma_{1,2}^{2}\right)}}}{}\right),}, \tag{6.22}
\end{align*}
$$

where $\varepsilon$ in (6.22) equals zero, and (6.22) becomes (6.21).
For the proof of Remark 4, see the Appendix 6.6.3.
6.2.1.5 HD and AF with VG Protocols at the Relay ( $\Omega=H D, \omega \wedge V G$ )

Remark 5: In this scenario, $U_{1}$ operates under the HD and AF with VG protocols. Before forwarding a signal to $U_{2}, U_{1}$ amplifies the received signal shown as (6.2), where $\varepsilon=0$, by the
amplification coefficient $\kappa_{V G}$ given by (6.9b). The OP of $U_{2}$ is then expressed in closed form as:

$$
\begin{align*}
\Theta_{2}{ }^{H D, V G} & =1-\prod_{i=1}^{2} \operatorname{Pr}\left(R_{i \rightarrow 2}^{H D, V G}>R_{2}^{*}\right)=\operatorname{Pr}\left(R_{1 \rightarrow 2}^{H D}<R_{2}^{*}\right)+\operatorname{Pr}\left(R_{1 \rightarrow 2}^{H D}>R_{2}^{*}, R_{2 \rightarrow 2}^{H D, V G}<R_{2}^{*}\right) \\
& =\left(1-\lambda_{1}\right)+\lambda_{1}\left(1-\frac{2 e^{\frac{R_{2}^{* *}\left(\rho_{1}^{2}+\rho_{0}\right)}{\left(\alpha_{1} R_{2}^{* *}-\alpha_{2}\right) \rho_{0} \rho_{1}^{2} \sigma_{0,1}^{2}}} \sqrt{\frac{1}{\sigma_{1,2}}} K_{1}\left(\frac{2 \sqrt{\frac{1}{\sigma_{1,2}}}}{\sqrt{\frac{\left(\alpha_{1} R_{2}^{* *}-\alpha_{2}\right) \rho_{\rho} \rho_{1}^{2} \sigma_{0,1}^{2}}{R_{2}^{* *}}}}\right)}{\sqrt{\frac{\left(\alpha_{1} R_{2}^{* *}-\alpha_{2}\right) \rho_{0} \rho_{1}^{2} \sigma_{0,1}^{2}}{R_{2}^{* *}}}}\right) \cdot \tag{6.23}
\end{align*}
$$

For the proof of Remark 5, see the Appendix 6.6.4.

### 6.2.1.6 FD and AF with VG Protocols at the Relay $(\Omega=F D, \omega \triangleq V G)$

Remark 6: In this scenario, $U_{1}$ operates under the FD and AF with VG protocols. Before forwarding a signal to $U_{2}, U_{1}$ amplifies the received signal shown as (6.2), where $\varepsilon=1$, by the amplification coefficient $\kappa_{V G}$ given by (6.9b). The OP of $U_{2}$ is then expressed in closed form as:
$\Theta_{2}{ }^{F D, V G}=1-\prod_{i=1}^{2} \operatorname{Pr}\left(R_{i \rightarrow 2}^{\Omega, \omega}>R_{2}^{*}\right)=\operatorname{Pr}\left(R_{1 \rightarrow 2}^{F D}<R_{2}^{*}\right)+\operatorname{Pr}\left(R_{1 \rightarrow 2}^{F D}>R_{2}^{*}, R_{2 \rightarrow 2}^{F D, V G}<R_{2}^{*}\right)$
$=\left(1-\lambda_{1}\right)+\lambda_{1}\left(1-\frac{2 e^{-\frac{R_{2}^{* *}\left(\rho_{1}^{2}+\rho_{0}\right)}{\left(\alpha_{2}-\alpha_{1} R_{2}^{*}\right) \rho_{0} \rho_{1}^{2} \sigma_{0,1}^{2}}} \sqrt{\frac{1}{\sigma_{1,2}^{2}}}\left(\alpha_{2}-\alpha_{1} R_{2}^{* *}\right) \rho_{0} \sigma_{0,1}^{2} K_{1}\left(\frac{2 \sqrt{\frac{1}{\sigma_{1,2}^{2}}}}{\sqrt{\frac{\left(\alpha_{2}-\alpha_{1} R_{2}^{* *}\right) \rho_{0} \rho_{1}^{2} \sigma_{0,1}^{2}}{R_{2}^{* *}}}}\right)}{\left(\left(\alpha_{2}-\alpha_{1} R_{2}^{* *}\right) \rho_{0} \sigma_{0,1}^{2}+\varepsilon R_{2}^{* *} \rho_{1} \sigma_{1,1}^{2}\right) \sqrt{\frac{\left(\alpha_{2}-\alpha_{1} R_{2}^{* *}\right) \rho_{\rho_{0} \rho_{1}^{2} \sigma_{0,1}^{2}}^{R_{2}^{* *}}}{}}}\right)$.
where $\varepsilon$ in (6.24) equals zero, and (6.24) becomes (6.23).
For the proof of Remark 6, see the Appendix 6.6.4.

### 6.2.2 System Throughput

The sum of the achievable received data at $U_{i}$, which is also referred to as the system throughput $P_{s y s}^{\Omega, \omega}$, is the sum of the throughput results of all $U_{i}$ in the system, expressed as:

$$
\begin{equation*}
P_{s y s}^{\Omega, \omega}=P_{1}^{\Omega}+P_{2}^{\Omega, \omega}=\left(1-\Theta_{1}^{\Omega}\right) R_{1}^{*}+\left(1-\Theta_{2}^{\Omega, \omega}\right) R_{2}^{*}, \tag{6.25}
\end{equation*}
$$

where $\Omega=\{H D, F D\}$ and $\omega=\{D F, F G, V G\}$.

### 6.2.3 Energy Efficiency

Technological development has significantly increased the amount of electricity consumed and seriously affected the living environment. Thus, minimal energy consumption on each bit of data transmitted through the network is an essential requirement of next generation G-WNs. In this section, the dissertation evaluates the EE of each scenario:

$$
\begin{equation*}
E E_{s y s}^{\Omega, \omega}=\frac{P_{1}^{\Omega}+P_{2}^{\Omega, \omega}}{\rho_{0}+\rho_{1}}=\frac{\left(1-\Theta_{1}^{\Omega}\right) R_{1}^{*}+\left(1-\Theta_{2}^{\Omega, \omega}\right) R_{2}^{*}}{\rho_{0}+\rho_{1}} \tag{6.26}
\end{equation*}
$$

### 6.3 Protocol Switching Selection

In this section, the dissertation proposes a PSS mechanism. Of the six protocols analyzed above, none significantly surpasses any of the other protocols. Each protocol has its own advantages in different situations. The results of the analysis presented in the next section demonstrate the advantages of each protocol more clearly. To optimize the system's performance, it is therefore necessary that the relay is equipped with a sensor which can switch between the six protocols.

Figure 6.2 shows the mechanism of switching between protocols HD/FD and DF/AF with FG/VG. Each protocol is substituted into its corresponding analysis function. The results of the analysis are used to decide which protocol is optimal and should be applied to forward a signal to the next user at the moment of evaluation.


Figure 6.2: PSS mechanism.

To optimize QoS for network users, the OP is analyzed in all six scenarios according to the relevant functions for selecting the best protocol with the lowest OP result.

The minimum OP result in the HD and DF/AF with FG/VG protocols is selected according to:

$$
\begin{equation*}
P S S_{\Theta}^{H D, \omega}=\min \left\{\Theta_{1}^{H D}\right\}+\min \left\{\Theta_{2}^{H D, \omega}\right\} \tag{6.27}
\end{equation*}
$$

and the minimum OP result in the FD and DF/AF with FG/VG protocols is selected according to:

$$
\begin{equation*}
P S S_{\Theta}^{F D, \omega}=\min \left\{\Theta_{1}^{F D}\right\}+\min \left\{\Theta_{2}^{F D, \omega}\right\} \tag{6.28}
\end{equation*}
$$

where $\Theta_{1}^{\Omega}$ is given by (6.17) and $\Theta_{2}^{\Omega, \omega}$ is given by (6.19), (6.20), (6.21), (6.22), (6.23) and (6.24) for $\Omega=\{H D, F D\}$ and $\omega=\{D F, F G, V G\}$, in pairs and respectively.

Since the HD protocol is not affected by the LI channel, $P S S_{\Theta}^{H D, \omega}<P S S_{\Theta}^{F D, \omega}$ is therefore obvious. The dissertation proposes an outage threshold denoted by $T_{\Theta}$. The mechanism switches between the HD and FD protocols according to:

$$
\begin{equation*}
P S S_{\Theta}=P S S_{\Theta}^{H D, \omega} \tag{6.29}
\end{equation*}
$$

or

$$
\begin{equation*}
P S S_{\Theta}=P S S_{\Theta}^{F D, \omega}, \tag{6.30}
\end{equation*}
$$

where (6.29) is for $T_{\Theta}<P S S_{\Theta}^{H D, \omega}<P S S_{\Theta}^{F D, \omega},(6.30)$ is for $P S S_{\Theta}^{H D, \omega} \approx P S S_{\Theta}^{F D, \omega}<T_{\Theta}$ and $T_{\Theta}$ is the outage threshold.

The outstanding feature of NOMA is that all users are served in the same time slot by sharing the same power domain to improve user throughput. In this dissertation, the mechanism switches the protocols to optimize the throughput of the C-NOMA system. The system performance is directly proportional to the system throughput. With a higher throughput, users can reach a higher data bit rate. The throughput results of all six scenarios of $U_{1}$ and $U_{2}$ were evaluated, and the best protocol to reach the optimal system throughput was selected according to:

$$
\begin{equation*}
P S S_{P}=\max \left\{P_{1}^{\Omega}\right\}+\max \left\{P_{2}^{\Omega, \omega}\right\}=\max \left\{\left(1-\Theta_{1}^{\Omega}\right) R_{1}^{*}\right\}+\max \left\{\left(1-\Theta_{2}^{\Omega, \omega}\right) R_{2}^{*}\right\} \tag{6.31}
\end{equation*}
$$

Given battery capacity limitations, the G-WNs technology requires that the minimum possible energy is spent. In this study, the EE results of all six scenarios were investigated and presented. In these results, the mechanism selects the best EE protocol for bits of data per joule (b/J) transmitted through the network considered by the $P S S_{E E}$ according to:

$$
\begin{equation*}
P S S_{E E}=\max \left\{E E^{\Omega, \omega}\right\}=\frac{\max \left\{P_{1}^{\Omega}\right\}+\max \left\{P_{2}^{\Omega, \omega}\right\}}{\rho_{0}+\rho_{1}} . \tag{6.32}
\end{equation*}
$$

### 6.4 Numerical Results and Discussion

The results presented below are true and accurate to the best of my knowledge without any copying from any previous research results. The dissertation uses the simulation parameters given in Table 4:

Table 4: Simulation parameters.

| Symbols | Values | Description |
| :---: | :---: | :---: |
| $\sigma_{0,1}^{2}$ | 0.5 | Expected channel gain from BS to $U_{1}$ |
| $\sigma_{1,2}^{2}$ | 0.3 | Expected channel gain from $U_{1}$ to $U_{2}$ |
| $\sigma_{1,1}^{2}$ | 0.01 | Expected LI channel from $U_{1}$ to $U_{2}$ |
| $\alpha_{1}$ | 0.25 | PA factor of $U_{1}$ |
| $\alpha_{2}$ | 0.75 | PA factor of $U_{2}$ |
| $R_{1}^{*}$ | 0.2 | Bit rate threshold of $U_{1}$ |
| $R_{2}^{*}$ | 0.2 | Bit rate threshold of $U_{2}$ |
| $\rho_{0}$ | $\{-20, \ldots, 40\}$ | SNRs at BS (optional) |
| $\rho_{1}$ | $\{-20, \ldots, 40\}$ | SNRs at $U_{1}$ (optional) |

Note: The dissertation uses the Monte Carlo simulation method with $10^{6}$ random samples for each channel.

Note: In all the figures, the markers indicate the analysis results whereas the solid or dashed lines indicate the Monte Carlo simulation results. The simulation results are based on the statistics of $10^{6}$ samples. Monte Carlo simulation results are used to compare and verify the analysis results. Where the results approximately converge, the analysis results can be accepted. Certain previous studies included no simulation results. In the dissertation, I propose Algorithm 6.1 for Monte Carlo simulations to investigate the OP:

```
Algorithm 6.1 Algorithm for Monte Carlo simulations.
Input: Initialize the variablesin Table 4, generate \(10^{6}\) random samples for each channel \(h_{0,1}\),
    \(h_{1,2}\), and \(h_{1,1}\);
Output: OP result of \(U_{i}\);
    for \(\operatorname{SNR} \rho=\{-20, \ldots, 40\}\) do
        for each sample in \(10^{6}\) generated samples do
            Calculate \(\boldsymbol{S I N R} \gamma_{i}^{\Omega, \omega}\) of each protocol by submitting variables, \(\boldsymbol{S N R}\), and sample
            into Equations (6.4), (6.7), and (6.11);
            Calculate the instantaneous bit rate \(R_{i \rightarrow j}^{\Omega, \omega}\) of each protocol by submitting \(\boldsymbol{S I N R}\) into
            Equations (6.5), (6.8), and (6.13);
            if the instantaneous bit rate \(R_{i \rightarrow j}^{\Omega, \omega}\) is compared to \(R_{j}^{*}\) with the conditions of Equations
            (6.16), (6.18), (6.19), (6.20), (6.21), (6.22), (6.23), and (6.24) then
                count the number of True times;
            else
                Go the next sample;
            end if
        end for
        The OP result is the ratio of the number of True times per \(10^{6}\);
        Go to the next \(\boldsymbol{S N R}\);
    end for
    return Monte Carlo simulation results;
```


### 6.4.1 Numerical Results and Discussion for Outage Probability

The results of the first analysis enable the OP at $U_{1}$ in both HD and FD mode to be evaluated. With the same simulation parameters as in Table 4, the HD scenario yielded better OP results than the FD scenario. For low SNR, the OP results of $U_{1}$ in HD and FD mode were approximately the same, for example where the SNR was 0 dB . However, as the SNR increased, the results of the OP at $U_{1}$ in FD mode were worse than in HD mode. In the FD scenario, $U_{1}$ was affected by the LI channel from its own transmitter antenna to the receiver antenna. The effect of the LI channel became increasingly powerful and affected the QoS of $U_{1}$. However, the analysis results of $U_{1}$ still obtained good results, as shown in Figure 6.3.

To ensure fairness for both $U_{1}$ and $U_{2}$, the required instantaneous bit rate thresholds in both $U_{1}$ and $U_{2}$ for $R_{1}^{*}=R_{2}^{*}=0.2 \mathrm{bps} / \mathrm{Hz}$ were selected.

Next, I investigated the OP of $U_{2}$ with $U_{1}$ in $\mathrm{HD} / \mathrm{FD}$ mode and AF with FG/VG protocols. Figure 6.4a and Figure 6.4 b show the OP results of $U_{2}$ with $U_{1}$ in HD and FD relaying modes, respectively.

Figure 6.4a shows OP results of $U_{1}$ in HD mode. At a SNR less than $0 \mathrm{~dB}, U_{2}$ has been received cooperation from $U_{1}$ in the HD and DF protocols, yielding a better OP result than the other protocols. The results in the figure are indicated with square markers. The advantage of the DF protocol is its simplicity, and $U_{2}$ only has to decode its own information $x_{2}$. $U_{1}$, however, operates under the AF protocol with FG/VG, and $U_{2}$ must decode its own information $x_{2}$ symbol with the effect of noise $x_{1}$ and AWGNs $n_{1}$ and $n_{2}$. As the SNR increased, the OP results in the AF with FG/VG protocols improved and surpassed those with the DF protocol. At low SNR, the OP results for $U_{2}$ in AF with FG and AF with VG were approximately the same. As the SNR increased, the AF with VG protocol surpassed the AF with FG protocol, for example, at a SNR of 5 dB . However, with at higher SNR, the AF with both FG/VG converged and were better than the DF protocol. Furthermore, the OP results of $U_{2}$ in all the proposed scenarios with the cooperation of $U_{1}$ were better than without any relay support. These results show the effectiveness of cooperative multi-access wireless communication over channel fading. The results also show that no protocol outperforms any other protocol. The aim of this dissertation was to propose a protocol switching mechanism.

Figure 6.4 b shows $U_{1}$ in FD mode. In the DF scenario, $U_{1}$ forwards a signal to $U_{2}$ according to Equation (6.6). However, $U_{1}$ is affected by the LI channel $h_{1,1}$ from its own transmission antenna, thereby impacting the OP result at $U_{2}$. $U_{2}$ achieved a better OP result than $U_{1}$, as shown in Figure 6.4, because $U_{1}$ cooperated and prioritized the allocation of a larger PA factor. Generally, the FD and DF scenario also have OP results better than FD and AF with FG/VG at a low SNR, for example, at SNR $\rho_{0}=\rho_{1}=-5 \mathrm{~dB}$. However, as the SNR increased, the results of the OP of $U_{2}$ in AF with both FG and VG protocols improved and were better than the DF protocol. The AF protocol with VG yielded better results than the AF protocol with FG at some $\operatorname{SNR}$, for example, at $\operatorname{SNR} \rho_{0}=\rho_{1}=\{-5, \ldots, 20\} \mathrm{dB}$. Figure 6.4 shows that the AF protocol with VG was better than the AF protocol with FG. As the SNR increased, the OP results of both AF with VG and AF with FG scenarios attained approximately the same
results, but better than the results in the case of the DF protocol.


Figure 6.3: OP of $U_{1}$ in $\mathrm{HD} / \mathrm{FD}$ mode.


Figure 6.4: OP results of $U_{1}$ and $U_{2}$ in $\mathrm{HD} / \mathrm{FD}$ and $\mathrm{DF} / \mathrm{AF}$ with $\mathrm{FG} / \mathrm{VG}$ protocols.

### 6.4.2 Numerical Results and Discussion for System Throughput

The achievable system throughput of all six scenarios is examined in this section. Figure 6.5 shows that the DF protocol provides better throughput results than the other protocols at low

SNR. As the SNR increased, the achievable throughput results of $U_{2}$ in both AF with FG and VG scenarios improved. However, an interesting observation can be made in Figure 6.5. At some SNR, the AF with VG protocol returns better throughput results than the DF protocol, for example, at SNR $\rho_{0}=\rho_{1}=5 \mathrm{~dB}$. Finally, as SNR keep increasing, the achievable throughput of all scenarios approximate and reach the threshold $R_{2}^{*}=0,2 \mathrm{bps} / \mathrm{Hz}$.


Figure 6.5: System throughput of $U_{2}$ in $\mathrm{HD} / \mathrm{FD}$ and $\mathrm{DF} / \mathrm{AF}$ with FG and VG protocols.

### 6.4.3 Numerical Results and Discussion for Energy Efficiency

Energy waste is a serious problem which affects the living environment. The G-WNs are being studied by researchers for their environmentally friendly potential. In G-WNs, devices must
consume the least amount of energy for the total amount of data transferred and still ensure QoS for users. This section describes the deployment of EE in wireless communications. Figure 6.6 shows the effect of the incorporated EE in all six scenarios, with HD and FD relaying, respectively. At low SNR, the DF protocol returned superior EE results than the AF protocol with FG/VG because the DF protocol used $100 \%$ power to forward the $x_{2}$ symbol without considering noise. In previous studies, to simplify their simulations, the authors assumed that the power of the BS and relay were equal. The present study, however, investigates the differing transmission powers of the BS and relay to find the optimal transmission power of the relay which corresponds to the power of the BS.


Figure 6.6: EE of HD/FD and DF, HD/FD and AF with FG/VG scenarios.

### 6.4.4 Protocol Switching Selection Mechanism

Section 6.3 presented a proposed mechanism for six pairing protocols. In this section, the PSS mechanism will be applied to ascertain the best protocol.
6.4.4.1 PSS Based on Outage Probability : As shown in Figure 6.4, the results of OP in both $U_{1}$ and $U_{2}$ depend on the protocols used at $U_{1}$ corresponding to various SNR. Therefore, the protocols were switched to ensure the best system performance, as described in Proposition 1. Before the signal is forwarded to the next user, the relay pre-evaluates system performance and selects the best protocol. Figure 6.7 shows the OP results of all six scenarios. Table 5 presents the OP of each scenario and protocol, the minimum value (in bold font) being the best value at the same SNR. The outage threshold $T_{\Theta}=0.005$. Meanwhile, the signal was forwarded from $U_{1}$ to $U_{2}$ with a $99.5 \%$ rate of success. At low SNR , the OP result of $U_{2}$ with HD/FD and DF protocols at the relay was approximately the same, but better than other protocols at, for example, $\mathrm{SNR} \rho_{0}=\rho_{1}=-5 \mathrm{~dB}$. The simulation results were generated in Matlab simulation software and are shown in Table 5. The simulation results show that the system performance depends on the transition protocol at $U_{1}$ and the SNR. A PSS is therefore necessary to select the appropriate protocol for optimal system performance. By applying (6.27), the PSS performed system performance evaluations in all six scenarios to select the optimal protocol for user service quality, as shown in Figure 6.7. Furthermore, the PSS's outage results achieved the expected outage threshold $T_{\Theta}=0.005$ in SNR greater than 10 dB .


Figure 6.7: OP results of PSS.

Table 5: Comparison of the OP results.

| Protocols | $\mathbf{- 5} \mathbf{d B}$ | $\mathbf{0} \mathbf{d B}$ | $\mathbf{5} \mathbf{d B}$ | $\mathbf{1 0} \mathbf{d B}$ | $\mathbf{3 0} \mathbf{d B}$ |
| :---: | :---: | :---: | :---: | :---: | :---: |
| HD and DF | $\mathbf{0 . 4 7 1 8 3 1}$ | $\mathbf{0 . 1 8 2 7 9 1}$ | 0.061839 | 0.019983 | 0.000201 |
| FD and DF | 0.472334 | 0.183569 | 0.062732 | 0.020917 | 0.001154 |
| HD and AF with FG | 0.894059 | 0.337188 | 0.075005 | 0.016100 | $9.6 \times 10^{-5}$ |
| FD and AF with FG | 0.894160 | 0.337820 | 0.075887 | 0.017037 | 0.001049 |
| HD and AF with VG | 0.920599 | 0.262177 | $\mathbf{0 . 0 4 5 4 3 6}$ | $\mathbf{0 . 0 1 0 7 5 5}$ | $9.6 \times 10^{-5}$ |
| FD and AF with VG | 0.920675 | 0.262880 | 0.046345 | 0.011697 | $\mathbf{0 . 0 0 1 0 4 8}$ |
| PSS | 0.471831 | 0.182791 | 0.045436 | 0.010755 | 0.001048 |

Note: These statistical results were extracted from Matlab simulation software.
The bold results are better than other results. The PSS thus selects the corresponding protocols.
6.4.4.2 PSS Based on Throughput - Figure 6.8 shows a comparison of the throughput achieved at $U_{2}$ in all six scenarios. The results of the analysis and simulations of all six scenarios were extracted correctly from Matlab software and presented in Table 6. The achieved throughput of all scenarios with HD or FD approximate each other, with the HD and FD protocol markers overlapping. By applying (6.28), the PSS evaluates the system throughput in all six scenarios to select the protocol with the highest system throughput, as indicated by the red-dotted line in Figure 6.8. At $\mathrm{SNR}=5 \mathrm{~dB}$, we can seen that PSS selects the AF protocol with VG instead of the DF protocol.


Figure 6.8: System throughput results of PSS.

Table 6: Comparison of throughput results.

| Protocols | $\mathbf{- 5} \mathbf{~ d B}$ | $\mathbf{0} \mathbf{d B}$ | $\mathbf{5} \mathbf{d B}$ | $\mathbf{1 0} \mathbf{d B}$ | $\mathbf{3 0} \mathbf{d B}$ |
| :---: | :---: | :---: | :---: | :---: | :---: |
| HD and DF | $\mathbf{0 . 1 0 5 6 3 3}$ | $\mathbf{0 . 1 6 3 4 4 1}$ | 0.187632 | 0.196003 | 0.199959 |
| FD and DF | 0.105533 | 0.163286 | 0.187453 | 0.195816 | 0.199769 |
| HD and AF with FG | 0.021188 | 0.132562 | 0.184998 | 0.196779 | 0.199980 |
| FD and AF with FG | 0.021167 | 0.132435 | 0.184822 | 0.196592 | 0.199790 |
| HD and AF with VG | 0.015880 | 0.147564 | $\mathbf{0 . 1 9 0 9 1 2}$ | $\mathbf{0 . 1 9 7 8 4 8}$ | 0.199980 |
| FD and AF with VG | 0.015864 | 0.147423 | 0.190730 | 0.197660 | $\mathbf{0 . 1 9 9 7 9 0}$ |
| PSS | 0.105633 | 0.163441 | 0.190912 | 0.197848 | 0.199790 |

Note: The dissertation uses the Monte Carlo simulation method with $10^{6}$ iterations.
The bold results are better than other results. The PSS thus selects the corresponding protocols.
6.4.4.3 PSS Based on EE : Figure 6.9 compares the results of EE in all six scenarios. Although $U_{1}$ was operated in HD or FD mode, the EE of these scenarios were approximately the same. The scenarios of $\mathrm{HD} / \mathrm{FD}$ and DF , in pairs, had more EE results than the AF scenario with $\mathrm{FG} / \mathrm{VG}$. In the $\mathrm{HD} / \mathrm{FD}$ and DF scenarios, the received signal at $U_{2}$ only contained the information symbol $x_{2}$, given by (6.6), without sharing the transmission power factor with symbol $x_{1}$, given by (6.10). The DF protocol therefore reached higher throughput and better EE than the AF protocol at low SNR. However, EE in all six scenarios remained approximately the same as the SNR increased.

As shown in Figures 6.3-6.9, system performance was not only affected by the protocols but also the SNR. In this section, the impact of SNR on system performance was researched. Instead of assuming $\rho_{0}=\rho_{1}$ as in previous investigations, a variable SNR was evaluated. The aim of this investigation was to find the minimum SNR pair able to ensure system performance. Figure 6.11 shows the OP results of $U_{2}$ with vector $\rho_{0}=\{-20, \ldots, 40\}$ and vector $\rho_{1}=\{-20, \ldots, 40\}$. For example, at SNR $\rho_{0}=-20 \mathrm{~dB}$, there is no value of $\rho_{1}$ to ensure system performance. Therefore, the BS must increase the $\rho_{0}$. For example, at $\rho_{0}=10 \mathrm{~dB}$, the PSS assigned the value $\rho_{1}=10$ dB as an optimal pairing value. If the system continued to increase $\rho_{0}$ or $\rho_{1}$, the extra SNR would have made the system performance decrease or be wasted, for example $\rho_{0}=10 \mathrm{~dB}$ and $\rho_{1}=40 \mathrm{~dB}$, or $\rho_{0}=40 \mathrm{~dB}$ and $\rho_{1}=40 \mathrm{~dB}$.

The dissertation also examined the impact of vector $\rho_{1}$ and vector $\rho_{2}$ on $U_{2}$ throughput in the six proposed scenarios. The results of this analysis were compared and the best protocol was selected. For example, for $\rho_{0}=40 \mathrm{~dB}$ and $\rho_{1}=0 \mathrm{~dB}$, the throughput of $U_{2}$ with $U_{1}$ in HD mode was better than others. In another example, for $\rho_{0}=0 \mathrm{~dB}$ and $\rho_{1}=40 \mathrm{~dB}$, the throughput results of $U_{2}$ with $U_{1}$ in $\mathrm{HD} / \mathrm{FD}$ and AF with VG protocols were better than others.

Finally, EE of the six scenarios was evaluated for $\rho_{0}=\{-20, \ldots, 40\}$ and $\rho_{1}=\{-20, \ldots, 40\}$, as shown in Figure 6.2. The system had the best EE with $U_{1}$ in HD/FD and DF protocols, especially at $\operatorname{SNR} \rho_{0}=\rho_{1}=-5 \mathrm{~dB}$, as shown in Figure 6.9.


Figure 6.9: EE results of PSS.


Figure 6.10: EE results, where $\rho_{0}=\{-20, \ldots, 40\}$ and $\rho_{1}=\{-20, \ldots, 40\}$.


Figure 6.11: Impact of SNR, where $\rho_{0}=\{-20, \ldots, 40\}$ and $\rho_{1}=\{-20, \ldots, 40\}$.


Figure 6.12: System throughput of $U_{2}$, where $\rho_{0}=\{-20, \ldots, 40\}$ and $\rho_{1}=\{-20, \ldots, 40\}$.

### 6.5 Conclusion

In the dissertation, I studied six relay scenarios deployed in a C-NOMA system. The results of the research show that no protocol was more suitable than any other. At some SNR, the DF protocol was more suitable than the AF protocol, especially at low SNR. At other SNR, the AF protocol was more suitable than the DF protocol, especially at high SNR. I therefore proposed a PSS mechanism which could ascertain the optimal protocol to forward a signal to the next
user in order to optimize the system's performance in terms of OP, system throughput and EE. A Monte Carlo simulation algorithm was also proposed. The simulation results were used to verify the analysis results and were presented in closed form. These results of the analysis can be deployed for future G-WNs.

### 6.6 Appendix

### 6.6.1 Proof of Theorem 1

This section presents the OP of $U_{1}$ in HD/FD mode.
By substituting (6.3) and (6.4) into (6.5) and combining with the conditional outage in (6.16), we obtain the following expression:

$$
\begin{align*}
\Theta_{1}^{\Omega}=1- & \prod_{j=1}^{2} \\
& \operatorname{Pr}\left(R_{1 \rightarrow j}^{\Omega}>R_{j}^{*}\right)=1-\operatorname{Pr}\left(R_{1 \rightarrow 1}^{\Omega}>R_{1}^{*}, R_{1 \rightarrow 2}^{\Omega}>R_{2}^{*}\right)  \tag{6.33}\\
= & 1-\operatorname{Pr}(\{\underbrace{\left|h_{0,1}\right|^{2}>\frac{R_{1}^{* *}\left(\varepsilon\left|h_{1,1}\right|^{2} \rho_{1}+1\right)}{\alpha_{1} \rho_{0}},\left|h_{1,1}\right|^{2}>0}_{\lambda_{0}}\}, \\
& \{\underbrace{\left|h_{0,1}\right|^{2}>\frac{R_{2}^{* *}\left(\varepsilon\left|h_{1,1}\right|^{2} \rho_{1}+1\right)}{\left(\alpha_{2}-\alpha_{1} R_{2}^{* *}\right) \rho_{0}},\left|h_{1,1}\right|^{2}>0}_{\lambda_{1}}\}) .
\end{align*}
$$

$\lambda_{0}$ in (6.33) can be solved by applying PDF (6.14), as follows

$$
\begin{equation*}
\lambda_{0}=\int_{0}^{\infty} \int_{\frac{R_{1}^{* *}\left(\varepsilon y \rho_{1}+1\right)}{\alpha_{1} \rho_{0}}}^{\infty} \frac{1}{\sigma_{0,1}^{2} \sigma_{1,1}^{2}} e^{-\left(\frac{x}{\sigma_{0,1}^{2}}+\frac{y}{\sigma_{1,1}^{2}}\right)} d x d y=e^{-\frac{R_{R_{*}^{* *}}^{\alpha_{1} \rho_{0} \sigma_{0,1}^{2}}}{\alpha_{1} \rho_{0} \sigma_{0,1}^{2}+\varepsilon R_{1}^{* *} \rho_{1} \sigma_{1,1}^{2}} . . . . ~ . ~} \tag{6.34}
\end{equation*}
$$

Similarly, $\lambda_{1}$ in (6.33) is also solved and expressed as:

$$
\begin{align*}
\lambda_{1} & =\int_{0}^{\infty} \int_{\frac{R_{2}^{* *}\left(\varepsilon y \rho_{1}+1\right)}{\left(\alpha_{2}-\alpha_{1} R_{2}^{* *}\right) \rho_{0}}}^{\infty} \frac{1}{\sigma_{0,1}^{2} \sigma_{1,1}^{2}} e^{-\left(\frac{x}{\sigma_{0,1}^{2}}+\frac{y}{\sigma_{1,1}^{2}}\right)} d x d y \\
& =e^{-\frac{R_{2}^{*}}{\left(\alpha_{2}-\alpha_{1} R_{2}^{*}\right) \rho_{0} \sigma_{0,1}^{2}}} \frac{\left(\alpha_{2}-\alpha_{1} R_{2}^{* *}\right) \rho_{0} \sigma_{0,1}^{2}}{\left(\alpha_{2}-\alpha_{1} R_{2}^{* *}\right) \rho_{0} \sigma_{0,1}^{2}+\varepsilon R_{2}^{* *} \rho_{1} \sigma_{1,1}^{2}}, \tag{6.35}
\end{align*}
$$

where $\varepsilon=0$ and $U_{1}$ operates in HD mode, and where $\varepsilon=1$ and $U_{1}$ operates in FD mode.

### 6.6.2 Proof of Remarks 1 and 2

This section presents the OP of $U_{2}$, where $U_{1}$ functions in HD/FD and the DF protocol.

By applying (6.7) into (6.8) and combining with the conditional outage in (6.19) or (6.20), we obtain the following expression:

$$
\begin{align*}
\Theta_{2}^{\Omega, D F} & =1-\prod_{i=1}^{2} \operatorname{Pr}\left(R_{i \rightarrow 2}^{\Omega, D F}>R_{2}^{*}\right)=1-\operatorname{Pr}\left(R_{1 \rightarrow 2}^{\Omega}>R_{2}^{*}, R_{1 \rightarrow 2}^{\Omega, D F}>R_{2}^{*}\right) \\
& =1-\operatorname{Pr}(\{\underbrace{\left|h_{0,1}\right|^{2}>\frac{R_{2}^{* *}\left(\varepsilon\left|h_{1,1}\right|^{2} \rho_{1}+1\right)}{\left(\alpha_{2}-\alpha_{1} R_{2}^{* *}\right) \rho_{0}},\left|h_{1,1}\right|^{2}>0}_{\lambda_{1}}\},\{\underbrace{\left|h_{1,2}\right|^{2}>\frac{R_{2}^{* *}}{\rho_{1}}}_{\lambda_{2}}\}), \tag{6.36}
\end{align*}
$$

where $\Omega=\{H D, F D\}$ and $\lambda_{1}$ in (6.36) is given by (6.35). It is not necessary to rewrite. $\lambda_{2}$ can be solved by applying the $\operatorname{PDF}$ (6.14) as follows:

$$
\begin{equation*}
\lambda_{2}=\int_{\frac{R_{2}^{* *}}{\rho_{1}}}^{\infty} \frac{1}{\sigma_{1,2}^{2}} e^{-\frac{x}{\sigma_{1,2}}} d x=e^{-\frac{R_{2}^{* *}}{\rho_{1} \sigma_{1,2}^{2}}} . \tag{6.37}
\end{equation*}
$$

### 6.6.3 Proof of Remark 3 and 4

This section presents the OP of $U_{2}$ with $U_{1}$ in HD/FD and AF with FG protocol.
By substituting (6.11) for $\omega=F G$ into (6.13) and combining with the conditional outage in (6.21) or (6.22), we obtain the following expression:

$$
\begin{equation*}
\Theta_{2}^{\Omega, F G}=1-\prod_{i=1}^{2} \operatorname{Pr}\left(R_{i \rightarrow 2}^{\Omega, F G}>R_{2}^{*}\right)=1-\operatorname{Pr}(\underbrace{R_{1 \rightarrow 2}^{\Omega}>R_{2}^{*}}_{\lambda_{1}}, \underbrace{R_{1 \rightarrow 2}^{\Omega, F G}>R_{2}^{*}}_{\lambda_{3}}), \tag{6.38}
\end{equation*}
$$

where $\lambda_{1}$ in (6.38) is still given by (6.35), and $\lambda_{3}$ can be solved as follows:

$$
\lambda_{3}=\operatorname{Pr}\left(\left|h_{0,1}\right|^{2}>\frac{R_{2}^{* *}\left(\varepsilon\left|h_{1,1}\right|^{2} \rho_{1}+1+\frac{\rho_{0} \sigma_{1,2}^{2}+1}{\rho_{1}^{2}\left|h_{1,2}\right|^{2}}\right)}{\left(\alpha_{2}-\alpha_{1} R_{2}^{* *}\right) \rho_{0}},\left|h_{1,2}\right|^{2}>0,\left|h_{1,1}\right|^{2}>0\right)
$$

$$
\begin{align*}
\lambda_{3} & =\int_{0}^{\infty} \int_{0}^{\infty} \frac{1}{\int_{0}} \frac{1}{R_{2}^{* *}\left(\varepsilon z \rho_{1}+1+\frac{\rho_{0} \sigma_{1,2}^{2}+1}{\rho_{1}^{2} y}\right)} \\
& e^{\left(\alpha_{2}-\alpha_{1} R_{2}^{* *}\right) \rho_{0}} e_{1,2}^{2 \sigma_{1,1}^{2}} \\
& =\frac{R_{2}^{* *} \frac{x}{\left.\sigma_{0,1}^{2}+\frac{y}{\sigma_{1,2}^{2}}+\frac{z}{\sigma_{1,1}^{2}}\right)} d x d y d z}{\left(\left(\alpha_{2}-\alpha_{1} R_{2}^{* *}\right) \rho_{0} \sigma_{0,1}^{2}+\varepsilon R_{2}^{* *} \rho_{1} \sigma_{1,1}^{2}\right) \sqrt{\frac{\left(\alpha_{2}-\alpha_{1} R_{2}^{* *}\right) \rho_{0} \rho_{1}^{2} \sigma_{0,1}^{2}}{R_{2}^{* *}\left(1+\rho_{0} \sigma_{1,2}^{2}\right)}}} \tag{6.39}
\end{align*}
$$

where $\varepsilon=0$ in both $\lambda_{1}$ and $\lambda_{3}$ while $U_{1}$ operates in HD and the AF with FG protocol, and, where $\varepsilon=1$ in both $\lambda_{1}$ and $\lambda_{3}$ while $U_{1}$ operates in FD and the AF with FG protocol.

### 6.6.4 Proof of Remarks 5 and 6

This section presents the OP of $U_{2}$ while $U_{1}$ functions in HD/FD and the AF with VG protocol.
By substituting (6.11) for $\omega=V G$ into (6.13) and combining with the conditional outage in (6.23) or (6.24), we obtain the following expression:

$$
\begin{equation*}
\Theta_{2}{ }^{\Omega, V G}=1-\prod_{i=1}^{2} \operatorname{Pr}\left(R_{i \rightarrow 2}^{\Omega, F G}>R_{2}^{*}\right)=1-\operatorname{Pr}(\underbrace{R_{1 \rightarrow 2}^{\Omega}>R_{2}^{*}}_{\lambda_{1}}, \underbrace{R_{1 \rightarrow 2}^{\Omega, V G}>R_{2}^{*}}_{\lambda_{4}}), \tag{6.40}
\end{equation*}
$$

where $\lambda_{1}$ is also given by (6.35), and $\lambda_{4}$ can be solved as follows:

$$
\begin{align*}
\lambda_{4} & =\int_{0}^{\infty} \int_{0}^{\infty} \frac{1}{\int_{2}^{R_{2}^{* *}\left(\varepsilon z \rho_{1}+1+\frac{\rho_{0} y+1}{\rho_{1}^{2} y}\right)}}{ }^{\frac{\left(\alpha_{2}-\alpha_{1} R_{2}^{* *}\right) \rho_{0}}{\sigma_{0,1}^{2} \sigma_{1,2}^{2} \sigma_{1,1}^{2}} e^{-\left(\frac{x}{\sigma_{0,1}^{2}}+\frac{y}{\sigma_{1,2}^{2}}+\frac{z}{\sigma_{1,1}^{2}}\right)} d x d y d z} \\
& =\frac{e^{-\frac{R_{2}^{* *}\left(\rho_{1}^{2}+\rho_{0}\right)}{\left(\alpha_{2}-\alpha_{1} R_{2}^{* *}\right) \rho_{0} \rho_{1}^{2} \sigma_{0,1}^{2}} 2} \sqrt{\frac{1}{\sigma_{1,2}^{2}}}\left(\alpha_{2}-\alpha_{1} R_{2}^{* *}\right) \rho_{0} \sigma_{0,1}^{2} K_{1}\left(\frac{2 \sqrt{\frac{1}{\sigma_{1,2}^{2}}}}{\sqrt{\frac{\left(\alpha_{2}-\alpha_{1} R_{2}^{* *}\right) \rho_{0} \rho_{1}^{2} \sigma_{0,1}^{2}}{R_{2}^{* *}}}}\right.}{\left(\left(\alpha_{2}-\alpha_{1} R_{2}^{* *}\right) \rho_{0} \sigma_{0,1}^{2}+\varepsilon R_{2}^{* *} \rho_{1} \sigma_{1,1}^{2}\right) \sqrt{\frac{\left(\alpha_{2}-\alpha_{1} R_{2}^{* *}\right) \rho_{0} \rho_{1}^{2} \sigma_{0,1}^{2}}{R_{2}^{* *}}}} \tag{6.41}
\end{align*}
$$

where $\varepsilon=0$ in both $\lambda_{1}$ and $\lambda_{4}$ while $U_{1}$ operates in HD and the AF with VG protocol, and where $\varepsilon=1$ in both $\lambda_{1}$ and $\lambda_{4}$ while $U_{1}$ operates in FD and the AF with VG protocol.

## Part II - Instantaneous AF Factor Maximization

IN studies [87, 88], the authors investigated C-NOMA SWIPT networks seeking to maximize the sum achievable user rate in the same cluster, based on PA and EH strategies. Specifically, the authors in [88] deployed MRC to combine the received signals from the BS and relay. The authors in $[89,90]$ improved the performance of MISO-NOMA networks with SWIPT and TAS techniques. To the best of our knowledge, MRC and selection combining (SC) are two methods which trade off between performance and complexity. The MRC technique maximizes linear combining but is difficult to implement since it requires multiple signals over multiple channel estimations and complex hardware. The SC technique is simpler to deploy since SC requires the best signal selected from multiple signals. In [91], the authors examined the MIMO-NOMA network and offered TAS/SC to optimize OP performance using the AF-FG protocol. Notice that the works in the present study also select the best antenna pairs at the BS and user $U_{1}$ in the FTS, and user $U_{1}$ and user $U_{2}$ in the STS, where user $U_{1}$ operates under the AF-VG protocol.

The major works of the present goal are:

- A proposed emerging cooperative MIMO-NOMA network model. The network model deploys a combination of TAS/SC and SWIPT protocols. Hence, the study provides deep insight how MIMO and TAS improve system performance;
- Stronger users functioning as relays to cooperate with weaker users. Various relaying technologies are examined, such as DF, AF-FG and AF-VG protocols.
- Maximization of the instantaneous amplify coefficient based on maximization of the instantaneous CSI, which is deployed in the AF-VG scenario. To the best of my knowledge, this has never been previously proposed.
- Three scenarios are investigated: cooperative MIMO-NOMA is considered in combination with the SWIPT, TAS and (i) DF protocols, (ii) AF-FG protocols and (iii) AF-VG protocols. The OPs are obtained in novel closed form. The analytic theoretical results are proved and verified by Monte Carlo simulation results.

Note that the outcomes in the Chapter 6 (Part II) have been published in the paper [TTNam05] entitled "Emerging Cooperative MIMO - NOMA Networks Combining TAS and SWIPT Protocols Assisted by an AF-VG Relaying Protocol with Instantaneous Amplifying Factor Maximization", in (Elsevier) AEU - International Journal of Electronics and Communications, vol. 135, art. ID 153695 (2021). DOI: 10.1016/j.aeue.2021.153695. IF 2.924

### 6.7 System Model

The present study examines a cooperative MIMO-NOMA network for emerging 5G wireless networks. Figure 6.13 depicts the system model with a BS, a near user $U_{1}$ as a relay, and a user $U_{2}$ which is far from the BS. I denote $\mathcal{A}_{0}$, where $\mathcal{A}_{0}>1, \mathcal{A}_{1}$, where $\mathcal{A}_{1}>1$, and $\mathcal{A}_{2}$, where $\mathcal{A}_{2}>1$, as the number of antennas at the $\mathrm{BS}, U_{1}$ and $U_{2}$, respectively. I apply the following notation:

- $[\cdot]_{r \times c}$ or $[\cdot]_{r \times c \times l}$, representing the two dimensions (2D) of $r \times c$ or three dimensions (3D) of the $r \times c \times l$ matrix.
- max $\{.\}_{r \times c}$ or $\max \{.\}_{r \times c \times l}$, representing the maximum function for obtaining the maximized element from the 2 D or 3 D matrix.
- $\exp ($.$) , representing the exponent function.$
- $\operatorname{Pr}\{$.$\} , representing the probability function.$
- $E\{.\}_{r \times c}$ or $E\{.\}_{r \times c \times l}$, representing the mean function for obtaining the average value of the 2 D or 3 D matrix.
- $\beta_{1}($.$) , representing the modified Bessel function.$

In addition, I assume that the BS has full knowledge of the CSI. As with the system model in [92], the cooperative MIMO-NOMA network shown in Figure 6.13 contains two time slots.


Figure 6.13: Proposed emerging cooperative MIMO-NOMA network with TAS and SWIPT.

### 6.7.1 First time slot

In NOMA theory, the BS broadcasts a superimposed signal by combining the two independent messages $x_{1}$ of user $U_{1}$ and $x_{2}$ of user $U_{2}$ to the strongest user $U_{1}$. However, the BS also transmits energy for harvesting at user $U_{1}$ by applying the PS protocol. It assumes that the system model has no direct down-link from the BS to the user $U_{2}$. Therefore, the overall signal received at $U_{1}$ is:

$$
\begin{equation*}
\mathbf{Y}_{1}=\sqrt{1-\lambda} \mathbf{H}_{1}\left(\sqrt{\alpha_{1} P_{0}} x_{1}+\sqrt{\alpha_{2} P_{0}} x_{2}\right)+n_{1} \tag{6.42}
\end{equation*}
$$

where $P_{0}$ is the transmission power at the BS . The PA factors for user $U_{1}$ and $U_{2}$ are denoted $\alpha_{1}$ and $\alpha_{2}$, respectively, constrained to $\alpha_{1}<\alpha_{2}$ and $\alpha_{1}+\alpha_{2}=1 ; n_{1} \sim C N\left(0, N_{0}\right)$ is the AWGN with zero mean and variance $N_{0}$, and $\lambda$ is the PS factor [92, 93], where $0 \leq \lambda \leq 1$. Three cases exist, as follows:

- For $\lambda=0$, the power domain $P_{0}$ at the BS is only used to transmit information.
- For $\lambda=1$, the BS only transmits energy for EH at $U_{1}$, without transmitting information.
- Otherwise, where $0<\lambda<1$, the BS transmits $\lambda P_{0}$ for EH, while the term $(1-\lambda) P_{0}$ relates to information transmission.

However, it is important to note that the dissertation is different from the work in [92]. The BS and the user $U_{1}$ as shown in Figure 6.14 are equipped with MIMO antennas, where $\mathcal{A}_{0}>1$ and $\mathcal{A}_{1}>1$, respectively. Therefore, $\mathbf{H}_{1}$ in (6.42) is the pre-coding channel matrix from the $\mathcal{A}_{0}$ transmit antennas at the BS to the $\mathcal{A}_{1}$ receiver antennas at $U_{1}$, as follows:

$$
\mathbf{H}_{1}=\left[\begin{array}{ccc}
h_{1}^{(1,1)} & \cdots & h_{1}^{\left(1, \mathcal{A}_{1}\right)}  \tag{6.43}\\
\vdots & \ddots & \vdots \\
h_{1}^{\left(\mathcal{A}_{0}, 1\right)} & \cdots & h_{1}^{\left(\mathcal{A}_{0}, \mathcal{A}_{1}\right)}
\end{array}\right]_{\mathcal{A}_{0} \times \mathcal{A}_{1}},
$$

where $h_{1}^{\left(a_{0}, a_{1}\right)} \in \mathbf{H}_{1}$ for $a_{0} \in \mathcal{A}_{0}$ and $a_{1} \in \mathcal{A}_{1}$ is a channel from the transmission antenna $a_{0}$ at the BS to a receiver antenna $a_{1}$ at the user $U_{1}$ (Rayleigh distribution). In addition, each fading channel $h_{1}^{(., .)}$follows $h_{1}^{(., .)}=d_{1}^{-\omega}$, where $d_{1}$ is the distance from the BS to user $U_{1}$ and the coefficient $\omega$ is the path-loss exponent factor.

The SIC mechanism is another aspect of NOMA theory and is implemented at the terminal UE. Therefore, user $U_{1}$ implements SIC to detect its own information. In [6], [TTNam03], the authors investigated NOMA networks with $N$ random multiple users which deployed SIC to detect the information with the largest PA factor to receive superimposed signals and remove the detected information from these signals. The users repeat SIC until they detect their own information. Without losing generality, I considered two users in the model (Fig. 6.13), and therefore, only SIC phases occurred at user $U_{1}$. In the first SIC phase, user $U_{1}$ detects the $x_{2}$ symbol of $U_{2}$ as a result of the constraint of the PA factors $\alpha_{2}>\alpha_{1}$. In the second SIC phase, user $U_{1}$ detects its own symbol $x_{1}$ after removing the $x_{2}$ symbol from the receiving superimposed signals $\mathbf{Y}_{\mathbf{1}}$, given by (6.42).

In contrast with the proposals in [57, 92], [TTNam03], which explored cooperative SISONOMA schemes, I investigated a cooperative MIMO-NOMA scheme with a TAS protocol. Fortunately, the authors in [TTNam06] also investigated a MIMO-NOMA network with TAS and obtained SINR, given by [TTNam06, Eqs. (11), (12)], where the user detects information by applying SIC. I also examined a cooperative MIMO-NOMA network with TAS and SWIPT and compared it to the work in [TTNam06] (without SWIPT).

As a result of the combination of the MIMO and TAS/SC protocols, user $U_{1}$ selects the best received signal max $\left\{\left|\mathbf{Y}_{1}\right|\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}}$ for SIC. In the first SIC phase, user $U_{1}$ decodes the $x_{2}$ symbol
from the best received signal max $\left\{\left|\mathbf{Y}_{1}\right|\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}}$ by treating the $x_{1}$ symbol and AWGN $n_{1}$ as interference. When user $U_{1}$ decodes the $x_{2}$ symbol, the SINR is therefore obtained as follows:

$$
\begin{equation*}
\gamma_{1-x_{2}}=\frac{(1-\lambda) \max \left\{\left|\mathbf{H}_{1}\right|^{2}\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}} \alpha_{2} \rho_{0}}{(1-\lambda) \max \left\{\left|\mathbf{H}_{1}\right|^{2}\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}} \alpha_{1} \rho_{0}+1}, \tag{6.44}
\end{equation*}
$$

where $\rho_{0}$ is the transmission SNR and $\rho_{0}=P_{0} / N_{0}$.
In the second SIC phase, user $U_{1}$ decodes its own $x_{1}$ symbol from the best received signal $\max \left\{\left|\mathbf{Y}_{1}\right|\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}}$ by treating AWGN $n_{1}$ as interference, after removing the $x_{2}$ symbol from the best received signal. When user $U_{1}$ decodes the $x_{1}$ symbol, the SINR is therefore obtained as follows:

$$
\begin{equation*}
\gamma_{1-x_{1}}=(1-\lambda) \max \left\{\left|\mathbf{H}_{1}\right|^{2}\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}} \alpha_{1} \rho_{0} . \tag{6.45}
\end{equation*}
$$

The instantaneous bit rate threshold [79] at user $U_{1}$ when it decodes $x_{i}$, where $i=\{2,1\}$, is expressed as follows:

$$
\begin{equation*}
R_{1-x_{i}}=\frac{1}{2} \log _{2}\left(1+\gamma_{1-x_{i}}\right) . \tag{6.46}
\end{equation*}
$$

In a related work, Chen et al. [35] investigated a MIMO system containing a source which served a destination. By deploying the TS model in [35, Fig. 2], the authors separated the transmission block into two time slots. The FTS was used to transfer energy [35, Eq. (3)], while the STS was used to transfer information [35, Eq. (4)]. In [92], the authors investigated a cooperative SISO-NOMA network where the EH was expressed as [92, Eq. (8)]. In this study, the relay $U_{1}$ instead harvested energy from the best instantaneous channel according to (6.42), as follows:

$$
\begin{equation*}
P_{E H}=\varepsilon \lambda P_{0} \max \left\{\left|\mathbf{H}_{\mathbf{1}}\right|^{2}\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}}, \tag{6.47}
\end{equation*}
$$

where $\varepsilon$ is the EH coefficient.

### 6.7.2 Second time slot

As assumed, in the example of a cooperative MIMO-NOMA network with no direct down-link from the BS to user $U_{2}$, user $U_{1}$ is deployed as a relay to assist the weakest user $U_{2}$. In previous studies [92], [TTNam03], the authors deployed a DF protocol to forward signals. However, Yue et al. [57] implemented AF-FG relaying. Tran et al. [TTNam04] examined a cooperative SISONOMA assisted by the deployment of several forwarding protocols, for example DF and AF with FG/VG. Their results verified that cooperative SISO-NOMA with the AF-VG protocol performs better than with other relaying protocols. These preliminary results were the motivation for the current proposal to determine which relaying protocol is more effective in a cooperative MIMONOMA network as shown in Figure 6.13. I therefore investigate a cooperative MIMO-NOMA
network, as shown in Figure 6.13, under three different relaying scenarios: DF, AF-FG, and AF-VG.
6.7.2.1 Decode-and-forward protocol For the DF protocol, relay $U_{1}$ decodes the $x_{2}$ symbol according to (6.44). The $x_{2}$ symbol is recovered and forwards a beamforming superimposed signal to user $U_{2}$ via relay $U_{1}$. The received signal at user $U_{2}$ can therefore be expressed as follows:

$$
\begin{equation*}
\mathbf{Y}_{2}^{(D F)}=\mathbf{H}_{2} \sqrt{P_{1}} x_{2}+n_{2}, \tag{6.48}
\end{equation*}
$$

where $P_{1}$ is the transmission power at $U_{1}$ and $n_{2} \sim C N\left(0, N_{0}\right)$ is the AWGN which follows zero mean and variance $N_{0}$.

However, the channel $h_{2}^{\left(a_{1}, a_{2}\right)}$ in the pre-coding matrix channel $\mathbf{H}_{2}$, where $a_{1} \in \mathcal{A}_{1}$ and $a_{2} \in \mathcal{A}_{2}$, is a channel from the transmitting antenna $a_{1}$ in the $\mathcal{A}_{1}$ antenna set at $U_{1}$ to a receiving antenna $a_{2}$ in the $\mathcal{A}_{2}$ antenna set at user $U_{2}$, using a Rayleigh distribution for propagation. Each fading channel is represented by $h_{2}^{(. . .)}$where $h_{2}^{(., .)}=d_{2}^{-\omega}, d_{2}$ is the distance from user $U_{1}$ to user $U_{2}$, and the coefficient $\omega$ is the path-loss exponent factor.

$$
\mathbf{H}_{2}=\left[\begin{array}{ccc}
h_{2}^{(1,1)} & \cdots & h_{2}^{\left(1, \mathcal{A}_{2}\right)}  \tag{6.49}\\
\vdots & \ddots & \vdots \\
h_{2}^{\left(\mathcal{A}_{1}, 1\right)} & \cdots & h_{2}^{\left(\mathcal{A}_{1}, \mathcal{A}_{2}\right)}
\end{array}\right]_{\mathcal{A}_{1} \times \mathcal{A}_{2}}
$$

As a result of the combination of TAS and SIC, the SINR obtained at user $U_{2}$ when it decodes its own data symbol $x_{2}$ from the best received signal max $\left\{\left|\mathbf{Y}_{\mathbf{2}}\right|\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}}$ can be expressed as follows:

$$
\begin{equation*}
\gamma_{2-x_{2}}^{(D F)}=\max \left\{\left|\mathbf{H}_{2}\right|^{2}\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}} \rho_{1}, \tag{6.50}
\end{equation*}
$$

where SNR $\rho_{1}=P_{1} / N_{0}$.
The achievable bit rate reached at user $U_{2}$ when it decodes the $x_{2}$ symbol from the best received signal max $\left\{\left|\mathbf{Y}_{\mathbf{2}}\right|\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}}$ can be expressed as follows:

$$
\begin{equation*}
R_{2-x_{2}}^{(D F)}=\frac{1}{2} \log _{2}\left(1+\gamma_{2-x_{2}}^{(D F)}\right) . \tag{6.51}
\end{equation*}
$$

6.7.2.2 Amplify-and-forward protocol with FG/VG In this case, user $U_{1}$ deploys the AF protocol to forward the received signals. Because the TAS protocol is implemented, the relay $U_{1}$ therefore selects the best received signal max $\left\{\left|\mathbf{Y}_{\mathbf{1}}\right|\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}} . U_{1}$ amplifies the best received signal max $\left\{\left|\mathbf{Y}_{\mathbf{1}}\right|\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}}$ according to the amplifying coefficient $K_{\theta}$ before forwarding the signal to $U_{2}$. User $U_{2}$ therefore receives the signals as follows:

$$
\begin{equation*}
\mathbf{Y}_{2}^{\left(A F_{\theta}\right)}=\mathbf{H}_{2} \sqrt{P_{1}} \max \left\{\left|\mathbf{Y}_{\mathbf{1}}\right|\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}} K_{\theta}+n_{2}, \tag{6.52}
\end{equation*}
$$

where $\mathbf{Y}_{1}$ in (6.52) is given by (6.42), $K_{\theta}$ is the amplifying coefficient, and $\theta=F G$, for AF-FG [TTNam06, Eq. (9a)] and $\theta=V G$ for AF-VG [79, Eq. (8)] or [TTNam06, Eq. (9b)]. However, it is worth noting that the system model as shown in Figure 6.13 is different from the studies in [57, 92, 93],[TTNam04]. Given the considered TAS protocol, the amplifying coefficient $K_{\theta}$ is:

$$
\begin{align*}
K_{\theta} & =\sqrt{\frac{\rho_{1}}{\rho_{0} E\left\{\left|\mathbf{H}_{\mathbf{2}}\right|^{2}\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}}+1}}  \tag{6.53}\\
& =\sqrt{\frac{\rho_{1}}{\rho_{0} \max \left\{\left|\mathbf{H}_{\mathbf{2}}\right|^{2}\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}}+1}}, \tag{6.54}
\end{align*}
$$

where (6.53) is valid for $\theta=F G$ and (6.54) is valid for $\theta=V G . K_{F G}$ is based on the mean CSI statistics $E\left\{\left|\mathbf{H}_{2}\right|^{2}\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}}$. This term is simple from a theoretical point of view yet challenging to obtain in practice. I therefore propose maximizing the instantaneous amplifying coefficient $K_{V G}$ by maximizing the instantaneous CSI max $\left\{\left|\mathbf{H}_{\mathbf{2}}\right|\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}}$. In addition, I propose maximizing the instantaneous amplifying coefficient $K_{V G}$ to optimize the QoS of user $U_{2}$. This is proved and verified in the numerical results with a dedicated discussion.

User $U_{2}$ decodes its own $x_{2}$ symbol from the best received signal max $\left\{\left|\mathbf{Y}_{\mathbf{2}}\right|\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}}$ based on the TAS protocols by substituting (6.42) and (6.53) or (6.54) into (6.52). The SINR is obtained when user $U_{2}$ decodes the $x_{2}$ symbol by treating the $x_{1}$ symbol and AWGNs $n_{1}$ and $n_{2}$ as interference. After some algebraic manipulation, the SINR can be presented as follows:

$$
\begin{equation*}
\gamma_{2-x_{2}}^{\left(A F_{\theta}\right)}=\frac{(1-\lambda) \max \left\{\left|\mathbf{H}_{1}\right|^{2}\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}} \alpha_{2} \rho_{0}}{(1-\lambda) \max \left\{\left|\mathbf{H}_{1}\right|^{2}\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}} \alpha_{1} \rho_{0}+1+\psi_{\theta}} \tag{6.55}
\end{equation*}
$$

where $\psi_{\theta}=\frac{1}{K_{\theta}^{2} \max \left\{\left|\mathbf{H}_{2}\right|^{2}\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}} \rho_{1}}$.
The achievable rate by user $U_{2}$ when it decodes the $x_{2}$ symbol from the best received signal $\max \left\{\left|\mathbf{Y}_{\mathbf{2}}\right|\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}}$ is:

$$
\begin{equation*}
R_{2-x_{2}}^{\left(A F_{\theta}\right)}=\frac{1}{2} \log _{2}\left(1+\gamma_{2-x_{2}}^{\left(A F_{\theta}\right)}\right) \tag{6.56}
\end{equation*}
$$

### 6.8 System Performance Analysis

This section describes the system performance of the network model depicted in Figure 6.13 in terms of OP and throughput at $U_{1}$ and $U_{2}$ :

1. At $U_{1}$, I analyzed the OP performance of the NOMA network with a combination of MIMO, TAS and SWIPT;
2. At $U_{2}$, I investigated the OP performance of the NOMA network with the deployment of $U_{1}$ as a cooperative relay operating with the DF , AF-FG or AF-VG protocols.

### 6.8.1 Outage probability at the user $U_{1}$

Theorem 1: The outage event at user $U_{1}$ occurs when it cannot successfully decode either the $x_{2}$ or the $x_{1}$ symbol from the best received signal $\max \left\{\left|\mathbf{Y}_{\mathbf{1}}\right|\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}}$, which is the best channel after TAS. For clarity, user $U_{1}$ receives the best superimposed signal max $\left\{\left|\mathbf{Y}_{\mathbf{1}}\right|\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}}$, and then the TAS protocol selects the best channel to maximize the instantaneous CSI max $\left\{\left|\mathbf{H}_{\mathbf{1}}\right|\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}}$ from the pre-coding channel matrix $\mathbf{H}_{1}$. User $U_{1}$ deploys SIC and obtains the SINR $\gamma_{1-x_{i}}$, where $i=\{2,1\}$, given by (6.44) and (6.45), and obtains the instantaneous bit rate threshold $R_{1-x_{i}}$, where $i=\{2,1\}$, given by (6.46). The instantaneous bit rate threshold $R_{1-x_{i}}$ is then compared to the user bit rate threshold $R_{i}^{*}$, where $i=\{2,1\}$. If the instantaneous bit rate threshold $R_{1-x_{i}}$ is less than the user bit rate threshold $R_{i}^{*}$, an outage event will occur, i.e., the outage events will occur under two dependent probability cases:

- First case: The instantaneous bit rate threshold $R_{1-x_{i}}$ given by (6.46), where $i=2$, cannot reach the bit rate threshold $R_{2}^{*}$ of user $U_{2}$ when user $U_{1}$ decodes the $x_{2}$ symbol from the best received signal max $\left\{\left|\mathbf{Y}_{1}\right|\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}} ;$
- Second case: The instantaneous bit rate threshold $R_{1-x_{i}}$ as (6.46), where $i=2$, is able to reach the bit rate threshold $R_{2}^{*}$ of user $U_{2}$ when user $U_{1}$ decodes the $x_{2}$ symbol from the best received signal max $\left\{\left|\mathbf{Y}_{\mathbf{1}}\right|\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}}$. However, the instantaneous bit rate threshold $R_{1-x_{i}}$ given by (6.46), where $i=1$, cannot reach its own bit rate threshold $R_{1}^{*}$ when user $U_{1}$ decodes the $x_{1}$ symbol, also from the best received signal max $\left\{\left|\mathbf{Y}_{\mathbf{1}}\right|\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}}$.

Remark 1: The OP at $U_{1}$ can be expressed as follows:

$$
\begin{equation*}
O_{1}=\operatorname{Pr}\{\underbrace{R_{1-x_{2}}<R_{2}^{*}}_{\mathcal{Q}_{1}}\}+\operatorname{Pr}\{\underbrace{R_{1-x_{2}} \geq R_{2}^{*}}_{\mathcal{Q}_{2}}, \underbrace{R_{1-x_{1}}<R_{1}^{*}}_{\mathcal{Q}_{3}}\} . \tag{6.57}
\end{equation*}
$$

I obtain the OP at $U_{1}$ in a closed form from (6.57) as follows:

$$
\begin{equation*}
O_{1}=\mathcal{Q}_{1}+\mathcal{Q}_{2} \mathcal{Q}_{3} \tag{6.58}
\end{equation*}
$$

where $\mathcal{Q}_{1}, \mathcal{Q}_{2}$, and $\mathcal{Q}_{3}$, respectively, are given by:

$$
\begin{gather*}
\mathcal{Q}_{1}=\prod_{a_{0}=1}^{\mathcal{A}_{0}} \prod_{a_{1}=1}^{\mathcal{A}_{1}}\left(1-\exp \left(-\frac{\gamma_{2}^{*}}{(1-\lambda)\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{*}\right) \rho_{0} \sigma_{1}^{2}}\right)\right)  \tag{6.59}\\
\mathcal{Q}_{2}=1-\mathcal{Q}_{1} \tag{6.60}
\end{gather*}
$$

and

$$
\begin{equation*}
\mathcal{Q}_{3}=\prod_{a_{0}=1}^{\mathcal{A}_{0}} \prod_{a_{1}=1}^{\mathcal{A}_{1}}\left(1-\exp \left(-\frac{\gamma_{1}^{*}}{(1-\lambda) \alpha_{1} \rho_{0} \sigma_{1}^{2}}\right)\right) \tag{6.61}
\end{equation*}
$$

where $\gamma_{i}^{*}=2^{2 R_{i}^{*}}-1$ for $i=\{2,1\}, \sigma_{1}^{2}=E\left\{\left|\mathbf{H}_{1}\right|^{2}\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}}$.
I also obtain an approximation of the OP at $U_{1}$ in closed form by applying the CDF defined by (6.78) and (6.79):

$$
\begin{equation*}
O_{1}=1-\mathcal{L}_{1} \mathcal{L}_{2}, \tag{6.62}
\end{equation*}
$$

where $\mathcal{L}_{1}$ and $\mathcal{L}_{2}$, respectively, are given by:

$$
\begin{equation*}
\mathcal{L}_{1}=1-\sum_{\eta=0}^{\mathcal{A}_{0} \mathcal{A}_{1}} \frac{\left(\mathcal{A}_{0} \mathcal{A}_{1}\right)!}{\eta!\left(\mathcal{A}_{0} \mathcal{A}_{1}-\eta\right)!} \exp \left(-\frac{\eta \gamma_{2}^{*}}{(1-\lambda)\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{*}\right) \rho_{0} \sigma_{1}^{2}}\right), \tag{6.63}
\end{equation*}
$$

and

$$
\begin{equation*}
\mathcal{L}_{2}=1-\sum_{\eta=0}^{\mathcal{A}_{0} \mathcal{A}_{1}} \frac{\left(\mathcal{A}_{0} \mathcal{A}_{1}\right)!}{\eta!\left(\mathcal{A}_{0} \mathcal{A}_{1}-\eta\right)!} \exp \left(-\frac{\eta \gamma_{1}^{*}}{(1-\lambda) \alpha_{1} \rho_{0} \sigma_{1}^{2}}\right) \tag{6.64}
\end{equation*}
$$

Refer to the Appendix for the proof.

### 6.8.2 Outage probability at user $U_{2}$

Theorem 2: The outage event at user $U_{2}$ occurs when user $U_{1}$ cannot successfully decode the $x_{2}$ symbol from the best received signal max $\left\{\left|\mathbf{Y}_{1}\right|\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}}$ or when user $U_{1}$ successfully decodes the $x_{2}$ symbol from the best received signal max $\left\{\left|\mathbf{Y}_{1}\right|\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}}$ but user $U_{2}$ cannot successfully decode the $x_{2}$ symbol from the best received signal max $\left\{\left|\mathbf{Y}_{2}^{(\Phi)}\right|\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}}$, where $\Phi=\left\{D F, A F_{F G}, A F_{V G}\right\}$, from the best channel max $\left\{\left|\mathbf{H}_{2}\right|\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}}$ after TAS., i.e., the outage events at user $U_{2}$ occur under two probability-dependent cases.

- First case: This is the same case as described in Remark 1. The instantaneous bit rate threshold $R_{1-x_{2}}$ cannot reach the bit rate threshold $R_{2}^{*}$ of user $U_{2}$ when user $U_{1}$ decodes the $x_{2}$ symbol from the best received signal max $\left\{\left|\mathbf{Y}_{1}\right|\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}}$, i.e., $R_{1-x_{2}}<R_{2}^{*}$.
- Second case: The instantaneous bit rate threshold $R_{1-x_{2}}$ can reach the bit rate threshold $R_{2}^{*}$ of user $U_{2}$ when user $U_{1}$ decodes the $x_{2}$ symbol from the best received signal $\max \left\{\left|\mathbf{Y}_{1}\right|\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}}$, i.e., $R_{1-x_{2}} \geq R_{2}^{*}$. However, the instantaneous bit rate threshold $R_{2-x_{2}}^{(\Phi)}$, where $\Phi=\left\{D F, A F_{F G}, A F_{V G}\right\}$, cannot reach the bit rate threshold $R_{2}^{*}$ when user $U_{2}$ decodes the $x_{2}$ symbol from the best received signal $\max \left\{\left|\mathbf{Y}_{2}\right|\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}}$, i.e., $R_{2-x_{2}}^{(\Phi)}<R_{2}^{*}$.

The OP at user $U_{2}$ side can therefore be expressed as follows:

$$
\begin{equation*}
O_{2}^{(\Phi)}=\operatorname{Pr}\{\underbrace{R_{1-x_{2}}<R_{2}^{*}}_{\mathcal{Q}_{1}}\}+\operatorname{Pr}\{\underbrace{R_{1-x_{2}} \geq R_{2}^{*}}_{\mathcal{Q}_{2}}, \underbrace{R_{2-x_{2}}^{(\Phi)}<R_{2}^{*}}_{\mathcal{Q}_{4}^{(\Phi)}}\} . \tag{6.65}
\end{equation*}
$$

### 6.8.2.1 Decode-and-forward protocol

Remark 2: From (6.65), the OP at user $U_{2}$ in cooperation with user $U_{1}$ with the DF protocol
is rewritten and obtained in closed form as follows:

$$
\begin{align*}
O_{2}^{(D F)} & =\operatorname{Pr}\{\underbrace{R_{1-x_{2}}<R_{2}^{*}}_{\mathcal{Q}_{1}}\}+\operatorname{Pr}\{\underbrace{R_{1-x_{2}} \geq R_{2}^{*}}_{\mathcal{Q}_{2}}, \underbrace{R_{2-x_{2}}^{(D F)}<R_{2}^{*}}_{\mathcal{Q}_{4}^{(D F)}}\}  \tag{6.66}\\
& =\mathcal{Q}_{1}+\mathcal{Q}_{2} \mathcal{Q}_{4}^{(D F)}, \tag{6.67}
\end{align*}
$$

where $\mathcal{Q}_{1}, \mathcal{Q}_{2}$ and $\mathcal{Q}_{4}^{(D F)}$ are given by (6.59), (6.60) and (6.68), respectively, as follows:

$$
\begin{equation*}
\mathcal{Q}_{4}^{(D F)}=\prod_{a_{1}=1}^{\mathcal{A}_{1}} \prod_{a_{2}=1}^{\mathcal{A}_{2}}\left(1-\exp \left(-\frac{\gamma_{2}^{*}}{\rho_{1} \sigma_{2}^{2}}\right)\right), \tag{6.68}
\end{equation*}
$$

where $\sigma_{2}^{2}=E\left\{\left|\mathbf{H}_{2}\right|^{2}\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}}$.
In addition, the approximation of the OP at user $U_{2}$ in closed form by applying the CDF (6.78) and (6.79) can be obtained as follows:

$$
\begin{equation*}
O_{2}^{(D F)}=1-\mathcal{L}_{1} \mathcal{L}_{3}, \tag{6.69}
\end{equation*}
$$

where $\mathcal{L}_{1}$ and $\mathcal{L}_{3}$ are given by (6.63) and (6.70), respectively, as follows:

$$
\begin{equation*}
\mathcal{L}_{3}=1-\sum_{\mu=0}^{\mathcal{A}_{1} \mathcal{A}_{2}} \frac{\left(\mathcal{A}_{1} \mathcal{A}_{2}\right)!}{\mu!\left(\mathcal{A}_{1} \mathcal{A}_{2}-\mu\right)!} \exp \left(-\frac{\mu \gamma_{2}^{*}}{\rho_{0} \sigma_{2}^{2}}\right) . \tag{6.70}
\end{equation*}
$$

6.8.2.2 Amplify-and-forward protocol It is worth noting that it is important to compare the DF and AF protocols. In fact, when the relay $U_{1}$ uses the DF protocol, it receives the best signal max $\left\{\left|\mathbf{Y}_{1}\right|\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}}$. After that, it decodes and recovers the messages in the superimposed signals before forwarding the signals to the next user $U_{2}$. User $U_{2}$ then receives the superimposed signals $\mathbf{Y}_{2}$ and decodes its own message $x_{2}$ from the best received signal max $\left\{\left|\mathbf{Y}_{2}\right|\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}}$.

In the case of relay node $U_{1}$ with the AF protocol, it selects the best signal max $\left\{\left|\mathbf{Y}_{1}\right|\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}}$ from the best instantaneous channel $\max \left\{\left|\mathbf{H}_{1}\right|\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}}$ based on the TAS protocol. Relay $U_{1}$ then amplifies the best received signal max $\left\{\left|\mathbf{Y}_{1}\right|\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}}$ with the amplifying coefficient $K_{\theta}$ and forwards it to the next user $U_{2}$.

Therefore, the OP at user $U_{2}$, in cooperation with $U_{1}$ and AF-FG/VG, can be split into two independent OP cases. The first case is when the relay node cannot decode the $x_{2}$ symbol from the best received signal max $\left\{\left|\mathbf{Y}_{1}\right|\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}}$, and the second case is when the OP occurs when user $U_{2}$ cannot decode the $x_{2}$ symbol from the best received signal max $\left\{\left|\mathbf{Y}_{2}\right|\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}}$.

Remark 3: The OP at user $U_{2}$ in cooperation with relay $U_{1}$ and the AF protocol is obtained by applying the PDF given by (6.77) and the modified Bessel function in [TTNam04]:

$$
\begin{align*}
O_{2}^{\left(A F_{\theta}\right)} & =\operatorname{Pr}\left\{R_{1-x_{2}}<R_{2}^{*}\right\} \text { and } \operatorname{Pr}\left\{R_{2-x_{2}}^{\left(A F_{\theta}\right)}<R_{2}^{*}\right\}  \tag{6.71}\\
& =\mathcal{Q}_{1} \mathcal{Q}_{4}^{\left(A F_{\theta}\right)}, \tag{6.72}
\end{align*}
$$

where $\mathcal{Q}_{1}$ is given by (6.59) and $\mathcal{Q}_{4}^{\left(A F_{F G}\right)}$ is obtained as follows:

$$
\left.\begin{array}{l}
\mathcal{Q}_{4}^{\left(A F_{F G}\right)}= \\
\prod_{a_{0}=1}^{\mathcal{A}_{0}} \prod_{a_{1}=1}^{\mathcal{A}_{1}}\left(1-\frac{2 \exp \left(-\frac{\gamma_{2}^{*}}{(1-\lambda)\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{*}\right) \rho_{0} \sigma_{1}^{2}}\right) \sqrt{\frac{1}{\sigma_{2}^{2}}} \beta_{1}\left(\frac{2 \sqrt{\frac{1}{\sigma_{2}^{2}}}}{\frac{(1-\lambda)\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{*}\right) \rho_{0} \rho_{1}^{2} \sigma_{1}^{2}}{\gamma_{2}^{*}\left(1+\rho_{0} \sigma_{2}^{2}\right)}}\right.}{}\right)  \tag{6.73}\\
\sqrt{\frac{(1-\lambda)\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{*}\right) \rho_{0} \rho_{1}^{2} \sigma_{1}^{2}}{\gamma_{2}^{*}\left(1+\rho_{0} \sigma_{2}^{2}\right)}}
\end{array}\right) .
$$

In [57], the authors studied a cooperative SISO-NOMA network with AF-FG relaying. Although the AF-FG protocol is simpler than the AF-VG protocol from an analytical point of view, the average CSI $E\left\{\left|\mathbf{H}_{1}\right|^{2}\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}}$ statistic is a challenge to predict in practice. This was an additional motivation to research AF-VG relay deployment in our study. The amplifying coefficient $K_{V G}$ was presented in [TTNam04 Eq. (9b)]. The authors examined the AF-VG protocol which assisted a cooperative SISO-NOMA network. However, in the system model depicted in Figure 6.13, I considered multiple antennas in combination with the TAS protocol. To this aim, the research proposes an additional contribution in maximizing the instantaneous CSI max $\left\{\left|\mathbf{H}_{\mathbf{2}}\right|\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}}$ for the amplifying coefficient $K_{V G}$, given by (6.54). The $\mathcal{Q}_{4}^{\left(A F_{V G}\right)}$ term can therefore be solved and presented as follows:

$$
\left.\begin{array}{l}
\mathcal{Q}_{4}^{\left(A F_{V G}\right)}= \\
\prod_{a_{0}=1}^{\mathcal{A}_{0}} \prod_{a_{1}=1}^{\mathcal{A}_{1}}\left(1-\frac{2 \exp \left(-\frac{\gamma_{2}^{*}\left(\rho_{0}+\rho_{1}^{2}\right)}{(1-\lambda)\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{*}\right) \rho_{0} \rho_{1}^{2} \sigma_{1}^{2}}\right) \sqrt{\frac{1}{\sigma_{2}^{2}}} \beta_{1}\left(\frac{2 \sqrt{\frac{1}{\sigma_{2}^{2}}}}{\sqrt{\frac{(1-\lambda)\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{*}\right) \rho_{0} \rho_{1}^{2} \sigma_{1}^{2}}{\gamma_{2}^{*}}}}\right.}{}\right)  \tag{6.74}\\
\sqrt{\frac{(1-\lambda)\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{*}\right) \rho_{0} \rho_{1}^{2} \sigma_{1}^{2}}{\gamma_{2}^{*}}}
\end{array}\right) .
$$

The authors investigated the SOP for a NOMA system with two users, given by [32, Eq. (17)]. Obviously, the OP performance for the cooperative MIMO-NOMA network depicted in Figure 6.13 is given as follows:

$$
\begin{equation*}
O_{s y s}^{(\Phi)}=\frac{O_{1}+O_{2}^{(\Phi)}}{2} \tag{6.75}
\end{equation*}
$$

Refer to the Appendix for the proof.

### 6.8.3 System throughput performance

We obtain the OP performance at relay $U_{1}$ and user $U_{2}$ from (6.58), and for the DF and AF scenarios from (6.66) and (6.71), respectively. The system throughput [94, Eq. (21)], which
refers to the sum of achievable rates at the two users, is expressed as:

$$
\begin{equation*}
T_{\text {sys }}^{(\Phi)}=T_{1}+T_{2}^{(\Phi)}=\left(1-O_{1}\right) R_{1}^{*}+\left(1-O_{2}^{(\Phi)}\right) R_{2}^{*} . \tag{6.76}
\end{equation*}
$$

### 6.9 Numerical Results

In this section, I present the numerical results and discussion to prove the analytical expressions derived in the previous sections. The analytical results and Monte Carlo simulation results have the same parameters as the fixed PA factors for users $U_{1}$ and $U_{2}$, where $\alpha_{1}=0.25$ and $\alpha_{2}=0.75$, respectively, and the user bit rate thresholds $R_{1}^{*}=R_{2}^{*}=0.2 \mathrm{bps} / \mathrm{Hz}$. The BS is equipped with antennas $\mathcal{A}_{0}=4$, and $U_{1}$ and $U_{2}$ with antennas $\mathcal{A}_{1}=\mathcal{A}_{2}=2$. In addition, each $h_{1}^{\left(a_{0}, a_{1}\right)} \in \mathbf{H}_{1}$ or each $h_{2}^{\left(a_{1}, a_{2}\right)} \in \mathbf{H}_{2}$ randomly generates $1 e^{7}$ samples under Rayleigh distributions using surveys of Monte Carlo simulations for empirical statistical results. Therefore, the expected mean CSI from $B S \rightarrow U_{1}$ and $U_{1} \rightarrow U_{2}$ for $\sigma_{1}^{2}=E\left\{\left|\mathbf{H}_{1}\right|^{2}\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1} \times 1 e^{7}}=E\left\{\left|h_{1}^{\left(a_{0}, a_{1}\right)}\right|^{2}\right\}_{1 \times 1 e^{7}}=5 e^{-5}$, where $a_{0} \in \mathcal{A}_{0}, a_{1} \in \mathcal{A}_{1}$ and $\sigma_{2}^{2}=E\left\{\left|\mathbf{H}_{2}\right|^{2}\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2} \times 1 e^{7}}=E\left\{\left|h_{2}^{\left(a_{1}, a_{2}\right)}\right|^{2}\right\}_{1 \times 1 e^{7}}=3 e^{-5}$, where $a_{1} \in \mathcal{A}_{1}$ and $a_{2} \in \mathcal{A}_{2}$. It is important to note that the analytical results and Monte Carlo simulation results are presented exactly according to our investigations with Matlab software. The authors in [57] assumed that the transmitting power at the BS and the AF relaying node were equal, i.e., $(P s=\operatorname{Pr}=P)$ for simplicity. The $\mathrm{SNR} \rho_{s}=\rho_{r}$ were also assumed in other major studies, for example in [56], $P_{s}$ and $P_{r}$ were the normalized transmitting powers at the BS and device $D_{1}$, where $\rho=\frac{P_{s}}{N_{0}}=\frac{P_{r}}{N_{0}}$. Note that most of the figures in the manuscript contain two-dimensional graphics. These may be difficult to understand if the SNR $\rho_{0} \neq \rho_{1}$. Therefore, I also assume the $\operatorname{SNR} \rho_{0}=\rho_{1}$. In addition, I do not ever select transmitting powers for the BS and device $U_{1}$ as fixed values. From the perspective in the present study, I investigate and provide the system performances trends based on various SNR $\rho_{0}=\rho_{1}=\{20, \ldots, 60\} d B$. The graphs plot the respective Monte Carlo simulation results and theoretical analytical results. I investigated four EH cases with PS factor $\lambda=\{0,0.2,0.5,0.8\}$.

Figure 6.14 depicts the OP performance at user $U_{1}$ over a cooperative MIMO-NOMA network in combination with the TAS and SWIPT protocols. The OP results were obtained for four different PS factors: $\lambda=\{0,0.2,0.5,0.8\}$. For $\lambda=0$, the OP is best, because the entire power domain $P_{0}$ is used to transmit information and user $U_{1}$ harvests $P_{E H}=0$, given by (6.47). For $\lambda=0.8$, the OP results at user $U_{1}$ are worst, because only a minor portion of the power domain $0.2 P_{0}$ is used to transmit information $x_{1}$ and $x_{2}$. However, both the BS and user $U_{1}$ are equipped with multiple antennas $\mathcal{A}_{0}=4$ and $\mathcal{A}_{1}=2$, and thus the OP performance at user $U_{1}$ improves due to both $\operatorname{Pr}\left\{R_{1-x_{2}}<R_{2}^{*}\right\} \rightarrow 0$ and $\operatorname{Pr}\left\{R_{1-x_{1}}<R_{1}^{*}\right\} \rightarrow 0$ when the $\operatorname{SNR} \rho_{0} \rightarrow \infty$. The graphs plot the analytical results obtained from (6.58) and the Monte Carlo simulation results obtained from (6.57). From Figure 6.14 , we can observe that the analytical results are proved and verified by the simulated and approximated results given by (6.62).

Figure 6.15 depicts the OP performance at user $U_{2}$ over a cooperative MIMO-NOMA in combination with SWIPT and the TAS protocol, assisted by the relay $U_{1}$ with the DF or AFFG/VG protocol. I examined the OP performance at user $U_{2}$ in three scenarios. In the first


Figure 6.14: OP performance at $U_{1}$ over a cooperative MIMO-NOMA network with TAS and SWIPT protocols.
scenario, user $U_{2}$ is assisted by user $U_{1}$ as a relay with the DF protocol. In the second scenario, $U_{2}$ is assisted by user $U_{1}$ as a relay with the AF-FG protocol. In the third scenario, user $U_{2}$ is also assisted by user $U_{1}$ as a relay with the AF-VG protocol. The solid lines plot the Monte Carlo simulation results of the OP at user $U_{2}$ for DF given by (6.66), the dashed lines plot AF-FG given by (6.71), where $\theta=F D$, and the dotted lines plot AF-VG given by (6.71), where $\theta=V G$. The graphs show the analytical results at user $U_{2}$ in the DF, AF-FG and AF-VG scenarios, which are obtained by (6.67) and (6.72), where $\theta=F G$, and (6.72), where $\theta=V G$, respectively. Similarly, as shown in Figure 6.14, the OP performance at user $U_{2}$ obtains the best result for the PS coefficient, $\lambda=0$. For the same values of $\lambda$, the OP performances at user $U_{2}$ in the AF-VG scenario, plotted with the larger red indicators, are far more impressive than those with the DF and AF-FG protocols, plotted with the black and smaller blue indicators, respectively, as a result of relay $U_{1}$ operations and amplification of the best received signal $\max \left\{\left|\mathbf{Y}_{1}\right|\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}}$ through maximization of the instantaneous amplifying coefficient $K_{V G}$ before the signal is forwarded to user $U_{2}$. At the same SNR, we obtain $O_{2}^{\left(A F_{V G}\right)}<O_{2}^{\left(A F_{F G}\right)}<O_{2}^{(D F)}$, and $O_{2}^{(\Phi, \lambda=0)}<O_{2}^{(\Phi, \lambda=0.2)}<O_{2}^{(\Phi, \lambda=0.5)}<O_{2}^{(\Phi, \lambda=0.8)}$ (lower values represent better performance). The OP performance at user $U_{2}$ using DF for $\lambda=0.8$ is the worst case. However, $O_{2}^{(D F, \lambda=0.8)}$ is certainly improved, tending to zero, through the addition of more antennas $\mathcal{A}_{0}$ or $\mathcal{A}_{1}$ or increasing the SNR $\rho_{0}=\rho_{1} \rightarrow \infty$.

Based on the obtained OP performance charted in Figures 6.14 and 6.15, then I investigated the achievable throughput. From Figure 6.16, we can easily observe that throughput at $U_{1}$ for $\lambda=0$ is the best achievable result. From Figure 6.14, we obtain $O_{1}^{(\lambda=0)}<O_{1}^{(\lambda=0.2)}<O_{1}^{(\lambda=0.5)}<$ $O_{1}^{(\lambda=0.8)}$. As a result, we obtain $T_{1}^{(\lambda=0)}>T_{1}^{(\lambda=0.2)}>T_{1}^{(\lambda=0.5)}>T_{1}^{(\lambda=0.8)}$ at the same SNR. However, user $U_{1}$ for $\lambda=0$ cannot harvest any energy, and $T_{1}^{(\lambda=0.8)}$ is the worst result at low SNR, for example SNR $\rho<55 d B$. However, $T_{1}^{(\lambda=0.8)} \rightarrow 0.2 \mathrm{bps} / \mathrm{Hz}$ when the SNR $\rho$ tends to infinity, for example SNR $\rho=55 d B, T_{1}^{(\lambda=0.8)}=T_{1}^{(\lambda=0)}=0.2 \mathrm{bps} / \mathrm{Hz}$. This verifies that in the case of the PS factor for $\lambda=0.8$, the user not only achieved the same performance as the PS


Figure 6.15: OP performance at $U_{2}$ over a cooperative MIMO-NOMA network with the TAS and DF, AF-FG and AF-VG protocols using TAS and SWIPT.
factor for $\lambda=0$ but also harvested much more energy.


Figure 6.16: System throughput performance at $U_{1}$ over a cooperative MIMO-NOMA network with the TAS and SWIPT protocols.

Figure 6.17 depicts the throughput of $U_{2}$ in the DF, AF-FG and AF-VG scenarios, with four possible values of $\lambda=\{0,0.2,0.5,0.8\}$. As in Figure 6.15 , we obtain $O_{2}^{(\Phi, \lambda=0)}<O_{2}^{(\Phi, \lambda=0.2)}<$ $O_{2}^{(\Phi, \lambda=0.5)}<O_{2}^{(\Phi, \lambda=0.8)}$. We also obtain $T_{2}^{(\Phi, \lambda=0)}>T_{2}^{(\Phi, \lambda=0.2)}>T_{2}^{(\Phi, \lambda=0.5)}>T_{2}^{(\Phi, \lambda=0.8)}$ at the same SNR. The throughput of $U_{2}$ in the case of $\lambda=0$ in cooperation with $U_{1}$ with the AFFG/VG protocols can easily achieve its bit rate threshold $R_{2}^{*}=0.2 \mathrm{bps} / \mathrm{Hz}$. The throughput of $U_{2}$ for the same value of $\lambda$ with the AF-VG protocol outperforms the other relaying protocols, for example, $T_{2}^{\left(A F_{V G}\right)} \gg T_{2}^{\left(A F_{F G}\right)} \gg T_{2}^{(D F)}$ for $\lambda=0.8$ at almost all SNR.

Figures $6.14,6.15,6.16$ and 6.17 depict the OP and throughput performance at users $U_{1}$ and $U_{2}$ in three scenarios (and four cases for each scenario). Next, I investigated the system OP


Figure 6.17: System throughput performance at $U_{2}$ over a cooperative MIMO-NOMA network with the TAS and DF/AF protocols.
performance given by (6.75) and the system throughput performance given by (6.76). Figure 6.18 depicts interesting OP performance in the three scenarios, which perfectly match. For clarity, the OP performance of the $\Phi$ scenario is $O_{s y s}^{(\Phi)}=\left(O_{1}+O_{2}^{(\Phi)}\right) / 2$, given by (6.75). The results in Figures 6.15 and 6.16 indicate $O_{1} \gg O_{2}^{(\Phi)} \cong 0$. Therefore, $O_{\text {sys }}^{(\Phi)}=\left(O_{1}+O_{2}^{(\Phi)}\right) / 2 \simeq O_{1} / 2$.


Figure 6.18: OP performance over a cooperative MIMO-NOMA network with the TAS and DF/AF protocols.

The results in Figure 6.18 indicate that the OP performances in the three scenarios perfectly match (irrespective of the value of $\lambda$ ). Figure 6.19 plots the system throughput of the three scenarios according to the user throughput performance graphed in Figures 6.16 and 6.17. It is very interesting when $O_{s y s}^{(D F)} \simeq O_{s y s}^{\left(A F_{F G}\right)} \simeq O_{s y s}^{\left(A F_{V G}\right)}$, as shown in Figure 5.6, but $T_{s y s}^{\left(A F_{V G}\right)} \gg$ $T_{s y s}^{\left(A F_{F G}\right)} \gg T_{s y s}^{(D F)}$, as shown in Figure 6.19. From Figure 6.15, we can observe that $O_{2}^{\left(A F_{V G}\right)} \ll$ $O_{2}^{\left(A F_{F G}\right)} \ll O_{2}^{(D F)}$. Therefore, user $U_{2}$ easily achieves its bit rate threshold $R_{2}^{*}$ with $T_{2}^{\left(A F_{V G}\right)} \approx$
$R_{2}^{*}$ at low SNR, for example, $T_{s y s}^{\left(A F_{V G}, \lambda=0.8\right\}} \gg T_{s y s}^{\left(A F_{F G}, \lambda=0.8\right\}} \gg T_{s y s}^{(D F, \lambda=0.8\}}$ at SNR $\rho_{0}=\rho_{1}=$ 40 dB . Finally, the throughput performances in the three scenarios tend to the sum of the bit rate thresholds $R_{1}^{*}+R_{2}^{*}=0.4 \mathrm{bps} / H z$ when $\operatorname{SNR} \rho \rightarrow \infty$.


Figure 6.19: System throughput over a cooperative MIMO-NOMA network with the TAS and DF/AF protocols.

### 6.10 Conclusion

Based on the outcomes in Chapter 6 (Part I) [TTNam04], I examined a NOMA networking concept which deployed several emerging technologies: C-NOMA, MIMO, TAS, SWIPT, DF, AF-FG and AF-VG. To assist in the reduction of hardware costs, I designed a pre-coding channel matrix which can be applied to support the TAS protocol. I also investigated three different scenarios and obtained novel closed forms. To improve system performance, I proposed maximization of the instantaneous amplifying coefficient. This was based on maximization of the instantaneous channel gains. To the best of my knowledge, this type of study has not been previously conducted. The analytical and simulation results showed that a complex NOMA network in combination with the cooperative protocols, MIMO, TAS, SWIPT and AF-VG outperformed the DF and AF-FG protocols.

Certain issues may be examined in future work. These include improvement of system performance through distribution over Nakagami- $m$ fading channels, where $m>1$ [TTNam08], the use of EH to forward signals, and the exploitation of an adaptive PS factor instead of a fixed PS factor for QoS fairness for users.

### 6.11 Appendix

### 6.11.1 Proof of Remark 1

The PDF and CDF over Rayleigh distribution can be expressed, respectively, as follows:

$$
\begin{gather*}
f_{\left|h_{i}\right|^{2}}(x)=\frac{1}{\sigma_{i}^{2}} \exp \left(-\frac{x}{\sigma_{i}^{2}}\right), \text { where } x \geq 0  \tag{6.77}\\
F_{\gamma_{i-x_{j}}}(x) \stackrel{(j=2)}{=}\left\{\begin{array}{l}
\sum_{\varphi=0}^{S D} \frac{(-1)^{\varphi}(S D)!}{\varphi!(S D-\varphi)!} \exp \left(-\frac{\varphi x}{(1-\lambda)\left(\alpha_{2}-\alpha_{1} x\right) \rho_{0} \sigma_{i}^{2}}\right), \text { where } x<\alpha_{2} / \alpha_{1}, \\
1, \text { where } x \geq \alpha_{2} / \alpha_{1}
\end{array}\right. \tag{6.78}
\end{gather*}
$$

and

$$
\begin{equation*}
F_{\gamma_{i-x_{j}}}(x) \stackrel{(j=1)}{=} \sum_{\varphi=0}^{S D} \frac{(-1)^{\varphi}(S D)!}{\varphi!(S D-\varphi)!} \exp \left(-\frac{\varphi x}{(1-\lambda) \alpha_{1} \rho_{0} \sigma_{i}^{2}}\right), \text { where } x \geq 0 \tag{6.79}
\end{equation*}
$$

where $S$ and $D$ are the antennas at the source and destination, respectively.
By substituting (6.46), where $i=2$, into (6.57), we obtain:

$$
\begin{equation*}
\mathcal{Q}_{1}=\operatorname{Pr}\left\{R_{1-x_{2}}<R_{2}^{*}\right\}=\operatorname{Pr}\left\{\gamma_{1-x_{2}}<\gamma_{2}^{*}\right\} \tag{6.80}
\end{equation*}
$$

After some algebraic manipulation, we obtain:

$$
\begin{equation*}
\mathcal{Q}_{1}=\operatorname{Pr}\left\{\max \left\{\left|\mathbf{H}_{\mathbf{1}}\right|^{2}\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}}<\frac{\gamma_{2}^{*}}{(1-\lambda)\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{*}\right) \rho_{0}}\right\} \tag{6.81}
\end{equation*}
$$

By applying the PDF given by (6.77), we obtain:

$$
\begin{align*}
\mathcal{Q}_{1} & =\prod_{a_{0}=1}^{\mathcal{A}_{0}} \prod_{a_{1}=1}^{\mathcal{A}_{1}}\left(1-\int_{\frac{\gamma_{2}^{*}}{(1-\lambda)\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{*}\right) \rho_{0}}}^{\infty} \frac{1}{\sigma_{1}^{2}} \exp \left(-\frac{x}{\sigma_{1}^{2}}\right) d x\right) \\
& =\prod_{a_{0}=1}^{\mathcal{A}_{0}} \prod_{a_{1}=1}^{\mathcal{A}_{1}}\left(1-\exp \left(-\frac{\gamma_{2}^{*}}{(1-\lambda)\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{*}\right) \rho_{0} \sigma_{1}^{2}}\right)\right) \tag{6.82}
\end{align*}
$$

where $\gamma_{2}^{*}<\alpha_{2} / \alpha_{1}$. If $\gamma_{2}^{*} \geq \alpha_{2} / \alpha_{1} ; \mathcal{Q}_{1}$ always tends to one.
$\mathcal{Q}_{2}$ is negative $\mathcal{Q}_{1}$. Therefore, $\mathcal{Q}_{2}$ can be easily obtained from (6.60).
Similarly, we substitute (6.46), where $i=1$, into (6.57), and obtain:

$$
\begin{equation*}
\mathcal{Q}_{3}=\operatorname{Pr}\left\{R_{1-x_{1}}<R_{1}^{*}\right\}=\operatorname{Pr}\left\{\gamma_{1-x_{1}}<\gamma_{1}^{*}\right\} \tag{6.83}
\end{equation*}
$$

After some algebraic manipulation, we obtain the condition where user $U_{1}$ cannot decode
the $x_{1}$ symbol from the best channel gain $\max \left\{\left|\mathbf{H}_{1}\right|\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}}$, as follows:

$$
\begin{equation*}
\mathcal{Q}_{3}=\operatorname{Pr}\left\{\max \left\{\left|\mathbf{H}_{\mathbf{1}}\right|^{2}\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}}<\frac{\gamma_{1}^{*}}{(1-\lambda) \alpha_{1} \rho_{0}}\right\} . \tag{6.84}
\end{equation*}
$$

Similarly (6.82), we apply the PDF (6.77) and obtain:

$$
\begin{align*}
\mathcal{Q}_{3} & =\prod_{a_{0}=1}^{\mathcal{A}_{0}} \prod_{a_{1}=1}^{\mathcal{A}_{1}}\left(1-\int_{\frac{\gamma_{1}^{*}}{(1-\lambda) \alpha_{1} \rho_{0}}}^{\infty} \frac{1}{\sigma_{1}^{2}} \exp \left(-\frac{x}{\sigma_{1}^{2}}\right) d x\right) \\
& =\prod_{a_{0}=1}^{\mathcal{A}_{0}} \prod_{a_{1}=1}^{\mathcal{A}_{1}}\left(1-\exp \left(-\frac{\gamma_{1}^{*}}{(1-\lambda) \alpha_{1} \rho_{0} \sigma_{1}^{2}}\right)\right) . \tag{6.85}
\end{align*}
$$

By substituting $\mathcal{Q}_{1}, \mathcal{Q}_{2}$ and $\mathcal{Q}_{3}$ into (6.57), we obtain the closed form (6.58) for the OP at user $U_{1}$.

### 6.11.2 Proof of Remark 2

By substituting (6.51) into (6.66), we obtain the OP condition where user $U_{2}$ cannot decode the $x_{2}$ symbol from the best received signal max $\left\{\left|\mathbf{Y}_{2}\right|\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}}$ received from relay $U_{1}$, which uses the DF protocol:

$$
\begin{equation*}
\mathcal{Q}_{4}^{(D F)}=\operatorname{Pr}\left\{R_{2-x_{2}}^{(D F)}<R_{2}^{*}\right\}=\operatorname{Pr}\left\{\gamma_{2-x_{2}}^{(D F)}<\gamma_{2}^{*}\right\} . \tag{6.86}
\end{equation*}
$$

After some algebraic manipulation and applying the $\operatorname{PDF}(6.77)$, we obtain $\mathcal{Q}_{4}^{(D F)}$ as follows:

$$
\begin{align*}
\mathcal{Q}_{4}^{(D F)} & =\operatorname{Pr}\left\{\max \left\{\left|\mathbf{H}_{2}\right|\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}}<\frac{\gamma_{2}^{*}}{\rho_{0}}\right\} \\
& =\prod_{a_{1}=1}^{\mathcal{A}_{1}} \prod_{a_{2}=1}^{\mathcal{A}_{2}}\left(1-\int_{\frac{\gamma_{2}^{*}}{\rho_{0}}}^{\infty} \frac{1}{\sigma_{2}^{2}} \exp \left(-\frac{x}{\sigma_{2}^{2}}\right) d x\right) \\
& =\prod_{a_{1}=1}^{\mathcal{A}_{1}} \prod_{a_{2}=1}^{\mathcal{A}_{2}}\left(1-\exp \left(-\frac{\gamma_{2}^{*}}{\rho_{0} \sigma_{2}^{2}}\right)\right) . \tag{6.87}
\end{align*}
$$

By substituting $\mathcal{Q}_{1}, \mathcal{Q}_{2}$ and $\mathcal{Q}_{4}^{(D F)}$ into (6.67), we obtain the closed form of the OP at user $U_{2}$, which cooperates with user $U_{1}$ and exploits the DF protocol.

In the case where user $U_{1}$ exploits the AF-FG protocol, $\mathcal{Q}_{4}^{\left(A F_{F G}\right)}$ refers to the probability that user $U_{2}$ cannot decode the $x_{2}$ symbol from the best received signal max $\left\{\left|\mathbf{Y}_{2}^{\left(A F_{F G}\right)}\right|\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}}$. By substituting (6.42), (6.49) and (6.53), where $\theta=F G$, into (6.52) and applying the TAS protocol, we obtain the best signal $\max \left\{\left|\mathbf{Y}_{2}^{\left(A F_{F G}\right)}\right|\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}}$. After SIC, we obtain the SINR from (6.55) when user $U_{2}$ decodes the $x_{2}$ symbol from the best signal $\max \left\{\left|\mathbf{Y}_{2}^{\left(A F_{F G}\right)}\right|\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}}$. By substituting (6.55) into (6.56) and applying the outage condition as in (6.71), where $\theta=F G$,
we obtain $\mathcal{Q}_{4}^{\left(A F_{F G}\right)}$ as follows:

$$
\begin{equation*}
\mathcal{Q}_{4}^{\left(A F_{F G}\right)}=\operatorname{Pr}\left\{R_{2-x_{2}}^{\left(A F_{F G}\right)}<R_{2}^{*}\right\}=\operatorname{Pr}\left\{\gamma_{2-x_{2}}^{\left(A F_{F G}\right)}<\gamma_{2}^{*}\right\} . \tag{6.88}
\end{equation*}
$$

After some algebraic manipulation, we obtain:

$$
\begin{equation*}
\mathcal{Q}_{4}^{\left(A F_{F G}\right)}=1-\operatorname{Pr}\left\{\max \left\{\left|\mathbf{H}_{1}\right|\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}} \geq \frac{\gamma_{2}^{*}\left(\frac{\rho_{0} \sigma_{2}^{2}+1}{\rho_{1}^{2} \max \left\{\left|\mathbf{H}_{2}\right|\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}}}+1\right)}{(1-\lambda)\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{*}\right) \rho_{0}}, \max \left\{\left|\mathbf{H}_{2}\right|\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}} \geq 0\right\} . \tag{6.89}
\end{equation*}
$$

By treating max $\left\{\left|\mathbf{H}_{\mathbf{1}}\right|\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}}$ and max $\left\{\left|\mathbf{H}_{2}\right|\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}}$ as randomly independent variables $x$ and $y$ and applying the $\operatorname{PDF}$ (6.77) and the modified Bessel function from [TTNam04], we obtain the expression (6.89) in approximately closed form as follows:

$$
\begin{align*}
\mathcal{Q}_{4}^{\left(A F_{F G}\right)} & =\prod_{a_{0}=1}^{\mathcal{A}_{0}} \prod_{a_{1}=1}^{\mathcal{A}_{1}}\left(1-\int_{0}^{\infty} \int_{\frac{\gamma_{2}^{*}\left(\frac{\rho_{0} \sigma_{2}^{2}+1}{\rho_{1}^{2} y}+1\right.}{(1-\lambda)\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{*}\right) \rho_{0}}}^{\infty} \frac{1}{\sigma_{1}^{2} \sigma_{2}^{2}} \exp \left(-\frac{x}{\sigma_{1}^{2}}-\frac{y}{\sigma_{2}^{2}}\right) d x d y\right) \\
& =\prod_{a_{0}=1}^{\mathcal{A}_{0}} \prod_{a_{1}=1}^{\mathcal{A}_{1}}\left(1-\frac{2 \exp \left(-\frac{\gamma_{2}^{*}}{(1-\lambda)\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{*}\right) \rho_{0}}\right) \sqrt{\frac{1}{\sigma_{2}^{2}} \beta_{1}}\left(\frac{2 \sqrt{\frac{1}{\sigma_{2}^{2}}}}{\sqrt{\frac{(1-\lambda)\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{*}\right) \rho_{0} \rho_{1}^{2}}{\gamma_{2}^{*}\left(1+\rho_{0} \sigma_{2}^{2}\right)}}}\right)}{\sqrt{\frac{(1-\lambda)\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{*}\right) \rho_{0} \rho_{1}^{2}}{\gamma_{2}^{*}\left(1+\rho_{0} \sigma_{2}^{2}\right)}}}\right), \tag{6.90}
\end{align*}
$$

where $\beta_{1}$ (.) refers to the modified Bessel function, and $\gamma_{2}^{*}<\alpha_{2} / \alpha_{1}$.
In the case where user $U_{1}$ exploits the AF-VG protocol, $\mathcal{Q}_{4}^{\left(A F_{V G}\right)}$ is the probability that user $U_{2}$ cannot decode the $x_{2}$ symbol from the best received signal max $\left\{\left|\mathbf{Y}_{2}^{\left(A F_{V G}\right)}\right|\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}}$. By substituting (6.42), (6.49) and (6.54), where $\theta=V G$, into (6.52) and applying the TAS protocol, we obtain the best signal max $\left\{\left|\mathbf{Y}_{2}^{\left(A F_{V G}\right)}\right|\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}}$. After SIC-ing, we obtain the SINR from (6.55) when user $U_{2}$ decodes the $x_{2}$ symbol from the best signal max $\left\{\left|\mathbf{Y}_{2}^{\left(A F_{F G}\right)}\right|\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}}$. By substituting (6.55) into (6.56) and applying the outage condition given by (6.71), where $\theta=V G$, we obtain $\mathcal{Q}_{4}^{\left(A F_{V G}\right)}$ as follows:

$$
\begin{equation*}
\mathcal{Q}_{4}^{\left(A F_{V G}\right)}=\operatorname{Pr}\left\{R_{2-x_{2}}^{\left(A F_{V G}\right)}<R_{2}^{*}\right\}=\operatorname{Pr}\left\{\gamma_{2-x_{2}}^{\left(A F_{V G}\right)}<\gamma_{2}^{*}\right\} . \tag{6.91}
\end{equation*}
$$

After some algebraic manipulation, we obtain:

$$
\begin{equation*}
\mathcal{Q}_{4}^{\left(A F_{V G}\right)}=1-\operatorname{Pr}\left\{\max \left\{\left|\mathbf{H}_{\mathbf{1}}\right|\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}} \geq \frac{\gamma_{2}^{*}\left(\frac{\rho_{0} \max \left\{\left|\mathbf{H}_{2}\right|\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}}+1}{\rho_{1} \max \left\{\left|\mathbf{H}_{2}\right|\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}}}+1\right)}{(1-\lambda)\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{*}\right) \rho_{0}}, \max \left\{\left|\mathbf{H}_{\mathbf{2}}\right|\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}} \geq 0\right\} . \tag{6.92}
\end{equation*}
$$

Similarly (6.90), $\mathcal{Q}_{4}^{\left(A F_{V G}\right)}$ can be solved by treating max $\left\{\left|\mathbf{H}_{\mathbf{1}}\right|\right\}_{\mathcal{A}_{0} \times \mathcal{A}_{1}}$ and $\max \left\{\left|\mathbf{H}_{\mathbf{2}}\right|\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}}$ as the randomly independent variables $x$ and $y$, respectively, and applying the $\operatorname{PDF}$ (6.77) and the modified Bessel function as follows:

$$
\left.\begin{array}{rl}
\mathcal{Q}_{4}^{\left(A F_{V G}\right)} & =\prod_{a_{0}=1}^{\mathcal{A}_{0}} \prod_{a_{1}=1}^{\mathcal{A}_{1}}\left(1-\int_{0}^{\infty} \int_{\frac{\gamma_{2}^{*}\left(\frac{\rho_{0} y+1}{\rho_{1} y}+1\right)}{(1-\lambda)\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{*}\right) \rho_{0}}}^{\infty} \frac{1}{\sigma_{1}^{2} \sigma_{2}^{2}} \exp \left(-\frac{x}{\sigma_{1}^{2}}-\frac{y}{\sigma_{2}^{2}}\right) d x d y\right) \\
& =\prod_{a_{0}=1}^{\mathcal{A}_{0}} \prod_{a_{1}=1}^{\mathcal{A}_{1}}\left(1-\frac{2 \exp \left(-\frac{\gamma_{2}^{*}\left(\rho_{0}+\rho_{1}^{2}\right)}{(1-\lambda)\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{*}\right) \rho_{0} \rho_{1}^{2} \sigma_{1}^{2}}\right) \sqrt{\frac{1}{\sigma_{2}^{2}}} \beta_{1}\left(\frac{2 \sqrt{\frac{1}{\sigma_{2}^{2}}}}{\sqrt{\frac{(1-\lambda)\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{*}\right) \rho_{0} \rho_{1}^{2} \sigma_{1}^{2}}{\gamma_{2}^{*}}}}\right)}{\sqrt{\frac{(1-\lambda)\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{*}\right) \rho_{0} \rho_{1}^{2} \sigma_{1}^{2}}{\gamma_{2}^{*}}}}\right) \tag{6.93}
\end{array}\right) .
$$

End of proof.

## Chapter 7:

## OP and SOP Improvement in IoT-NOMA Networks by Adopting SWIPT

## Part I - A Novel Design for a SWIPT Framework with a PS protocol

TNSPIRED by major previous studies, the following issues remain open and are addressed in the third aim of my dissertation:

- The present study proposes a low energy IoT network underlay C-NOMA technique, inspired by the feature study [95]. My research also investigates the effect of PS factors on the system performance of an IoT network;
- To improve the system throughput of an IoT network, the relay in the present study adopts FD mode to reach ultra-low latency;
- I assume that the near device, specified as a relay, does not have the power resources to forward a signal. I therefore propose a novel SWIPT model which uses harvested energy for the relay to forward signals. Instead of a fixed PS factor, I deploy an adaptive PS factor with a constrained SINR achieved at the far device and an approximately achieved SINR at the relay to ensure QoS fairness at the far device. I thus obtain a novel OP at the device in terms of accuracy and approximate closed forms;
- PLS acknowledges one of the most important issues in wireless communication networks. To the best of my knowledge, I consider exploiting an adaptive PS factor which may improve secrecy performance.

Note that the outcomes in the Chapter 7 (Part I) have been published in the paper [TTNam09] entitled "SWIPT Model Adopting a PS Framework to Aid IoT Networks Inspired by the Emerging Cooperative NOMA Technique", in (IEEE) IEEE Access, Vol. 9, pp. 61489-61512 (2021). DOI: 10.1109/access.2021.3074351. IF $\mathbf{3 . 7 4 5}$

### 7.1 System Models

The dissertation examines two individual down-link scenarios: (i) SWIPT underlay HD/FD relay, and (ii) secrecy SWIPT underlay HD/FD relay.

### 7.1.1 Concept and formulation of an underlay IoT network with HD relaying

The IoT network model depicted in Figure 7.1a has a source $S$ and two devices $D_{1}$ and $D_{2}$. The source $S$ at the center cell covers a certain area. The device $D_{1}$ is inside a certain area. However, I assume that device $D_{2}$ is outside the coverage area of source $S$. Therefore, no direct down-link from source $S$ to device $D_{2}$ exists. Device $D_{2}$ broadcasts to assist synchronization (SYN) with the devices nearby. In this case, device $D_{1}$ receives the SYN requirement of device $D_{2}$ and replies with an acknowledgment (ACK) to device $D_{2}$. Device $D_{2}$ sends a finish (FIN) message to accept cooperation from device $D_{1}$. Device $D_{1}$ is thus implemented as a relay to assist device $D_{2}$. This dissertation assumes that device $D_{1}$ fully sends its own CSI as feedback and the CSI from device $D_{2}$ to source $S$.

(a)

(b)

Figure 7.1: (a) An HD-IoT network underlay cooperative NOMA in combination with SWIPT; (b) PS diagram with HD relaying.

Two SWIPT techniques can be used: TS and PS. In [34], the authors fully presented RF-EH. The authors also adopted and compared TS and PS protocols [76, 77]. The authors presented TS diagrams in [76, Figure 2a] and [77, Figure 1b]. I observed that the previous TS diagrams required three time slots to complete a transmission block. The authors also presented PS diagrams in [76, Figure 3a] and [77, Figure 3b]. I observed that the previous PS diagrams required two time slots to complete a transmission block. I also observed that the PS protocol provided greater network capacity than the TS protocol. The present dissertation therefore applies the PS protocol, which is suitable for low latency and low energy IoT networks. Figure 7.1b illustrates EH and signal processing through the deployment of the PS protocol different
from the previous PS diagrams in [76, Figure 3a] and [77, Figure 3b]. Note that the PS diagram (Fig. 7.1b) with three tiers uses two time slots to complete a transmission block $T$ according to [77, 92, 95]. In the first half of the transmission block, the BS transmits wireless energy (tier 1) and information (tier 2) simultaneously to device $D_{1}$. In terms of SWIPT using a PS protocol, a portion of the power domain $P$ from the source is used during the first half of the time block for EH, while the remaining portion is used for information processing. The ratio of EH is determined according to the PS factor $\varepsilon$. Therefore, $\varepsilon P$ is used for EH , and the remaining $\xi P=(1-\varepsilon) P$ is used for information processing at device $D_{1}$, where $0 \leq \varepsilon \leq 1$. EH architecture was presented in [34, Figure 4c] and [77, Figure 4]. In the second half of the transmission block, device $D_{1}$ forwards information to $D_{2}$ by using the harvested energy (tier 1) and applying the DF protocol.

Source $S$ fully owns the CSI of near device $D_{1}$ and far device $D_{2}$. I assume a single transmitting antenna and single receiving antenna at each node. According to C-NOMA theory, source $S$ superimposes the messages $x_{1}$ and $x_{2}$ of devices $D_{1}$ and $D_{2}$ in the signal and transmits them to the near device $D_{1}$. The received signal at near device $D_{1}$ is expressed as:

$$
\begin{equation*}
\mathrm{y}_{1}^{(H D)}=h_{1} \sqrt{\xi^{(H D)} P}\left(\sqrt{\alpha_{1}} x_{1}+\sqrt{\alpha_{2}} x_{2}\right)+n_{1}, \tag{7.1}
\end{equation*}
$$

where PS factors $\varepsilon^{(H D)}$ and $\xi^{(H D)}$ are used for transmitting wireless energy and information, respectively, and $\xi^{(H D)}+\varepsilon^{(H D)}=1$. $h_{1}$ is the fading channel from source $S$ to near device $D_{1}$. Note that fading channel $h_{1}$ is modeled according to a Rayleigh fading channel such that $h_{1}=d_{1}^{-\omega}$, where $d_{1}$ and $\omega$ are the distance $S \rightarrow D_{1}$ and path-loss exponent, respectively. The coefficient $P$ is the power domain at source $S$. The devices share the spectrum in the same power domain $P$. Therefore, the messages $x_{1}$ and $x_{2}$ of the devices $D_{1}$ and $D_{2}$ are superimposed according to different PA factors $\alpha_{1}$ and $\alpha_{2}$. As shown in Figure 7.1, with constraint distance $S \rightarrow D_{1}$ being less than distance $S \rightarrow D_{2}$, we obtain the PA factor rule $\alpha_{1}<\alpha_{2}$ and $\alpha_{1}+\alpha_{2}=1$. $n_{1}$ is the AWGN such that $n_{1} \sim\left(0, N_{0}\right)$, with zero mean and variance $N_{0}$.

After receiving the signal according to (7.1), the near device $D_{1}$ implements SIC to detect its own message $x_{1}$. However, $\alpha_{1}<\alpha_{2}$ are constrained in this study. Therefore, the near device $D_{1}$ must decode the message $x_{2}$ of the far device $D_{2}$ by treating the message $x_{1}$ and AWGN $n_{1}$ as interference. We obtain the SINR when the near device $D_{1}$ decodes message $x_{2}$ as follows:

$$
\begin{equation*}
\gamma_{1-x_{2}}^{(H D)}=\frac{\left|h_{1}\right|^{2} \xi^{(H D)} \rho \alpha_{2}}{\left|h_{1}\right|^{2} \xi^{(H D)} \rho \alpha_{1}+1}, \tag{7.2}
\end{equation*}
$$

where $\operatorname{SNR} \rho=P / N_{0}$.
After detecting message $x_{2}$, the near device $D_{1}$ eliminates message $x_{2}$ from the received signal (7.1) and decodes its own message $x_{1}$ by treating AWGN $n_{1}$ as interference. We obtain the SINR when the near device $D_{1}$ decodes message $x_{1}$ as follows:

$$
\begin{equation*}
\gamma_{1-x_{1}}^{(H D)}=\left|h_{1}\right|^{2} \xi^{(H D)} \rho \alpha_{1} . \tag{7.3}
\end{equation*}
$$

The instantaneous bit rate threshold is reached when the near device $D_{1}$ decodes the message $x_{i}$ :

$$
\begin{equation*}
R_{1-x_{i}}^{(H D)}=\frac{1}{2} \log _{2}\left(1+\gamma_{1-x_{i}}^{(H D)}\right), \tag{7.4}
\end{equation*}
$$

where $i=\{2,1\}$, respectively.

### 7.1.2 Concept and formulation of an IoT underlay cooperative NOMA network with FD relaying

The aim of the dissertation is to attain ultra-low latency. Deployment of the FD protocol at the near device $D_{1}$ reduces the time delay at device $D_{2}$ (Fig. 7.2a). $D_{1}$ is equipped with one antenna to receive the signal from source $S$ and another to forward the signal to device $D_{2}$. The resulting transmission block is shown in Figure 7.2b. It is important to note that only one time slot is available to finish a transmission block.


Figure 7.2: (a) An FD-IoT underlay cooperative NOMA network in combination with SWIPT; (b) PS diagram with FD relaying.

Figure 7.2b also illustrates EH and signal processing through the deployment of the PS protocols shown in Figure 7.1b. However, EH, information processing and information forwarding have three tiers. In tier 3, note the LI channel which is generated because $D_{1}$ adopts the FD protocol.

In an FD-IoT network model, the received signal from source $S$ at near device $D_{1}$ can be rewritten as follows:

$$
\begin{equation*}
\mathrm{y}_{1}^{(F D)}=\underbrace{h_{1} \sqrt{\xi^{(F D)} P}\left(\sqrt{\alpha_{1}} x_{1}+\sqrt{\alpha_{2}} x_{2}\right)}_{\text {Superimposed information }}+\underbrace{h_{L I} \eta \sqrt{\varepsilon^{(F D)} P} \tilde{x}}_{\text {Loop interference }}+\underbrace{n_{1}}_{\text {AWGN }} \tag{7.5}
\end{equation*}
$$

where PS factors $\varepsilon^{(F D)}$ and $\xi^{(F D)}$ are used for transmitting wireless energy and information, respectively, and $\xi^{(F D)}+\varepsilon^{(F D)}=1$. Notice that PS factors $\varepsilon^{(F D)}$ and $\xi^{(F D)}$ in (7.5) are different from the PS factors $\varepsilon^{(H D)}$ and $\xi^{(H D)}$ in (7.1). $h_{L I}$ is also modeled as a Rayleigh fading channel with constrained $\sigma_{L I}=E\left\{\left|h_{L I}\right|^{2}\right\}=\varpi E\left\{\left|h_{1}\right|^{2}\right\}$ for $0 \leq \varpi \leq 1$, which refers to the effect of the LI factor. It is important to note that the LI in (7.5) relates to the EH at $D_{1}$ given by (7.56). The near device $D_{1}$ uses harvested energy from source $S$ as transmit power to forward the signal to the far device $D_{2}$.

By applying SIC, the near device $D_{1}$ obtains the SINR when it decodes message $x_{2}$ by treating message $x_{1}$, the LI channel $h_{L I}$ and AWGN $n_{1}$ as interference, as follows:

$$
\begin{equation*}
\gamma_{1-x_{2}}^{(F D)}=\frac{\left|h_{1}\right|^{2} \xi^{(F D)} \rho \alpha_{2}}{\left|h_{1}\right|^{2} \xi^{(F D)} \rho \alpha_{1}+\left|h_{L I}\right|^{2} \eta^{2} \varepsilon^{(F D)} \rho+1} \tag{7.6}
\end{equation*}
$$

After message $x_{2}$ is detected, it is eliminated from the received signal (7.5). The near device $D_{1}$ decodes its own message $x_{1}$ by treating the LI channel $h_{L I}$ and AWGN $n_{1}$ as interference. The SINR is obtained as follows:

$$
\begin{equation*}
\gamma_{1-x_{1}}^{(F D)}=\frac{\left|h_{1}\right|^{2} \xi^{(F D)} \rho \alpha_{1}}{\left|h_{L I}\right|^{2} \eta^{2} \varepsilon^{(F D)} \rho+1} \tag{7.7}
\end{equation*}
$$

The instantaneous bit rate threshold is reached at the near device $D_{1}$ in an FD-IoT network model as follows:

$$
\begin{equation*}
R_{1-x_{i}}^{(F D)}=\log _{2}\left(1+\gamma_{1-x_{i}}^{(F D)}\right) \tag{7.8}
\end{equation*}
$$

where $i=\{2,1\}$, respectively.
After message $x_{2}$ of the far device $D_{2}$ is decoded and eliminated, the near device $D_{1}$ retrieves message $x_{2}$ and forwards it to the far device $D_{2}$ by adopting a DF protocol.

Researchers have investigated forwarding protocols such as DF [TTNam03], AF-FG [57] and AF-VG [TTNam06]. The authors proved that the AF-VG protocol produces the best performance [TTNam06]. However, the dissertation explores the use of the DF protocol since it may sufficiently satisfy the requirement that device $D_{1}$ correctly receives the signal transmitted from source $S$ and successfully decodes the retrieved message $x_{2}$ from $D_{2}$ before forwarding it to far device $D_{2}$. The dissertation also assumes that device $D_{1}$ has enough energy for independent operation. As a potential risk, device $D_{1}$ uses its own power to forward the signal to device $D_{2}$, which may lead to no power available at device $D_{1}$. Therefore, the AF protocol cannot be adopted at device $D_{1}$. Figures 7.1 b and 7.2 b depict that the near device $D_{1}$ uses harvested
energy given by (7.56) to forward the signal to far device $D_{2}$. The received signal at the far device $D_{2}$ is therefore expressed as follows:

$$
\begin{equation*}
y_{2}^{(\varphi)}=h_{1} h_{2} \eta \sqrt{\varepsilon^{(\varphi)} P} x_{2}+n_{2}, \tag{7.9}
\end{equation*}
$$

where $\varphi=\{H D, F D\}$ and $h_{2}$ is the fading channel from the near device $D_{1}$ to the far device $D_{2}$. As with $h_{1}$, the fading channel $h_{2}$ is modeled according to Rayleigh distribution such that $h_{2}=d_{2}^{-\omega}$, where $d_{2}$ is the distance $D_{1} \rightarrow D_{2}$ and $n_{2}$ is the AWGN at device $D_{2}$ such that $n_{2} \sim\left(0, N_{0}\right)$, with zero mean and variance $N_{0}$.

The far device $D_{2}$ implements SIC to decode its own message $x_{2}$ in the received signal (7.9) and obtains the SINR when it decodes $x_{2}$ by treating AWGN $n_{2}$ as interference, as follows:

$$
\begin{equation*}
\gamma_{2-x_{2}}^{(\varphi)}=\left|h_{1}\right|^{2}\left|h_{2}\right|^{2} \eta^{2} \varepsilon^{(\varphi)} \rho . \tag{7.10}
\end{equation*}
$$

The instantaneous bit rate threshold is reached when the far device $D_{2}$ decodes message $x_{2}$, as follows:

$$
R_{2-x_{2}}^{(\varphi)}= \begin{cases}\frac{1}{2} \log _{2}\left(1+\gamma_{2-x_{2}}^{(\varphi)}\right), & \text { where } \varphi=H D,  \tag{7.11}\\ \log _{2}\left(1+\gamma_{2-x_{2}}^{(\varphi)},\right. & \text { where } \varphi=F D .\end{cases}
$$

### 7.1.3 Concept and formulation of an IoTs underlay cooperative NOMA networks with PLS

In this section, I assume that the IoT network contains eavesdroppers $E_{1}$ and $E_{2}$ (Fig. 7.3a and 7.3b).

Note that the eavesdropper $E_{1}$ is allocated near $D_{1}$ or $S$, and the system models (Fig. 7.3a and 7.3 b ) are similar to those described in the featured studies [67] and [30]. Eavesdropper $E_{1}$ wants to eavesdrop device $D_{1}$. Device $D_{2}$ sends the SYN message to both the near device $D_{1}$ and eavesdropper $E_{1}$. In this case, $D_{1}$ and $E_{1}$ receive the SYN requirement of device $D_{2}$. However, eavesdropper $E_{1}$ is a passive device and not known in the network. Hence, only device $D_{1}$ replies with an ACK message to device $D_{2}$. Device $D_{2}$ sends a FIN message to accept cooperation from device $D_{1}$. Device $D_{1}$ is implemented as a relay to assist device $D_{2}$. Because eavesdropper $E_{1}$ is near device $D_{1}$, it therefore receives the signal from $S$ over the wiretapping channel $h_{3}$ as follows:

$$
\begin{equation*}
\mathrm{y}_{3}^{(\varphi)}=h_{3} \sqrt{\xi^{(\varphi)} P}\left(\sqrt{\alpha_{1}} x_{1}+\sqrt{\alpha_{2}} x_{2}\right)+n_{3}, \tag{7.12}
\end{equation*}
$$

where $h_{3}$ is the wiretapping channel modeled as a Rayleigh fading channel such that $h_{3}=d_{3}^{-\omega}$, $d_{3}$ denotes the distance from source $S$ to eavesdropper $E_{1}$, and $n_{3}$ is the AWGN at eavesdropper $E_{1}$ such that $n_{3} \sim\left(0, N_{0}\right)$, with zero mean and variance $N_{0}$.

The eavesdropper $E_{1}$ executes SIC to decode the data symbols $x_{2}$ and $x_{1}$ and obtains the


Figure 7.3: IoT networks with eavesdroppers.
respective SINR as follows:

$$
\begin{equation*}
\gamma_{3-x_{2}}^{(\varphi)}=\frac{\left|h_{3}\right|^{2} \xi^{(\varphi)} \rho \alpha_{2}}{\left|h_{3}\right|^{2} \xi^{(\varphi)} \rho \alpha_{1}+1} \tag{7.13}
\end{equation*}
$$

and

$$
\begin{equation*}
\gamma_{3-x_{1}}^{(\varphi)}=\left|h_{3}\right|^{2} \xi^{(\varphi)} \rho \alpha_{1} . \tag{7.14}
\end{equation*}
$$

The instantaneous bit rate threshold is reached when the eavesdropper $E_{1}$ decodes the message $x_{i}$, where $i=\{2,1\}$, as follows:

$$
R_{3-x_{i}}^{(\varphi)}= \begin{cases}\frac{1}{2} \log _{2}\left(1+\gamma_{3-x_{i}}^{(\varphi)}\right), & \text { where } \varphi=H D  \tag{7.15}\\ \log _{2}\left(1+\gamma_{3-x_{i}}^{(\varphi)}\right), & \text { where } \varphi=F D\end{cases}
$$

The secrecy bit rate threshold at the device $D_{1}$ is therefore expressed as:

$$
\begin{equation*}
\mathcal{R}_{1-x_{i}}^{(\varphi)}=\left[R_{1-x_{i}}^{(\varphi)}-R_{3-x_{i}}^{(\varphi)}\right]^{+}, \tag{7.16}
\end{equation*}
$$

where $i=\{2,1\}$.
The eavesdropper $E_{2}$ wants to eavesdrop device $D_{2}$. Device $D_{2}$ sends a SYN message to both the near device $D_{1}$ and eavesdropper $E_{2}$. In this case, $D_{1}$ and $E_{2}$ receive a SYN requirement for device $D_{2}$. However, eavesdropper $E_{2}$ is a passive device and outside the cell network. Hence, only device $D_{1}$ replies with an ACK message to device $D_{2}$. Device $D_{2}$ sends a FIN message
to accept cooperation with device $D_{1}$. Device $D_{1}$ is implemented as a relay to assist device $D_{2}$. Because eavesdropper $E_{2}$ is near device $D_{2}$, it therefore receives the forwarded signal from device $D_{1}$ over the wiretapping channel $h_{4}$ as follows:

$$
\begin{equation*}
y_{4}^{(\varphi)}=h_{1} h_{4} \eta \sqrt{\varepsilon^{(\varphi)} P} x_{2}+n_{4}, \tag{7.17}
\end{equation*}
$$

where $h_{4}$ is the wiretapping channel modeled as a Rayleigh fading channel where $h_{4}=d_{4}^{-\omega}, d_{4}$ denotes the distance from device $D_{1}$ to eavesdropper $E_{2}$, and $n_{4}$ is the AWGN at eavesdropper $E_{2}$ such that $n_{4} \sim\left(0, N_{0}\right)$, with zero mean and variance $N_{0}$.

The system models (Fig. 7.3a and 7.3b) resemble the system model in [72], where the eavesdropper is near the destination. However, the main aim in the dissertation is to guarantee QoS at the far device and prove that the suitable PS factor improves secrecy performance.

I assume that eavesdropper $E_{2}$ can decode the data symbol $x_{2}$ when eavesdropper $E_{2}$ eavesdrops device $D_{2}$. Eavesdropper $E_{2}$ therefore obtains the respective SINR and instantaneous bit rate threshold when it decodes the data symbol $x_{2}$ according to:

$$
\begin{equation*}
\gamma_{4-x_{2}}^{(\varphi)}=\left|h_{1}\right|^{2}\left|h_{4}\right|^{2} \eta^{2} \varepsilon^{(\varphi)} \rho, \tag{7.18}
\end{equation*}
$$

and

$$
R_{4-x_{2}}^{(\varphi)}=\left\{\begin{array}{l}
\frac{1}{2} \log _{2}\left(1+\gamma_{4-x_{2}}^{(\varphi)}\right), \text { where } \varphi=H D,  \tag{7.19}\\
\log _{2}\left(1+\gamma_{4-x_{2}}^{(\varphi)}\right), \text { where } \varphi=F D .
\end{array}\right.
$$

The secrecy bit rate threshold at device $D_{2}$ is therefore expressed as:

$$
\begin{equation*}
\mathcal{R}_{2}^{(\varphi)}=\left[R_{2-x_{2}}^{(\varphi)}-R_{4-x_{2}}^{(\varphi)}\right]^{+} . \tag{7.20}
\end{equation*}
$$

### 7.2 System Performance Analysis

The PDF $(f)$ and CDF $(F)$ over Rayleigh distributions are expressed, respectively, as:

$$
\begin{equation*}
f_{\left|h_{(.)}\right|^{2}}(x)=\frac{1}{\sigma_{(.)}^{2}} \exp \left(-\frac{x}{\sigma_{(.)}^{2}}\right), \tag{7.21}
\end{equation*}
$$

and

$$
\begin{equation*}
F_{\left|h_{(.)}\right|^{2}}(x)=1-\exp \left(-\frac{x}{\sigma_{(.)}^{2}}\right), \tag{7.22}
\end{equation*}
$$

where $x$ is a randomly independent variable such that $x \geq 0$ and $\sigma_{(.)}^{2}=E\left\{\left|h_{(.)}\right|^{2}\right\}$.

### 7.2.1 OP performance

Theorem 1: The OP at near device $D_{1}$ in an HD/FD-IoT network model follows either of two cases:

- The instantaneous bit rate threshold given by (7.4) or (7.8), where $i=2$ and when the near device $D_{1}$ decodes message $x_{2}$, cannot reach the data rate threshold $R_{2}$ of device $D_{2}$, i.e., $R_{1-x_{2}}^{(\varphi)}<R_{2}$, where $\varphi=\{H D, F D\}$.
- The instantaneous bit rate threshold given by (7.4) or (7.8), where $i=2$ and when the near device $D_{1}$ decodes message $x_{2}$, reaches the data rate threshold $R_{2}$ of the far device $D_{2}$. However, the near device $D_{1}$ cannot decode its own message $x_{1}$, i.e., $R_{1-x_{2}}^{(\varphi)} \geq R_{2}$ and $R_{1-x_{1}}^{(\varphi)}<R_{1}$, where $R_{1}$ is the data rate threshold of device $D_{1}$.

The OP at the near device $D_{1}$ is expressed as:

$$
\begin{equation*}
O P_{1}^{(\varphi)}=\operatorname{Pr}\left\{R_{1-x_{2}}^{(\varphi)}<R_{2}\right\}+\operatorname{Pr}\left\{R_{1-x_{2}}^{(\varphi)} \geq R_{2}, R_{1-x_{1}}^{(\varphi)}<R_{1}\right\} \tag{7.23}
\end{equation*}
$$

By applying the PDF and CDF given by (7.21) and (7.22), we obtain, in closed form, the OP at the near device $D_{1}$ for an HD-IoT model:

$$
\begin{align*}
O P_{1}^{(H D)} & =1-\exp \left(-\frac{\gamma_{2}^{(H D)}}{\xi^{(H D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(H D)}\right) \rho \sigma_{1}}\right) \\
& +\left[\exp \left(-\frac{\gamma_{2}^{(H D)}}{\xi^{(H D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(H D)}\right) \rho \sigma_{1}}\right)-\exp \left(-\frac{\gamma_{1}^{(H D)}}{\xi^{(H D)} \alpha_{1} \rho \sigma_{1}}\right)\right]^{+} \tag{7.24}
\end{align*}
$$

where the SINR threshold is $\gamma_{i}^{(H D)}=2^{2 R_{i}}-1$ for $i=\{2,1\}$, and $\sigma_{1}=E\left\{\left|h_{1}\right|^{2}\right\}$. From (7.24), we examine and then exploit three special cases. In the special first case, the OP at $D_{1}$ refers to OP as $O P_{1}^{(H D)}=1-\exp \left(-\gamma_{1}^{(H D)} /\left(\xi^{(H D)} \alpha_{1} \rho \sigma_{1}\right)\right)$, where $R_{2}<\frac{1}{2} \log _{2}\left(\frac{\alpha_{2}-\alpha_{1}}{\alpha_{1}}+1\right)$. In the second special case, the OP at $D_{1}$ refers to OP as $O P_{1}^{(H D)}=1-\exp \left(-\gamma_{2}^{(H D)} /\left(\xi^{(H D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(H D)}\right) \rho \sigma_{1}\right)\right)$, where $R_{2} \geq \frac{1}{2} \log _{2}\left(\frac{\alpha_{2}-\alpha_{1}}{\alpha_{1}}+1\right)$. In the third special case, OP at $D_{1}$ refers to $O P_{1}^{(H D)} \rightarrow 1$, where $R_{2} \geq \frac{1}{2} \log _{2}\left(\frac{\alpha_{2}}{\alpha_{1}}+1\right)$.

By applying the PDF given by (7.21), we obtain, in closed form, to the best of my knowledge, the novel closed form of OP at the near device $D_{1}$ for an FD-IoT model:

$$
\begin{align*}
O P_{1}^{(F D)} & =1-\frac{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)+\eta^{2} \varpi \varepsilon^{(F D)} \gamma_{2}^{(F D)}} \exp \left(-\frac{\gamma_{2}^{(F D)}}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right) \rho \sigma_{1}}\right) \\
& +\left[\frac{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)+\eta^{2} \varpi \varepsilon(F D)} \gamma_{2}^{(F D)} \exp \left(-\frac{\gamma_{1}^{(F D)}}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right) \rho \sigma_{1}}\right)\right. \\
& \left.-\frac{\xi^{(F D)} \alpha_{1}}{\xi^{(F D)} \alpha_{1}+\eta^{2} \varpi \varepsilon^{(F D)} \gamma_{1}^{(F D)}} \exp \left(-\frac{\gamma_{1}^{(F D)}}{\xi^{(F D)} \alpha_{1} \rho \sigma_{1}}\right)\right] \tag{7.25}
\end{align*}
$$

where $\gamma_{i}^{(F D)}=2^{R_{i}}-1$ for $i=\{2,1\}$. From (7.25), we examine and exploit three special cases. In the first special case, the OP at device $D_{1}$ refers to $O P_{1}^{(F D)}=1-\frac{\xi^{(F D)} \alpha_{1}}{\xi^{(F D)} \alpha_{1}+\eta^{2} \varpi \varepsilon^{(F D)} \gamma_{1}^{(F D)}} \times$ $\exp \left(-\frac{\gamma_{1}^{(F D)}}{\left.\xi^{F D}\right) \alpha_{1} \rho \sigma_{1}}\right)$, where $R_{2}<\log _{2}\left(\frac{\alpha_{2}-\alpha_{1}}{\alpha_{1}}+1\right)$. In the second special case, the OP at device $D_{1}$ refers to $O P_{1}^{(F D)}=1-Q_{3}$, where $R_{2} \geq \log _{2}\left(\frac{\alpha_{2}-\alpha_{1}}{\alpha_{1}}+1\right)$. In the third special case, the OP at device $D_{1}$ refers to $O P_{1}^{(F D)}=1$, where $R_{2} \geq \log _{2}\left(\frac{\alpha_{2}}{\alpha_{1}}+1\right)$.

Note that the OP performance at device $D_{1}$, where $D_{1}$ operates in FD mode and SNR $\rho \rightarrow \infty$, given by (7.25), will reach the floor as follows:

$$
\begin{align*}
F O P_{1}^{(F D)} & =1-\frac{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)+\eta^{2} \varpi \varepsilon^{(F D)} \gamma_{2}^{(F D)}} \\
& +\left[\frac{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)+\eta^{2} \varpi \varepsilon^{(F D)} \gamma_{2}^{(F D)}}-\frac{\xi^{(F D)} \alpha_{1}}{\xi^{(F D)} \alpha_{1}+\eta^{2} \varpi \varepsilon^{(F D)} \gamma_{1}^{(F D)}}\right]^{+} \tag{7.26}
\end{align*}
$$

From (7.24), note that $O P_{1}^{(H D)}$ may tend to zero when $\operatorname{SNR} \rho \rightarrow \infty$. However, $O P_{1}^{(F D)}$ given by (7.25) may tend to $F O P_{1}^{(F D)}$ when $\rho \rightarrow \infty$.

See Appendix 7.5.1 for proof.
Lemma 1: Based on Theorem 1, it is difficult to investigate the OP at the device in closed form, whereas massive devices joined the IoT network, for example, in [6] and [TTNam03]. Functioning as a relay, device $D_{1}$ must decode the data symbols in a superimposed signal sequentially and forward the superimposed signal to the destination. I therefore propose a mininstantaneous bit rate threshold framework to investigate OP performance at the devices. To illustrate, device $D_{1}$ receives the signal given by (7.1) for the HD scenario or (7.5) for the FD scenario. By applying SIC, device $D_{1}$ obtains the SINR when it decodes the data symbols given by (7.2) and (7.3) for the HD scenario or (7.6) and (7.7) for the FD scenario. In previous major studies, the authors in [7] and [TTNam03] assumed that devices owned the same data rate thresholds for fairness. By applying a min-rate framework, the OP event at device $D_{1}$ in the dissertation may occur when the min-instantaneous bit rate threshold cannot reach the data rate threshold $R=R_{1}=R_{2}$. The min-rate OP at device $D_{1}$ is therefore expressed as follows:

$$
\begin{align*}
\operatorname{MOP}_{1}^{(\varphi)} & =\max \left\{\operatorname{Pr}\left\{R_{1-x_{2}}^{(\varphi)}<R_{2}\right\}, \operatorname{Pr}\left\{R_{1-x_{1}}^{(\varphi)}<R_{1}\right\}\right\},  \tag{7.27}\\
& =1-\operatorname{Pr}\left\{\min \left\{R_{1-x_{2}}^{(\varphi)}, R_{1-x_{1}}^{(\varphi)}\right\} \geq R\right\}, \tag{7.28}
\end{align*}
$$

where $R_{1} \neq R_{2}$ in (7.27) and $R_{1}=R_{2}=R$ in (7.28).
By observation (7.28), only the minimum between the instantaneous bit rate thresholds is applied for comparison to the device data threshold $R$. If the minimum between the instantaneous bit rate thresholds achieves the device data threshold $R$, the maximum between the instantaneous bit rate thresholds achieves the device data threshold $R$ as a result. Therefore, the maximum between the instantaneous bit rate thresholds need not be used to investigate the OP performance at device $D_{1}$. I may observe that equation (7.28) has a less complicated
algorithm than equation (7.23). As a result, equation (7.28) provides less time to assess the OP performance at device $D_{1}$.

By applying the PDF given by (7.21), we obtain, in closed form, the OP at device $D_{1}$ in HD and FD modes as follows:

$$
\begin{align*}
M O P_{1}^{(H D)} & =1-\exp \left(-\frac{\max \left\{\frac{\gamma_{2}^{(H D)}}{\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(H D)}\right.}, \frac{\gamma_{1}^{(H D)}}{\alpha_{1}}\right\}}{\xi^{(F D)} \rho \sigma_{1}}\right)  \tag{7.29}\\
& =1-\exp \left(-\frac{\gamma^{(H D)}}{\xi^{(F D)} \rho \sigma_{1} \min \left\{\alpha_{2}-\alpha_{1} \gamma^{(H D)}, \alpha_{1}\right\}}\right) \tag{7.30}
\end{align*}
$$

and

$$
\begin{align*}
M O P_{1}^{(F D)} & =1-\min \left\{\exp \left(-\frac{\gamma_{2}^{(F D)}}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right) \rho \sigma_{1}}\right)\right. \\
& \times \frac{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)+\eta^{2} \varpi \varepsilon^{(F D)} \gamma_{2}^{(F D)}}, \\
& \exp \left(-\frac{\gamma_{1}^{(F D)}}{\xi^{(F D)} \alpha_{1} \rho \sigma_{1}}\right) \frac{\xi^{(F D)} \alpha_{1}}{\left.\xi^{(F D)} \alpha_{1}+\eta^{2} \varpi \varepsilon \gamma_{1}^{(F D)}\right\}}  \tag{7.31}\\
& =1-\exp \left(-\frac{\gamma^{(F D)}}{\xi^{(F D)} \rho \sigma_{1} \min \left\{\alpha_{2}-\alpha_{1} \gamma^{(F D)}, \alpha_{1}\right\}}\right) \\
& \times \frac{\xi^{(F D)} \min \left\{\alpha_{2}-\alpha_{1} \gamma^{(F D)}, \alpha_{1}\right\}}{\xi^{(F D)} \min \left\{\alpha_{2}-\alpha_{1} \gamma^{(F D)}, \alpha_{1}\right\}-\eta^{2} \varpi \varepsilon^{(F D)} \gamma^{(F D)}}, \tag{7.32}
\end{align*}
$$

where $R_{1} \neq R_{2}$ in (7.29) and (7.31) and $R_{1}=R_{2}=R$ in (7.30) and (7.32), $\gamma^{(H D)}=2^{2 R}-1$, and $\gamma^{(F D)}=2^{R}-1$.

From [95, Eq. (44)], the exponent function $\exp (-z) \approx 1-z$, where $z \rightarrow 0$ or SNR $\rho \rightarrow \infty$. Therefore, the OP performance at device $D_{1}$ in HD mode given by (7.29) and (7.30) can be obtained in novel approximated form as follows:

$$
\begin{align*}
A O P_{1}^{(H D)} & \approx\left\{\frac{\left.\left\{\frac{\gamma_{2}^{(H D)}}{\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(H D)}\right.}\right) \vee \frac{\gamma_{1}^{(H D)}}{\alpha_{1}}\right\}}{\xi^{(F D)} \rho \sigma_{1}} \wedge 1\right\},  \tag{7.33}\\
& \approx 1-\left[1-\frac{\gamma^{(H D)}}{\xi^{(F D)} \rho \sigma_{1} \min \left\{\alpha_{2}-\alpha_{1} \gamma^{(H D)}, \alpha_{1}\right\}}\right]^{+}, \tag{7.34}
\end{align*}
$$

such that $R_{1} \neq R_{2}$ in (7.33) and $R_{1}=R_{2}=R$ in (7.34).
Similarly, we also obtain the approximate OP performance at the device $D_{2}$ in FD mode as
follows:

$$
\begin{align*}
A O P_{1}^{(F D)} \approx 1- & \left\{\left(1-\left\{1 \wedge \frac{\gamma_{2}^{(F D)}}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right) \rho \sigma_{1}}\right\}\right)\right. \\
& \left.\times \frac{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)+\eta^{2} \varpi \varepsilon^{(F D)} \gamma_{2}^{(F D)}}\right) \\
& \left.\wedge\left(\left(1-\left\{1 \wedge \frac{\gamma_{1}^{(F D)}}{\xi^{(F D)} \alpha_{1} \rho \sigma_{1}}\right\}\right) \times \frac{\xi^{(F D)} \alpha_{1}}{\xi^{(F D)} \alpha_{1}+\eta^{2} \varpi \varepsilon^{(F D)} \gamma_{1}^{(F D)}}\right)\right\}  \tag{7.35}\\
\approx 1- & \left(1-\left\{1 \wedge \frac{\gamma^{(F D)}}{\xi^{(F D)} \rho \sigma_{1} \min \left\{\begin{array}{c}
\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)} \\
\alpha_{1}
\end{array}\right\}}\right\}\right) \\
& \times \frac{\xi^{(F D)} \min \left\{\alpha_{2}-\alpha_{1} \gamma^{(F D)}, \alpha_{1}\right\}}{}\left(\begin{array}{l}
\xi^{(F D)} \min \left\{\begin{array}{c}
\left.\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right\}+\eta^{2} \varpi \varepsilon(F D) \\
\alpha_{1}
\end{array}\right\}
\end{array}\right) \tag{7.36}
\end{align*}
$$

such that $R_{1} \neq R_{2}$ in (7.35) and $R_{1}=R_{2}=R$ in (7.36).
Note that I exploit the floor of the min-rate OP at device $D_{1}$, where $D_{1}$ operates in FD mode and SNR $\rho \rightarrow \infty$ given by (7.31) and (7.32):

$$
\begin{align*}
F O P_{1}^{(F D)} & =1-\min \left\{\frac{\xi^{(F D)} \alpha_{1}}{\xi^{(F D)} \alpha_{1}+\eta^{2} \varpi \varepsilon^{(F D)} \gamma_{1}^{(F D)}}, \frac{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)+\eta^{2} \varpi \varepsilon^{(F D)} \gamma_{2}^{(F D)}}\right\}  \tag{7.37}\\
& =1-\frac{\xi^{(F D)} \min \left\{\alpha_{2}-\alpha_{1} \gamma^{(F D)}, \alpha_{1}\right\}}{\xi^{(F D)} \min \left\{\alpha_{2}-\alpha_{1} \gamma^{(F D)}, \alpha_{1}\right\}-\eta^{2} \varpi \varepsilon^{(F D)} \gamma^{(F D)}} \tag{7.38}
\end{align*}
$$

From (7.25), (7.31) for $R_{1} \neq R_{2},(7.32)$ for $R_{1}=R_{2},(7.35)$ for $R_{1} \neq R_{2},(7.36)$ for $R_{1}=R_{2}$, (7.37) for $R_{1} \neq R_{2}$ and (7.38) for $R_{1}=R_{2}$, I exploit $O P_{1}^{(F D)}=M O P_{1}^{(F D)}=A O P_{1}^{(F D)}=$ $F O P_{1}^{(F D)}$ for SNR $\rho \rightarrow \infty$.

See Appendix 7.5.2 for proof.
Theorem 2: The OP at the far device $D_{2}$ with cooperation from the near device $D_{1}$ functioning in HD or FD mode has two cases:

- The near device $D_{1}$ cannot successfully decode message $x_{2}$ in the received signal (7.1) or (7.5). To illustrate, the achievable instantaneous bit rate threshold given by (7.4) or (7.8), where $i=2$, cannot reach the data rate threshold $R_{2}$ of far device $D_{2}$, i.e., $R_{1-x_{2}}^{(\varphi)}<R_{2}$ for $\varphi=\{H D, F D\}$.
- The near device $D_{1}$ successfully decodes message $x_{2}$ of far device $D_{2}$ in the received signal (7.1) or (7.5). The near device $D_{1}$ retrieves message $x_{2}$ and forwards it to the far device $D_{2}$ by using the harvested energy given by (7.56). However, the far device $D_{2}$
cannot successfully decode message $x_{2}$ in the received signal (7.9), i.e., $R_{1-x_{2}}^{(\varphi)} \geq R_{2}$ and $R_{2-x_{2}}^{(\varphi)}<R_{2}$.

The OP at the far device $D_{2}$ is expressed as:

$$
\begin{equation*}
O P_{2}^{(\varphi)}=\operatorname{Pr}\left\{R_{1-x_{2}}^{(\varphi)}<R_{2}\right\}+\operatorname{Pr}\left\{R_{1-x_{2}}^{(\varphi)} \geq R_{2}, R_{2-x_{2}}^{(\varphi)}<R_{2}\right\} \tag{7.39}
\end{equation*}
$$

By applying the PDF and CDF given by (7.21) and (7.22), respectively, we obtain, in closed form, the OP at the far device $D_{2}$ in an HD-IoT network model:

$$
\begin{align*}
O P_{2}^{(H D)} & =1-\exp \left(-\frac{\gamma_{2}^{(H D)}}{\xi^{(H D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(H D)}\right) \rho \sigma_{1}}\right) \\
& +\left[\exp \left(-\frac{\gamma_{2}^{(H D)}}{\xi^{(H D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(H D)}\right) \rho \sigma_{1}}\right)-\frac{2 B_{1}\left\{2 / \sqrt{\frac{\eta^{2} \varepsilon^{(H D)} \rho \sigma_{1} \sigma_{2}}{\gamma_{2}^{(H D)}}}\right\}}{\sqrt{\frac{\eta^{2} \varepsilon^{(H D)} \rho \sigma_{1} \sigma_{2}}{\gamma_{2}^{(H D)}}}}\right]^{+} \tag{7.40}
\end{align*}
$$

where $\sigma_{2}=E\left\{\left|h_{2}\right|^{2}\right\}$ and $B_{1}\{$.$\} is the second type of modified BesselK function [TTNam06].$
Similarly, we obtain the OP at the far device $D_{2}$ for an FD-IoT network model:

$$
\begin{align*}
O P_{2}^{(F D)} & =1-\exp \left(-\frac{\gamma_{2}^{(F D)}}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right) \rho \sigma_{1}}\right) \frac{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)+\eta^{2} \varpi \varepsilon^{(F D)} \gamma_{2}^{(F D)}} \\
& +\left[\exp \left(-\frac{\gamma_{2}^{(F D)}}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right) \rho \sigma_{1}}\right) \frac{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)+\eta^{2} \varpi \varepsilon^{(F D)} \gamma_{2}^{(F D)}}\right. \\
& \left.-\frac{2 B_{1}\left\{2 / \sqrt{\frac{\left.\eta^{2} \varepsilon^{(F D)}\right) \sigma_{1} \sigma_{1}}{\gamma_{2}^{(F D)}}}\right\}}{\sqrt{\frac{\eta^{2} \varepsilon^{(F F)} \rho \sigma_{1} \sigma_{2}}{\gamma_{2}^{(F D)}}}}\right]^{+} . \tag{7.41}
\end{align*}
$$

See Appendix 7.5.3 for proof.
Lemma 2: Based on Theorem 2, it is difficult to investigate the OP at the user in closed form, whereas multiple relaying nodes are deployed in IoT networks, for example, in [TTNam03]. The OP at device $D_{2}$ depends on the OP at device $D_{1}$. As in Lemma 1, I also deploy the mininstantaneous bit rate threshold framework to investigate the OP at device $D_{2}$. To illustrate, device $D_{1}$ receives a signal given by (7.1) for HD or (7.5) for FD. By applying SIC, device $D_{1}$ obtains the SINR when it decodes the data symbol $x_{2}$ given by (7.2) for HD or (7.6) for FD. Device $D_{1}$ obtains the instantaneous bit rate given by (7.4) for $\varphi=H D$ and $i=2$ or (7.8) for $\varphi=F D$ and $i=2$. Similarly, by applying SIC, device $D_{2}$ decodes its own data symbol $x_{2}$ in the received signal given by (7.9) and obtains the SINR and instantaneous bit rate threshold given by (7.10) and (7.11), respectively. As a result, the OP event at device $D_{2}$ in this dissertation may occur when the min-instantaneous bit rate threshold cannot reach the data rate threshold
$R_{2}$. The min-rate OP at device $D_{2}$ is therefore expressed as:

$$
\begin{align*}
\operatorname{MOP}_{2}^{(\varphi)} & =\max \left\{O_{1-x_{2}}^{(\varphi)}, O_{2-x_{2}}^{(\varphi)}\right\} \\
& =1-\operatorname{Pr}\left\{\min \left\{R_{1-x_{2}}^{(\varphi)}, R_{2-x_{2}}^{(\varphi)}\right\} \geq R_{2}\right\} . \tag{7.42}
\end{align*}
$$

The min-rate OP at device $D_{2}$ in HD and FD scenarios are obtained as follows:

$$
\begin{align*}
& \operatorname{MOP}_{2}^{(\varphi)}= 1-\left\{\exp \left(-\frac{\gamma_{2}^{(H D)}}{\xi^{(H D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(H D)}\right) \rho \sigma_{1}}\right) \frac{2 B_{1}\left\{2 / \sqrt{\frac{\eta^{2} \varepsilon^{(H D)} \rho \sigma_{1} \sigma_{2}}{\gamma_{2}^{(H D)}}}\right\}}{\sqrt{\frac{\eta^{2} \varepsilon^{(F D)} \rho_{1} \sigma_{2}}{\gamma_{2}^{(H D)}}}}\right\}  \tag{7.43}\\
&=1-\left\{\exp \left(-\frac{\gamma_{2}^{(F D)}}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right) \rho \sigma_{1}}\right) \frac{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)+\eta^{2} \varpi \varepsilon^{(F D)} \gamma_{2}^{(F D)}}\right. \\
& \wedge \frac{2 B_{1}\left\{2 / \sqrt{\frac{\eta^{2} \varepsilon^{(F D)} \rho \sigma_{1} \sigma_{2}}{\gamma_{2}^{(F D)}}}\right\}}{\left.\sqrt{\frac{\eta^{2} \varepsilon^{(F D)} \rho \sigma_{1} \sigma_{2}}{\gamma_{2}^{(F D)}}}\right\}} \tag{7.44}
\end{align*}
$$

From expressions (7.43) and (7.44), the approximations of the min-rate OP performance at device $D_{2}$ are expressed as:

$$
\begin{equation*}
A O P_{2}^{(H D)} \approx 1-\left\{\left(1-\left\{1 \wedge \frac{\gamma_{2}^{(H D)}}{\xi^{(H D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(H D)}\right) \rho \sigma_{1}}\right\}\right) \wedge \frac{2 B_{1}\left\{2 / \sqrt{\frac{\eta^{2} \varepsilon^{(H D)} \rho \sigma_{1} \sigma_{2}}{\gamma_{2}^{(H D)}}}\right\}}{\sqrt{\frac{\eta^{2} \varepsilon^{(F D)} \rho \sigma_{1} \sigma_{2}}{\gamma_{2}^{(H D)}}}}\right\} \tag{7.45}
\end{equation*}
$$

and

$$
\begin{align*}
A O P_{2}^{(F D)} \approx 1-\{ & \left(\left(1-\left\{1 \wedge \frac{\gamma_{2}^{(F D)}}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right) \rho \sigma_{1}}\right\}\right)\right. \\
& \left.\left.\times \frac{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)-\eta^{2} \varpi \varepsilon^{(F D)} \gamma_{2}^{(F D)}}\right) \wedge \frac{2 B_{1}\left\{2 / \sqrt{\frac{\eta^{2} \varepsilon^{(F D)} \rho \sigma_{1} \sigma_{2}}{\gamma_{2}^{(F D)}}}\right\}}{\sqrt{\frac{\eta^{2} \varepsilon^{(F D)} \rho \sigma_{1} \sigma_{2}}{\gamma_{2}^{(F D)}}}}\right\} \tag{7.46}
\end{align*}
$$

Let $W=2 B_{1}\left\{2 / \sqrt{\frac{\eta^{2} \varepsilon^{(F D)} \rho \sigma_{1} \sigma_{2}}{\gamma_{2}^{(F D)}}}\right\} / \sqrt{\frac{\eta^{2} \varepsilon^{(F D)} \rho \sigma_{1} \sigma_{2}}{\gamma_{2}^{(F D)}}}$ and $V=1-Q_{3}$. The expressions $W$ in (7.41) and (7.44) may tend to 1 , while $V$ may tend to the ceiling non-OP when $\operatorname{SNR} \rho \rightarrow \infty$. Therefore, we exploit the floor of OP $F O P_{2}^{(F D)}$ at device $D_{2}$ as follows:

$$
\begin{equation*}
F O P_{2}^{(F D)}=1-\frac{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)-\eta^{2} \varpi \varepsilon^{(F D)} \gamma_{2}^{(F D)}} \tag{7.47}
\end{equation*}
$$

From (7.41), (7.44), (7.46) and (7.47), it is worth noting that $O P_{2}^{(F D)}=M O P_{2}^{(F D)}=$ $A O P_{2}^{(F D)}=F O P_{2}^{(F D)}$ for SNR $\rho \rightarrow \infty$.

### 7.2.2 Secrecy OP performance

In this section, I assume the presence of an eavesdropper $E_{1}$ near device $D_{1}$ to eavesdrop device $D_{1}$ and eavesdropper $E_{2}$ near device $D_{2}$ to eavesdrop device $D_{2}$ in the IoT network shown in Figures 7.3 a and 7.3 b .

The SOP at device $D_{1}$ follows either of two cases:

- The secrecy instantaneous bit rate threshold $\mathcal{R}_{1-x_{2}}^{(\varphi)}$ cannot reach the bit rate threshold $R_{2}$.
- The secrecy instantaneous bit rate threshold $\mathcal{R}_{1-x_{2}}^{(\varphi)}$ reaches bit rate threshold $R_{2}$. However, The secrecy instantaneous bit rate threshold $\mathcal{R}_{1-x_{1}}^{(\varphi)}$ cannot reach bit rate threshold $R_{1}$.

The SOP performance at device $D_{1}$ is therefore expressed as:

$$
\begin{align*}
S O P_{1}^{(\varphi)} & =\operatorname{Pr}\left\{\left[R_{1-x_{2}}^{(\varphi)}-R_{3-x_{2}}^{(\varphi)}\right]^{+}<R_{2}\right\} \\
& +\operatorname{Pr}\left\{\left[R_{1-x_{2}}^{(\varphi)}-R_{3-x_{2}}^{(\varphi)}\right]^{+} \geq R_{2},\left[R_{1-x_{1}}^{(\varphi)}-R_{3-x_{1}}^{(\varphi)}\right]^{+}<R_{1}\right\} \\
& =1-\operatorname{Pr}\left\{\left[R_{1-x_{2}}^{(\varphi)}-R_{3-x_{2}}^{(\varphi)}\right]^{+} \geq R_{2},\left[R_{1-x_{1}}^{(\varphi)}-R_{3-x_{1}}^{(\varphi)}\right]^{+} \geq R_{1}\right\} \tag{7.48}
\end{align*}
$$

Theorem 3: It is a challenge to solve (7.48). However, the dissertation deploys a min-rate framework. Hence, the SOP performance at device $D_{1}$ occurs when the minimum of the secrecy rate given by (7.16), where $i=\{2,1\}$, cannot reach the data rate threshold $R$. The SOP at device $D_{1}$ is therefore expressed as:

$$
\begin{equation*}
S O P_{1}^{(\varphi)}=\operatorname{Pr}\left\{\left[R_{1-x_{1}}^{(\varphi)}-R_{3-x_{1}}^{(\varphi)}\right]^{+} \vee\left[R_{1-x_{2}}^{(\varphi)}-R_{3-x_{2}}^{(\varphi)}\right]^{+}<R\right\} \tag{7.49}
\end{equation*}
$$

I obtain SOP performance at device $D_{1}$ in HD mode as follows:

$$
\begin{align*}
& S O P_{1}^{(H D)}=1-\left\{\frac { \alpha _ { 2 } \psi \pi } { 2 K \xi ^ { ( H D ) } \rho \sigma _ { 3 } } \sum _ { k = 1 } ^ { K } \left(\frac{\sqrt{1-(2 \Omega-1)^{2}}}{\left(\alpha_{2}-\alpha_{1} \psi \Omega\right)^{2}}\right.\right. \\
& \times \exp \left(-\frac{\psi \Omega}{\xi^{(H D)}\left(\alpha_{2}-\alpha_{1} \psi \Omega\right) \rho \sigma_{3}}\right) \\
& \left.\times \exp \left(-\frac{\tilde{\gamma}_{2}^{(H D)} \psi \Omega-1}{\xi^{(H D)}\left(\alpha_{2}-\alpha_{1}\left(\tilde{\gamma}_{2}^{(H D)} \Omega-1\right)\right) \rho \sigma_{1}}\right)\right) \\
& \left.\wedge \frac{\sigma_{1}}{\sigma_{1}+\tilde{\gamma}_{1}^{(H D)} \sigma_{3}} \exp \left(-\frac{\gamma_{1}^{(H D)}}{\xi^{(H D)} \alpha_{1} \rho \sigma_{1}}\right)\right\} \tag{7.50}
\end{align*}
$$

where $K$ is the trade off between accuracy and processing time, $\Omega=\frac{1}{2}\left(\cos \left(\frac{2 k-1}{2 K} \pi\right)+1\right)$, and $\psi=\frac{1}{\alpha_{1} \tilde{\gamma}_{2}^{(H D)}}-1<\frac{\alpha_{2}}{\alpha_{1}}$, and $\tilde{\gamma}_{2}^{(H D)}=\gamma_{2}^{(H D)}+1$.

SOP performance at device $D_{1}$ in FD mode is expressed in closed form as follows:

$$
\begin{align*}
S O P_{1}^{(F D)} & =1-\left\{\left(\frac{\alpha_{2} \delta \pi}{2 K \xi^{(F D)} \rho \sigma_{3}+\eta^{2} \varepsilon^{(F D)} \varpi \tilde{\gamma}_{2}^{(F D)}}\right.\right. \\
& \times \sum_{k=1}^{K}\left(\frac{\sqrt{1-(2 \Omega-1)^{2}}}{\left(\alpha_{2}-\alpha_{1} \delta \Omega\right)^{2}+\eta^{2} \varepsilon^{(F D)} \varpi \tilde{\gamma}_{2}^{(F D)}} \exp \left(-\frac{\tilde{\gamma}_{2}^{(F D)} \delta \Omega-1}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \delta \Omega\right) \rho \sigma_{3}}\right)\right. \\
& \left.\left.\times \exp \left(-\frac{\delta \Omega}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1}\left(\tilde{\gamma}_{2}^{(F D)} \Omega-1\right)\right) \rho \sigma_{3}}\right)\right)\right) \\
& \wedge-\frac{1}{\eta^{2} \varepsilon^{(F D)} \varpi \tilde{\gamma}_{1}^{(F D)} \sigma_{3}} \exp \left(-\frac{\gamma_{1}^{(F D)}}{\xi^{(F D)} \alpha_{1} \rho \sigma_{1}}\right) \\
& \times\left(\exp \left(-\frac{\left(\xi^{(F D)} \alpha_{1}+\eta^{2} \varepsilon^{(F D)} \varpi \gamma_{1}^{(F D)}\right) \chi}{\xi^{(F D)} \alpha_{1} \eta^{2} \varepsilon^{(F D)} \varpi \gamma_{1}^{(F D)} \rho \sigma_{1} \sigma_{3}}\right)\right. \\
& \times\left(\operatorname { l i m } _ { \Gamma \rightarrow \infty } \left(\frac{\left.\left.\sum_{\gamma=1}^{\Gamma} \frac{1}{\gamma}-\ln \Gamma\right)-\ln \frac{\eta^{2} \varepsilon^{(F D)} \varpi \tilde{\gamma}_{1}^{(F D)}}{\xi^{(F D)} \alpha_{1}+\eta^{2} \varepsilon^{(F D)} \varpi \gamma_{1}^{(F D)}}+\ln \frac{\xi^{(F D)} \alpha_{1} \rho \sigma_{1} \sigma_{3}}{\xi}\right)}{\chi}\right.\right. \\
& \left.\left.-U\left\{1 ; 1 ; \frac{\left(\xi^{(F D)} \alpha_{1}+\eta^{2} \varepsilon^{(F D)} \varpi \gamma_{1}^{(F D)}\right) \chi}{\xi^{(F D)} \alpha_{1} \eta^{2} \varepsilon^{(F D)} \varpi \gamma_{1}^{(F D)} \rho \sigma_{1} \sigma_{3}}\right\}\right)\right\}, \tag{7.51}
\end{align*}
$$

where $\delta=\frac{1}{\tilde{\gamma}_{2}^{(F D)}\left(\alpha_{1}+\eta^{2} \varepsilon^{(F D)} \varpi\right)}-1<\frac{\alpha_{2}}{\alpha_{1}}, \chi=\sigma_{1}+\tilde{\gamma}_{1}^{(F D)} \sigma_{3}$, and $U\{. ; . ;$.$\} is Kummer's confluent$ hypergeometric function.

See Appendix 7.5.4 for proof.
The SOP events at far device $D_{2}$ occur in either of two cases:

- The instantaneous bit rate threshold obtained at near device $D_{1}$ when it decodes data symbol $x_{2}$ given by (7.5), where device $D_{1}$ functions in HD mode or (7.8) where device $D_{1}$ functions in FD mode, cannot reach the bit rate threshold $R_{2}$ of device $D_{2}$.
- The instantaneous secrecy bit rate threshold at near device $D_{1}$ when it decodes data symbol $x_{2}$ may reach the bit rate threshold $R_{2}$. However, the instantaneous secrecy bit rate threshold obtained at device $D_{2}$ when it decodes its own data symbol $x_{2}$ given by (7.16) cannot reach the bit rate threshold $R_{2}$.

The SOP at far device $D_{2}$ is therefore expressed as:

$$
\begin{align*}
\operatorname{SOP}_{2}^{(\varphi)} & =\operatorname{Pr}\left\{R_{1-x_{2}}^{(\varphi)}<R_{2}\right\}+\operatorname{Pr}\left\{R_{1-x_{2}}^{(\varphi)} \geq R_{2},\left[R_{2-x_{2}}^{(\varphi)}-R_{4-x_{2}}^{(\varphi)}\right]^{+}<R_{2}\right\} \\
& =1-\operatorname{Pr}\left\{R_{1-x_{2}}^{(\varphi)} \geq R_{2},\left[R_{i-x_{2}}^{(\varphi)}-R_{(i+2)-x_{2}}^{(\varphi)}\right]^{+} \geq R_{2}\right\} \tag{7.52}
\end{align*}
$$

where $i=\{2,1\}$.

However, the dissertation deploys a min-rate framework to obtain the OP at far device $D_{2}$ given by Lemma 2.

Theorem 4: By applying a min-rate framework, the SOP at far device $D_{2}$ cooperating with near device $D_{1}$ which functions in HD or FD mode and without eavesdropper $E_{1}$ will occur if the minimum between $R_{1-x_{2}}^{(\varphi)}$ and $\mathcal{R}_{2}^{(\varphi)}$ cannot reach the data rate threshold of device $D_{2}$.

The SOP at device $D_{2}$ is therefore expressed as:

$$
\begin{equation*}
S O P_{2}^{(\varphi)}=1-\operatorname{Pr}\left\{\min \left\{R_{1-x_{2}}^{(\varphi)},\left[R_{2-x_{2}}^{(\varphi)}-R_{4-x_{2}}^{(\varphi)}\right]^{+}\right\} \geq R\right\} \tag{7.53}
\end{equation*}
$$

I obtain the SOP at far device $D_{2}$ in closed form as follows:

$$
\begin{align*}
S O P_{2}^{(H D)}= & 1-\exp \left(-\frac{\gamma_{2}^{(H D)}}{\xi^{(H D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(H D)}\right) \rho \sigma_{1}}\right) \\
& +\left[\exp \left(-\frac{\gamma_{2}^{(H D)}}{\xi^{(H D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(H D)}\right) \rho \sigma_{1}}\right)-\frac{2 \sigma_{2} B_{1}\left(2 \sqrt{\frac{\eta^{2} \varepsilon^{(H D)} \rho \sigma_{1} \sigma_{2}}{\gamma_{2}^{(H D)}}}\right)}{\sqrt{\frac{\eta^{2} \varepsilon^{(H D)} \rho \sigma_{1} \sigma_{2}}{\gamma_{2}^{(H D)}}}\left(\sigma_{2}+\sigma_{4}+\gamma_{2}^{(H D)} \sigma_{4}\right)}\right]^{+} \tag{7.54}
\end{align*}
$$

and

$$
\begin{align*}
S O P_{2}^{(F D)} & =1-\exp \left(-\frac{\gamma_{2}^{(F D)}}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right) \rho \sigma_{1}}\right) \frac{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)+\eta^{2} \varpi \varepsilon^{(F D)} \gamma_{2}^{(F D)}} \\
& +\left[\exp \left(-\frac{\gamma_{2}^{(F D)}}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right) \rho \sigma_{1}}\right) \frac{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)+\eta^{2} \varpi \varepsilon^{(F D)} \gamma_{2}^{(F D)}}\right. \\
& \left.-\frac{2 \sigma_{2} B_{1}\left(2 \sqrt{\frac{\eta^{2} \varepsilon^{(F D)} \rho \sigma_{1} \sigma_{2}}{\gamma_{2}^{(F D)}}}\right)}{\sqrt{\frac{\eta^{2} \varepsilon^{(F D)} \rho \sigma_{1} \sigma_{2}}{\gamma_{2}^{(F D)}}}\left(\sigma_{2}+\sigma_{4}+\gamma_{2}^{(F D)} \sigma_{4}\right)}\right] \tag{7.55}
\end{align*}
$$

See Appendix 7.5.5 for proof.
Note, that I analyzed the SOP at device $D_{2}$ given by (7.54) and (7.55) with only eavesdropper $E_{2}$ without considering the effect from eavesdropper $E_{1}$. However, in a real IoT network, eavesdroppers may be allocated anywhere in the network's area of coverage. Here, I assume multiple eavesdroppers. The eavesdropper $E_{1}$ is positioned near device $D_{1}$, and eavesdropper $E_{2}$ is positioned near device $D_{2}$. From (7.52), the SOP at device $D_{2}$ in HD/FD IoT networks with multiple eavesdroppers $E_{1}$ and $E_{2}$ may be rewritten as $S O P_{2}^{(\varphi)}=1$ -$\operatorname{Pr}\left\{R_{1-x_{2}}^{(\varphi)}<R\right\}+\operatorname{Pr}\left\{R_{1-x_{2}}^{(\varphi)} \geq R, R_{2}^{(\varphi)}<R\right\}$. Finally, we obtain the SOP at device $D_{2}$ in HD and FD scenarios with multiple eavesdroppers as $S O P_{2}^{(H D)}=1-Q_{8}+\left[Q_{8}-Q_{11}^{(H D)}\right]^{+}$and $S O P_{2}^{(F D)}=1-Q_{10}+\left[Q_{10}-Q_{11}^{(F D)}\right]^{+}$. It is not necessary to present the expressions $Q_{8}, Q_{10}$ and $Q_{11}^{(\varphi)}$ again since they were given by $(7.91),(7.94)$ and (7.96), respectively.

### 7.2.3 Two-stage power resource allocation exploited to enhance system performance

The first-stage is to deliver the PS factor. In [77, 95, 96], the authors investigated network models with a fixed PS factor, i.e., $\varepsilon=0.4$. However, I considered how the PS factor affected system performance. By observation of (7.1), (7.5) and (7.9), I then exploited two interesting cases. The first SWIPT case has $\varepsilon=0$. All power resources $P$ at source $S$ are only used to transmit the signals to the near device $D_{1}$. In this case, the near device $D_{1}$ receives the signal given by (7.1) or (7.5) in the best received signal, but leads to the EH at the near device $D_{1}$ given by (7.56), which tends to zero. Therefore, the near device $D_{1}$ has no power resources remaining to forward signals. As a result, the OP at the far device $D_{2}$ always tends to one absolutely. The second SWIPT case has $\varepsilon=1$. All power resources $P$ at source $S$ are only used to transmit wireless power for EH at the near device $D_{1}$. As a result, the OP performances at devices $D_{1}$ and $D_{2}$ always tend to one absolutely.

From (7.1) or (7.5), the EH at the near device $D_{1}$ is expressed as:

$$
\begin{equation*}
E H^{(\varphi)}=\eta h_{1} \sqrt{\varepsilon^{(\varphi)} P} \tag{7.56}
\end{equation*}
$$

where $\eta$ is the collect factor such that $0 \leq \eta \leq 1$ [69]. I assume that EH is not affected by the limitations of electronic circuitry and battery capacity, i.e., $(\eta=1)$ as in $[34,69]$. It is worth highlighting why I selected the PS protocol and how my PS diagrams differ from the diagrams in major studies [67, 77]. Although based on multi-relays, the system models in [67, Figure 1] and [77, Figures 1a] serve only one destination. The system model in my dissertation (Fig. 7.1a, 7.2a) assumes it serves multiple devices. If I deploy a TS transmission time block structure [67, Figure 2] or [77, Figures 1b and 3b], it may lead to increased delay times in devices which need to be served simultaneously. The three-layer PS diagram (Fig. 7.1b) requires two time slots to finish a transmission block. The FTS is used to adopt SWIPT from source $S$ to device $D_{1}$. The top layer in Figure 7.1b is used for transmitting energy at source $S$, and the second layer is used for transmitting information at source $S$ to device $D_{1}$. Devices need to be served simultaneously to reduce latency. Therefore, the device information is superimposed by sharing different PA factors, where $\alpha_{2}>\alpha_{1},\left(1-\varepsilon^{(\varphi)}\right) \alpha_{2} P+\left(1-\varepsilon^{(\varphi)}\right) \alpha_{1} P=\left(1-\varepsilon^{(\varphi)}\right) P$, and $\left(1-\varepsilon^{(\varphi)}\right) P+\varepsilon^{(\varphi)} P=P$. Finally, as shown in the bottom layer in Figure 7.1 b , the signal from device $D_{1}$ is forwarded to device $D_{2}$ after harvesting energy using the DF protocol.

Proposition 1: Let us constrain the SINR when the near device $D_{1}$ decodes message $x_{1}$ given by (7.3) and the SINR when the far device $D_{2}$ decodes message $x_{2}$ given by (7.10), approximately as follows:

$$
\begin{equation*}
\gamma_{1-x_{1}}^{(H D)}=\gamma_{2-x_{2}}^{(H D)} \tag{7.57}
\end{equation*}
$$

In previous studies [57, 97] and [TTNam04], the authors investigated C-NOMA networks which adopt the AF protocol at the relay. Two AF techniques can be used: AF with VG/FG. The amplify factors with VG had instantaneous CSI $|h|^{2}$. The amplify factors with FG had
expected channel gains $E\left\{|h|^{2}\right\}$ given by [57, Eq. (7)], [97, Eq. (7)] and [TTNam04, Eq. (9a)]. Note that the present work assumes a source fully owned by CSI. Therefore, we substitute the expected channel gain $\sigma_{1}$ and $\sigma_{2}$ into (7.57). I determined the PS factor $\varepsilon^{(H D)}$ for expressions (7.3) and (7.10) equally. By substituting the expected channel gains $\sigma_{1}=E\left\{\left|h_{1}\right|^{2}\right\}$ and $\sigma_{2}=$ $E\left\{\left|h_{2}\right|^{2}\right\}$ into (7.57), we obtain the PS factor $\varepsilon^{(H D)}$ for an HD scenario under constraint given by (7.57) as follows:

$$
\begin{equation*}
\varepsilon^{(H D)}=\frac{\alpha_{1}}{\sigma_{2}+\alpha_{1}} \tag{7.58}
\end{equation*}
$$

Let us take advantage of the fact that $\varepsilon^{(H D)}$ is always greater than half and will tend to one if device $D_{2}$ is far away from $D_{1}$, i.e., $\varepsilon^{(H D)}>0.5$ and $\varepsilon^{(H D)} \rightarrow 1$, whereas $\sigma_{2} \rightarrow 0$. By substituting (7.58) into (7.1), we obtain the received signal at device $D_{1}$, which adopts the HD protocol. To reach ultra-low latency, the dissertation applies the PS framework shown in Figure 7.2 b . However, when we substitute (7.58) into (7.5), we always obtain $y_{1}^{(F D)}<y_{1}^{(H D)}$ because of the effect of LI. Therefore, we constrain the PS factor such that $0.5 \leq \varepsilon^{(F D)} \leq \varepsilon^{(H D)}<1$. I therefore propose the PS factor, where $D_{1}$ adopts the FD protocol, as follows:

$$
\begin{align*}
& \mathcal{A} \leftarrow \operatorname{int}\left\{\sigma_{2} / \sigma_{1}\right\} \\
& \varepsilon^{(F D)} \leftarrow \varepsilon^{(H D)} \\
& \underset{l \rightarrow \mathcal{A}}{\operatorname{Loop}}\left\{\varepsilon^{(F D)} \leftarrow \frac{l \varepsilon^{(F D)}+0.5}{l+1}\right\}, \tag{7.59}
\end{align*}
$$

where the $\operatorname{int}\{$.$\} function returns an integer value and \mathcal{A}$ is the adjusted factor. It is important to note that the adjusted factor $\mathcal{A}$ is the fraction of expected channel gain $\sigma_{2}$ of the expected channel gain $\sigma_{1}$. To illustrate, this means that the distance $D_{1} \rightarrow D_{2}$ is less than the distance $S \rightarrow D_{1}$ and that the PS factor for the FD scenario is significantly reduced, i.e., as the distances $d_{2} \ll d_{1}$, then $\sigma_{2} \gg \sigma_{1}$ as a result, and the PS factor $\varepsilon^{(F D)}$ will be adjusted and tend to half. In addition, if distance $D_{1} \rightarrow D_{2}$ is greater than the distance $S \rightarrow D_{1}$, then $d_{2}>d_{1}$ and $\sigma_{2}<\sigma_{1}$ as a result, and the PS factor $\varepsilon^{(F D)}$ will be adjusted and tend to $\varepsilon^{(H D)}$.

Proposition 2: In previous studies, the authors applied fixed PA factors [57, 92, 96]. In other studies, the authors adopted adaptive PA factors for multiple access based on the number of devices [6] or expected channel gain and the sum of the expected channel gain ratio [TTNam06]. In the second stage of power resource allocation, the dissertation proposes adaptive PA factors for multiple access IoT networks based on the density distance of the data symbol propagated from the source to the destination. Therefore, the data symbol of the farthest device, which was propagated with the farthest distance and path-loss exponent, is allocated the largest PA factor as follows:

$$
\begin{equation*}
\alpha_{1}=\frac{d_{1}^{\omega}}{d_{1}^{\omega}+\left(d_{1}+d_{2}\right)^{\omega}} \tag{7.60}
\end{equation*}
$$

and

$$
\begin{equation*}
\alpha_{2}=\frac{\left(d_{1}+d_{2}\right)^{\omega}}{d_{1}^{\omega}+\left(d_{1}+d_{2}\right)^{\omega}} . \tag{7.61}
\end{equation*}
$$

I propose Algorithm 7.1 for two-stage power resource allocation.

```
Algorithm 7.1 Two-stage power resource allocation
Output: PA factors and PS factors.
    Calculate \(\alpha_{1}=\frac{d_{1}{ }^{\omega}}{d_{1}{ }^{\omega}+\left(d_{1}+d_{2}\right)^{\omega}}\);
    Calculate \(\alpha_{2}=\frac{\left(d_{1}+d_{2}\right)^{\omega}}{d_{1}{ }^{\omega}+\left(d_{1}+d_{2}\right)^{\omega}}\) or \(1-\alpha_{1}\);
    Calculate \(\varepsilon^{(H D)}=\alpha_{1} /\left(\sigma_{2}+\alpha_{1}\right)\);
    \(\mathcal{A}=\operatorname{int}\left\{\sigma_{2} / \sigma_{1}\right\} ;\)
    Initialize \(\varepsilon^{(F D)}=\varepsilon^{(H D)}\);
    for \(l=1\) to \(\mathcal{A}\) do
        \(\varepsilon^{(F D)}=\frac{l \varepsilon^{(F D)}+0.5}{l+1}\)
    end for
    return \(\alpha_{1}, \alpha_{2}, \varepsilon^{(H D)}, \varepsilon^{(F D) ;}\)
```

Input: Initialize the parameters as distances $d_{1}=S \rightarrow D_{1}$ and $d_{2}=D_{1} \rightarrow D_{2}$, path-loss
exponent $\omega$, calculate expected channel gains $\sigma_{1}=d_{1}^{-\omega}$ and $\sigma_{2}=d_{2}^{-\omega}$

To confirm the theoretical results, I propose Monte Carlo simulations according to Algorithm 7.2, which examines the OP performance, and Algorithm 7.3, which examines the SOP performance at the devices.

Lei et al. [32, Eq. (17)] obtained the OP performance of a two-device downlink NOMA system. Generally, the OP system performance of two-device in an HD/FD-IoT model is the mean of the OP performance at the devices. However, the dissertation evaluates the OP performance of an IoT system based on the worst OP performance of a device among the OP performances of the devices as follows:

$$
\begin{equation*}
\mathcal{O}_{s y s}^{(\varphi)}=\max \left\{\mathcal{O}_{1}^{(\varphi)}, \mathcal{O}_{2}^{(\varphi)}\right\} \tag{7.62}
\end{equation*}
$$

where $\mathcal{O}_{i}^{(\varphi)}=\left\{O P_{i}^{(\varphi)}\right.$, MOP $_{i}^{(\varphi)}$, AOP $\left._{i}^{(\varphi)}\right\}$ for $i=\{2,1\}$.

### 7.2.4 System throughput performance

From the OP results obtained at the near device $D_{1}$ and the far device $D_{2}$, we obtain the system throughput performance of the two-device system as follows:

$$
\begin{equation*}
T^{(\varphi)}=\left(1-\mathcal{O}_{1}^{(\varphi)}\right) R_{1}+\left(1-\mathcal{O}_{2}^{(\varphi)}\right) R_{2} \tag{7.63}
\end{equation*}
$$

## Algorithm 7.2 OP and min-rate OP simulations

Input: Initialize the parameters as predefined data rates $R=R_{1}=R_{2} b p s / H z$, $\operatorname{SNRs} \rho$ in dB, expected channel gains $\sigma_{1}, \sigma_{2}, \sigma_{L I}$ with contributing LI factor $\varpi$, and randomly generate $1 e 6$ samples over each channel $h_{1}, h_{2}$ or $h_{L I}$. PA and PS factors are given by Algorithm 7.1.
Output: OP and min-rate OP simulation results at the devices.
Calculate $1 e 6$ SINR $\gamma_{n-x_{i}}^{(\varphi)}$, where $n=\{1,2\}, i=\{2,1\}$, and $\varphi=\{H D, F D\}$, at devices given by (7.2), (7.3), (7.6), (7.7) or (7.10) at SNR $\rho$ in the SNR range;
Calculate $1 e 6$ instantaneous data rate $R_{n-x_{i}}^{(\varphi)}$, where $n$ is a device in a number of devices, $i$ is a data symbol in a number of data symbols, and $\varphi=\{H D, F D\}$, at devices given by (7.4), (7.8) or (7.11);

Initialize Count $t_{n}^{(\varphi)}=0$ and $\operatorname{MCount}_{n}^{(\varphi)}=0$, where $n=\{1,2\}, i=\{2,1\}$ and $\varphi=$ $\{H D, F D\}$ at a SNR $\rho$ in the SNR range;
$L O O P=1 e 6 ;$
for $i=1$ to $L O O P$ do
// Count successful rate at $D_{1}$
if $\left(R_{1-x_{2}}^{(\varphi)} \geq R_{2} \& R_{1-x_{1}}^{(\varphi)} \geq R_{1}\right)$ then
$\operatorname{Count}_{1-x_{2}}^{(\varphi)} \leftarrow \operatorname{Count}_{1-x_{2}}^{(\varphi)}+1 ;$
end if
// Count successful rate at $D_{2}$
if $\left(R_{1-x_{2}}^{(\varphi)} \geq R_{2} \& R_{2-x_{2}}^{(\varphi)} \geq R_{2}\right)$ then
Count $_{2-x_{2}}^{(\varphi)} \leftarrow$ Count $_{2-x_{2}}^{(\varphi)}+1 ;$
end if
// Count successful min-rate at $D_{1}$
if $\left(\min \left\{R_{1-x_{1}}^{(\varphi)}, R_{1-x_{2}}^{(\varphi)}\right\} \geq R\right)$ then
$\operatorname{MCount}_{1}^{(\varphi)} \leftarrow \operatorname{MCount}_{1}^{(\varphi)}+1 ;$
end if
// Count successful min-rate at $D_{2}$
if $\left(\min \left\{R_{1-x_{2}}^{(\varphi)}, R_{2-x_{2}}^{(\varphi)}\right\} \geq R\right)$ then
$M C o u n t{ }_{2}^{(\varphi)} \leftarrow M \operatorname{Count}_{2}^{(\varphi)}+1 ;$
end if
end for
return
$O P_{1}^{(\varphi)} \leftarrow 1-\frac{\operatorname{Count}_{1}^{(\varphi)}}{L O O P} ;$
$O P_{2}^{(\varphi)} \leftarrow 1-\frac{\text { Count }_{2}^{(\varphi)}}{\text { LOOP }}$;
$M O P_{1}^{(\varphi)} \leftarrow 1-\frac{\operatorname{MCount}_{1}^{(\varphi)}}{\operatorname{LOOP}} ;$
$\operatorname{MOP}_{2}^{(\varphi)} \leftarrow 1-\frac{\operatorname{MCount}_{2}^{(\varphi)}}{\operatorname{LOOP} ;}$

## Algorithm 7.3 SOP and min-rate SOP simulations

Input: Initialize the parameters as expected channel gains $\sigma_{3}, \sigma_{4}$, randomly generate $1 e 6$ samples on each channel $h_{3}, h_{4}$ distributed by Rayleigh distributions and the variables given by Algorithms 7.1 and 7.2.
Output: SOP and min-rate SOP at the devices.
: Calculate $1 e 6$ SINRs $\gamma_{m-x_{i}}^{(\varphi)}$, where $m$ is a device or an eavesdropper with $m=\{1,2,3,4\}, i$ is a data symbol, where $i=\{2,1\}$ and $\varphi=\{H D, F D\}$, at the devices, given by (7.2), (7.3), $(7.6),(7.7),(7.10),(7.13),(7.14)$ and (7.18) at a SNR $\rho$ in the SNR range;
Calculate $1 e 6$ instantaneous data rate $R_{m-x_{i}}^{(\varphi)}$ at the devices, given by (7.4), (7.8) or (7.11);
Initialize Count ${ }_{m-x_{i}}^{(\varphi)}=0$;
$L O O P=1 e 6 ;$
for $i=1$ to $L O O P$ do
// Count successful secrecy rate at $D_{1}$ if $\left(\max \left\{R_{1-x_{1}}^{(\varphi)}-R_{3-x_{1}}^{(\varphi)}, 0\right\} \geq R_{1}\right)$ then

SCount $_{1-x_{1}}^{(\varphi)} \leftarrow$ SCount $_{1-x_{1}}^{(\varphi)}+1 ;$
end if
if $\left(\max \left\{R_{1-x_{2}}^{(\varphi)}-R_{3-x_{2}}^{(\varphi)}, 0\right\} \geq R_{2}\right)$ then
SCount $_{1-x_{2}}^{(\varphi)} \leftarrow$ SCount $_{1-x_{2}}^{(\varphi)}+1$;
end if
// Count successful secrecy rate at $D_{2}$
if $\left(\max \left\{R_{2-x_{2}}^{(\varphi)}-R_{4-x_{2}}^{(\varphi)}, 0\right\} \geq R_{2}\right)$ then
SCount $_{2-x_{2}}^{(\varphi)} \leftarrow$ SCount $_{2-x_{2}}^{(\varphi)}+1 ;$
end if
end for
return
$S O P_{1}^{(\varphi)} \leftarrow 1-\frac{\text { SCount }_{1-x_{2}}^{(\varphi)}}{\text { LOOP }} \times \frac{\text { SCount }_{1-x_{1}}^{(\varphi)}}{\text { LOOP }} ;$
$S O P_{2}^{(\varphi)} \leftarrow 1-\frac{\text { SCount }_{1-x_{2}}^{(\varphi)}}{\text { LOOP }} \times \frac{\text { SCount }_{2-x_{2}}^{(\varphi)}}{\text { LOOP }} ;$
Min-rate $S O P_{1}^{(\varphi)} \leftarrow 1-\frac{\text { SCount }_{1-x_{2}}^{(\varphi)}}{L O O P} \wedge \frac{\text { SCount }_{1-x_{1}}^{(\varphi)}}{L O O P}$;
Min-rate $S O P_{2}^{(\varphi)} \leftarrow 1-\frac{\text { SCount }_{1-x_{2}}^{(\varphi)}}{L O O P} \wedge \frac{S \text { Count }_{2-x_{2}}^{(\varphi)}}{L O O P}$;

### 7.2.5 QoS fairness

This subsection addresses the third aim and investigates Jain's fairness index based on the reachable throughput at the devices as follows:

$$
\begin{equation*}
J^{(\varphi)}=\frac{\left(\mathcal{O}_{1}^{(\varphi)}+\mathcal{O}_{2}^{(\varphi)}\right)^{2}}{2\left(\left(\mathcal{O}_{1}^{(\varphi)}\right)^{2}+\left(\mathcal{O}_{2}^{(\varphi)}\right)^{2}\right)} \tag{7.64}
\end{equation*}
$$

where Jain's fairness index $\mathcal{J}^{(\varphi)} \rightarrow 1$ and the devices are served with the same QoS in OP performance. However, whereas Jain's fairness index $J^{(\varphi)} \rightarrow 0$, it indicates that the devices are not served with the fairness QoS in OP performance. Therefore, I propose a sum of the cumulative flux deviation of device throughput from the mean flux throughput achieved at all devices, as follows:

$$
\begin{equation*}
\mathcal{T}^{(\varphi)}=\sum_{n=1}^{\mathcal{N}}\left|\left(1-\mathcal{O}_{n}^{(\varphi)}\right) R_{n}-\frac{1}{\mathcal{N}} \sum_{j=1}^{\mathcal{N}}\left(1-\mathcal{O}_{j}^{(\varphi)}\right) R_{j}\right| \tag{7.65}
\end{equation*}
$$

where $\mathcal{N}$ is the number of networked IoT devices.

### 7.3 Numerical Results and Discussion

The results presented in this section are true and accurate to the best of my knowledge, without any duplication from previous studies. In this study, I investigate the IoT network depicted in Figures 7.1, 7.2 and 7.3, containing HD-IoT and FD-IoT networks. The distances $S \rightarrow D_{1}$ denoted by $d_{1}, S \rightarrow E_{1}$ denoted by $d_{3}, D_{1} \rightarrow D_{2}$ denoted by $d_{2}$, and $D_{1} \rightarrow E_{2}$ denoted by $d_{4}$, are $d_{1}=d_{3}=10 \mathrm{~m}$ and $d_{2}=d_{4}=2 \mathrm{~m}$. The path-loss exponent factor is an indoor environment $\omega=4$. The expected channel gains over Rayleigh distributions from source $S$ to the near device $D_{1}$ and eavesdropper $E_{1}$ are $\sigma_{1}=\sigma_{3}=0.0004$, and from device $D_{1}$ to device $D_{2}$ and eavesdropper $E_{2} \sigma_{2}=\sigma_{4}=0.0625$. The LI factor is $\varpi=0.01$ and SNRs $\rho=\{10, \ldots, 40\} d B$. The energy is fully harvested without the effect of limitations in the energy collection circuitry and battery capacity, and thus, $\eta=1$ for simplicity [69]. The PA factors for the near device $D_{1}$ and far device $D_{2}$, given by (7.60) and (7.61), respectively, are $\alpha_{1}=0.3254$ and $\alpha_{2}=0.6746$. The devices $D_{1}$ and $D_{2}$ require the same data rate threshold such that $R_{1}=R_{2}=0.1 \mathrm{bps} / \mathrm{Hz}$.

I investigated three SWIPT cases:

- The first SWIPT case has a fixed PS factor $\varepsilon=0.4$, i.e., $40 \%$ of the power domain is harvested at the near device $D_{1}$.
- The second SWIPT case has a PS factor $\varepsilon^{(H D)}=0.8389$, given by (7.58). This means that $83.89 \%$ of the power domain $P$ is used to transmit energy to the near device $D_{1}$ for EH.
- The third SWIPT case has PS factor $\varepsilon^{(F D)}=0.5005$, given by (7.59). This means that $50.05 \%$ of the power domain $P$ is used to transmit energy to the near device $D_{1}$ for EH.


Figure 7.4: Scheme of the work in this aim.

Table 7: Table of parameters.

| Number of devices | 2 |
| :--- | :--- |
| Number of eavesdroppers | 2 |
| Distances $d_{1}=d_{3}$ | 10 m |
| Distances $d_{2}=d_{4}$ | 2 m |
| Path-loss exponent $\omega$ | 4 |
| Channel gains $\sigma_{1}=\sigma_{3}$ | 0.0004 |
| Channel gains $\sigma_{2}=\sigma_{4}$ | 0.0625 |
| LI coefficient $\varpi$ | 0.01 |
| Bit rate thresholds $R_{1}=R_{2}$ | $0.1 \mathrm{bps} / \mathrm{Hz}$ |
| Collection factor $\eta$ | 1 |
| Fixed PS factor $\varepsilon$ | 0.4 |
| PS factor for HD scenario $\varepsilon^{(H D)}$ | 0.8389 |
| PS factor for FD scenario $\varepsilon^{(F D)}$ | 0.5005 |
| SNR $\rho$ | $\{10, \ldots, 40\} d B$ |

Figure 7.4 briefly depicts the work of this aim.
In this study, I use various indicators and lines to plot the analysis (Ana) results and Monte Carlo simulation (Sim) results.

### 7.3.1 OP performance

7.3.1.1 Effect of the PS factor on OP performance The first aim of this dissertation was to investigate the effect of the PS factor $\varepsilon$ on system performance. Figures 7.5 a and 7.5 b depict OP performance at devices $D_{1}$ and $D_{2}$ with solid and dashed grids, respectively, where $D_{1}$ adopted either the HD or FD mode. The PS factors have two special cases: $\varepsilon^{(\varphi)}=0$ and $\varepsilon^{(\varphi)}=1$. Where $\varepsilon^{(\varphi)}=0$, the received signals at device $D_{1}$ given by (7.1) and (7.5) reached maximum volume, which indicates the best OP performance at $D_{1}$. However, the OP performance obtained at device $D_{2}$ always tended to one since the EH given by (7.56) at device $D_{1}$ tended to zero. As a result, device $D_{1}$ had no power to forward the signal to device $D_{2}$. Where $\varepsilon^{(\varphi)}=1$, the received signals given by (7.1) and (7.5) reached minimum volume, and EH given by (7.56) at device $D_{1}$ reached maximum volume. Therefore, no information was available to forward to $D_{2}$. As a result, both devices $D_{1}$ and $D_{2}$ always achieved OP performance which tended to one at all SNR $\rho$. We can observe that the OP performance at the devices was affected by the PS factors. The main aim of this dissertation was to exploit suitable PS factors to guarantee QoS fairness at the devices.
7.3.1.2 OP performance at the devices in the HD-IoT network model In the HD scenario, I investigated OP performance at devices $D_{1}$ and $D_{2}$ (Fig. 7.6a and 7.6b) for two PS cases: a fixed PS factor $\varepsilon=0.4$ as in [95] and a PS factor $\varepsilon^{(H D)}$ given by (7.58). We can observe in Figure 7.6a that the OP performance at device $D_{1}$ with fixed PS factor $\varepsilon=0.4$ was better than the OP performance with PS factor $\varepsilon^{(H D)}=0.8389$ given by (7.58) since the received signal $y_{1}^{(H D, \varepsilon=0.4)}$ was better than $y_{1}^{(H D, \varepsilon=0.8389)}$. However, it is important to observe in Figure 7.6b that the OP performance at device $D_{2}$ with PS factor $\varepsilon=0.8389$ was better than the OP performance with fixed PS factor $\varepsilon=0.4$ since device $D_{1}$ harvested more energy to forward the signal. These results verify that the IoT network according to my dissertation show improved service for the far user.

The analysis (Ana) OP results (larger-markers) achieved at $D_{1}$ and $D_{2}$ in an HD-IoT network were obtained from (7.24) and (7.40), respectively, and were verified by Monte Carlo simulation (Sim) results (solid-lines) obtained from (7.23) and (7.39), where $\varphi=H D$. I also applied minrate frameworks to investigate OP performances at the devices. The theoretical min-rate OP results (smaller-markers) achieved at devices $D_{1}$ and $D_{2}$ were obtained from (7.29) or (7.30) and (7.43), respectively. The theoretical min-rate OP performances were verified by min-rate Algorithm 7.2 results (dashed-lines) at devices $D_{1}$ from (7.27) or (7.28) and at $D_{2}$ from (7.42), where $\varphi=H D$. The approximate min-rate OP results (crossed-dotted lines) achieved at devices $D_{1}$ and $D_{2}$ were obtained from (7.33) or (7.34) and (7.45), respectively. We can observe that


Figure 7.5: Investigations of the effect of PS factors on the OP performance of the devices: (a) $D_{1}$ adopts HD mode; (b) $D_{1}$ adopts FD mode.
the approximate min-rate OP results match the theoretical and simulated min-rate OP results precisely, where SNR $\rho \rightarrow \infty$.

In Figure 7.6a, device $D_{1}$ with a fixed PS factor offered better performance with the PS factor in (7.58), in contrast with device $D_{2}$. However, the far device $D_{2}$ with PS factor in (7.58) obtained better performance, as shown in Figure 7.6b. IoT networks must ensure performance for the entire system (both near and far devices). However, it is trade off. If one device obtains better performance, another device obtains worse performance. Therefore, the third contribution in the dissertation is ensuring QoS for both the near and far devices. To prove this aim, I investigated Jain's index fairness in (7.64) and user throughput fairness in (7.65), plotted in Figure 7.9. We can observe that the fairness performance with PS in (7.58) provided the best performance. An investigation of the results showed that both the near and far devices obtained the same QoS. Finally, we may also conclude that the proposed adaptive PS factor serving the far device is better than the fixed PS factor.
7.3.1.3 OP performance at the devices in the FD-IoT network model In this subsection, I investigate the OP performances at devices $D_{1}$ and $D_{2}$, where $D_{1}$ functions in FD mode to reduce latency at device $D_{2}$, in accordance with the second aim. As indicated in the PS diagram in Figure 7.1b, the larger PS factor $\varepsilon$ better serves the far device $D_{2}$ in the HD scenario. However, I adopted an FD relay (Fig. 7.2a) and obtained a resulting PS diagram (Fig. 7.2b). Note that device $D_{1}$ in FD scenario was affected by the LI channel as in (7.5). As a result, the larger PS factor $\varepsilon^{(F D)}$ led to a larger LI. Thus, the SINR given by (7.6) and (7.7), obtained when $D_{1}$ decodes data symbols $x_{2}$ and $x_{1}$, respectively, were less than the SINR given by (7.2) and (7.3) at the same SNR. I therefore adjusted the PS factor $\varepsilon^{(F D)}$ in (7.59) to reduce diffraction at device $D_{1}$ and also to maintain QoS at device $D_{2}$. To illustrate, in the HD scenario, I constrained the SINR $\gamma_{1-x_{1}}^{(H D)}=\gamma_{2-x_{2}}^{(H D)}$ given by (7.57) and exploited the PS allocation $0.5<\varepsilon^{(H D)}<1$. If we reuse the PS factor $\varepsilon^{(H D)}$ in the FD scenario, it can lead to an large effect by the LI channel on OP performance at $D_{1}$. I therefore propose a PS factor which adopts an FD scenario given by (7.59). As a result, we obtain $0.5<\varepsilon^{(F D)}<\varepsilon^{(H D)}<1$. Figures 7.7a and 7.7 b depict OP performance at devices $D_{1}$ and $D_{2}$, respectively, where $D_{1}$ adopts FD mode.

In an HD scenario, the OP performance will tend to zero when SNR $\rho \rightarrow \infty$, as shown in Figure 7.6. Figures 7.7a and 7.7b plot the OP performances at the near and far devices for the FD scenario, where, however, the performances did not change at high SNR. For clarity, we observe equation (7.5), which is the received signal at device $D_{1}$. Device $D_{1}$ not only receives a signal from source $S$ but also receives LI. However, LI refers to the EH expression in (7.56). Therefore, a higher PS factor and higher SNR will lead to higher LI. As a result, OP performance at devices $D_{1}$ and $D_{2}$ will tend to their floor OP results (green dashed-dotted lines) when SNR $\rho \rightarrow \infty$. I exploited the floor OP at device $D_{1}$ given by (7.26), (7.37) or (7.38) and device $D_{2}$ by (7.47).

For a general perspective, I examined the OP performances given by (7.62) on the y-axis at left and throughput performances given by (7.63) on the y-axis at right, where $\varphi=\{H D, F D\}$ (Fig. 7.8). The black-circle markers and dotted-lines plot the best theoretical and simulated


Figure 7.6: OP performance over an HD-IoT network at (a) near device $D_{1}$; (b) far device $D_{2}$.


Figure 7.7: OP performance over an FD-IoT network at (a) near device $D_{1}$; (b) far device $D_{2}$.

OP results of an FD-IoT network model with PS factor $\varepsilon^{(F D)}=0.5005$ given by (7.59) at low SNR, i.e., $\rho \leq 30 d B$. The HD-IoT network model with PS factor $\varepsilon^{\{H D\}}$ given by (7.58) always attained better OP performance than the same scenario with fixed PS factor $\varepsilon=04$. These results verify the efficiency of the hypothesized PS factors for the SWIPT models. However, it is very interesting that the OP results of the HD-IoT scenario with PS factor $\varepsilon^{(H D)}$ obtained better OP performance with fixed PS factor $\varepsilon=0.4$ (left y -axis) but worse throughput performance (right y-axis) at low SNR, i.e., $\rho \leq 20 d B$. To illustrate, we can observe that the OP performance at device $D_{1}$ in HD mode with fixed PS factor $\varepsilon=0.4$ (Fig. 7.6a) significantly outperformed the OP at device $D_{2}$ also in HD mode with fixed PS factor $\varepsilon=0.4$ (Fig. 7.6b). This indicates that the devices in the HD scenario with fixed PS $\varepsilon=0.4$ were not served with QoS fairness at low SNR, i.e., from (7.63), we obtain $T^{(H D, \varepsilon=0.4)}=\left(1-\mathcal{O}_{1}^{(H D, \varepsilon=0.4)}\right) R_{1}+\left(1-\mathcal{O}_{2}^{(H D, \varepsilon=0.4)}\right) R_{2} \approx$ $\left(1-\mathcal{O}_{1}^{(H D, \varepsilon=0.4)}\right) R_{1}$ because $\mathcal{O}_{2}^{(H D, \varepsilon=0.4)} \approx 1$ at low SNR, i.e., $\rho \leq 20 d B$. Although affected by LI, the FD scenario where $\varepsilon^{(F D)}=0.5005$ achieved the best OP performance than the individual scenarios with both HD and FD relays using PS factors $\varepsilon=0.4$ and $\varepsilon^{(H D)}=0.8389$ at low SNR, e.g., $\rho<30 d B$. The throughput performance in individual FD scenarios achieved better throughput performance than the HD scenarios in almost all SNR periods which achieved their bit rate thresholds $T^{(\varphi)}=R_{1}+R_{2}=0.2 \mathrm{bps} / \mathrm{Hz}$.

### 7.3.2 QoS fairness

The main aim in the dissertation was to guarantee QoS for both the near and far devices. The OP performance of the devices should therefore be approximately together. Figure 7.9 depicts the QoS fairness of devices based on Jain's index fairness given by (7.64) and throughput fairness obtained from (7.65), indicated on the black left y-axis and the blue right y-axis, respectively. The results from Jain's index fairness show that the higher results have better fairness OP performance. The Jain's index fairness result with PS factor $\varepsilon^{(H D)}$ significantly outperforms the result with fixed PS factor $\varepsilon=0.4$ in the HD scenario. Similarly, the Jain's index fairness result with PS factor $\varepsilon^{(F D)}$ is always better than the result with fixed $\operatorname{PS}$ factor $\varepsilon=0.4$ in the FD scenario. The results for Jain's index fairness show that the higher results have better fairness performance. We can observe that the Jain's index fairness performance obtained in the HD/FD scenarios with PS factors given by (7.58) and (7.59) significantly outperform the same scenarios with fixed PS factor $\varepsilon=0.4$.

The throughput fairness results are also plotted (blue y-axis at right), given by (7.65) for $\mathrm{HD} / \mathrm{FD}$-IoT networks with $\operatorname{PS}$ factors $\varepsilon=0.4, \varepsilon^{(H D)}$ and $\varepsilon^{(F D)}$.

To illustrate, I inspected the difference in throughput performance of the devices by using (7.61). Extracting the analysis results, I exploited the throughput fairness peaks of the individual


Figure 7.8: The y-axis at left depicts OP performance obtained from (7.62); the y-axis at right depicts throughput performance obtained from (7.63), for scenarios $\varphi=\{H D, F D\}$ and PS cases $\varepsilon=\{0.4,(7.58),(7.59)\}$.
scenarios as follows:

$$
\begin{aligned}
& \max \left\{\begin{array}{c}
\mathcal{T}^{(H D, \varepsilon=0.4)} \\
\rho=\{10, \ldots, 40\}
\end{array}\right\}=0.0636 \mathrm{bps} / \mathrm{Hz} \text { for } \rho=18 \mathrm{~dB}, \\
& \max \left\{\begin{array}{c}
\mathcal{T}^{(H D, \varepsilon=0.8389)} \\
\rho=\{10, \ldots, 40\}
\end{array}\right\}=0.0178 \mathrm{bps} / \mathrm{Hz} \text { for } \rho=20 \mathrm{~dB} . \\
& \max \left\{\begin{array}{c}
\mathcal{T}^{(F D, \varepsilon=0.4)} \\
\rho=\{10, \ldots, 40\}
\end{array}\right\}=0.0605 \mathrm{bps} / \mathrm{Hz} \text { for } \rho=16 \mathrm{~dB}, \\
& \max \left\{\begin{array}{c}
\mathcal{T}^{(F D, \varepsilon=0.5005)} \\
\rho=\{10, \ldots, 40\}
\end{array}\right\}=0.0524 \mathrm{bps} / \mathrm{Hz} \text { for } \rho=16 \mathrm{~dB},
\end{aligned}
$$

These results show that my proposals are suitable for future IoT networks to serve devices with QoS fairness.


Figure 7.9: QoS fairness of the individual scenarios.

### 7.3.3 Secrecy OP performance

In another major section of the dissertation, I assumed that the IoT network presents passive eavesdroppers $E_{1}$ near device $D_{1}$ to eavesdrop $D_{1}$ and eavesdropper $E_{2}$ near $D_{2}$ to eavesdrop $D_{2}$. Significant studies related to the PLS issue in wireless communications have been con-
ducted previously. In [30, 32, 70] and [TTNam04], the authors investigated and improved SOP performance using MISO and MIMO in combination with the TAS protocol. In [72], the authors improved the SOP performance by increasing the number of relays or the Nakagami- $m$ coefficient. The authors in [74] examined single-input-multi-output (SIMO) SOP performance in combination with SWIPT. However, the research in my dissertation is significantly different to previous studies. Figure 7.3 shows a model using SISO and a single relay. The dissertation, however, focuses on PS diagram designs and proves that the PS factors may also improve SOP performance. Figures 7.10a and 7.10b plot the SOP performance at devices $D_{1}$ and $D_{2}$ in individual scenarios. It is interesting that the SOP performances at the devices in an FD-IoT network achieve better performance than in an HD-IoT network. In addition, the SOP at device $D_{2}$ with PS factors given by (7.58) and (7.59) outperforms itself when the PS factor is set to $\varepsilon=0.4$. These results prove that the PS factors may combat an eavesdropper. Note that the simulated SOP performances at devices $D_{1}$ and $D_{2}$ obtained by (7.49) and (7.53) were used to verify the respective theoretical SOP performances obtained by (7.50), (7.51), (7.54) and (7.55).

In Figure 7.7a, it is interesting to note that the OP performance at device $D_{1}$ in an FD-IoT network may be improved by increasing the SNR. However, OP performance at device $D_{1}$ in an FD-IoT network is limited by the floor of the OP performance given by (7.26), (7.37) or (7.38) because of the effect of LI. Specifically, in a secret FD-IoT network, device $D_{1}$ is affected not only by LI but also the eavesdropper $E_{1}$. Note that the eavesdropper receives the signal as (7.12) and then SIC as (7.13) and (7.14) without the effect of LI. Therefore, the eavesdropper $E_{1}$ may successfully decode the messages in a superimposed signal (7.12) if SNR $\rho \rightarrow \infty$. As a result, the SOP performance at device $D_{1}$ in an FD-IoT network (Fig. 7.7a) may tend to one since the secrecy instantaneous bit rate threshold given by (7.16) tends to zero if SNR $\rho \rightarrow \infty$.

Figure 7.11a and Figure 7.11b plot the SOP results at device $D_{2}$ in an HD-IoT network and FD-IoT network, respectively. The results are different from the SOP results at device $D_{2}$ in HD/FD IoT networks without eavesdropper $E_{1}$, as shown in Figure 7.10b. The results in Figure 7.10 b were therefore only dependent on the OP at device $D_{1}$. In addition, the SOP results at device $D_{2}$ did not change at high SNR, i.e., $\rho>30 d B$. However, the SOP results shown in Figure 7.11a and 7.11b tend to one if SNR $\rho \rightarrow \infty$. To illustrate, I investigated the SOP results at device $D_{1}$ when device $D_{1}$ cannot successfully decode $x_{2}$ because of the effect of the eavesdropper $E_{1}$ (dashed lines), and the SOP results at device $D_{2}$ when device $D_{2}$ cannot successfully decode $x_{2}$ because of the effect of the eavesdropper $E_{2}$ (dashed-dotted lines). Finally, I plot the SOP results at device $D_{2}$ (solid lines and various markers). It is very interesting that the SOP results at device $D_{2}$ at low SNR, i.e., $\rho<22 d B$, refer to the events when the secrecy instantaneous bit rate $R_{2}^{(\varphi)}$ of device $D_{2}$ cannot reach data rate threshold $R$. However, the SOP results at device $D_{1}$ at high SNR, i.e., $\rho>22 d B$, refer to the events when secrecy instantaneous bit rate $R_{1-x_{2}}^{(\varphi)}$ of device $D_{1}$ cannot reach data rate threshold $R$. It is important to note that the SOP results in HD/FD IoT networks with PS factors given by (7.58) and (7.59) are better than the results in the same individual scenarios with fixed PS factors. It means that the proposed PS diagrams as shown in Figures 7.1b and 7.2b may better combat the eavesdroppers.


Figure 7.10: Secrecy OP performance at devices (a) $D_{1}$ and (b) $D_{2}$.


Figure 7.11: Secrecy OP performance at device $D_{2}$ with two eavesdroppers in (a) HD-IoT networks and (b) FD-IoT networks.

### 7.4 Conclusion

I hypothesized that the EH in SWIPT can be used to forward signals. I designed an IoT network underlay C-NOMA in combination with SWIPT. To reach ultra-low latency, I designed a novel PS diagram. In the results, I obtained novel expressions in accurate and approximate closed forms. By applying the PS diagrams based on balancing EH and signal processing, the system performance of IoT networks achieved better OP performance, throughput, fairness and SOP. An analysis of the results verified that the PS balanced the model not only in assisting the far device but also guaranteeing the fairness of QoS of the devices in the IoT networks [TTNam09]. The analysis results were proved and verified by Monte Carlo simulation results and may be applied to future green and secure IoT networks. In fact, the system performance of the HD/FD IoT networks in this dissertation may be significantly improved by equipping multiple antennas [TTNam05, TTNam06] at network nodes, deploying multiple relays [TTNam07] or distributing over Nakagami- $m$ fading channels [TTNam08].

### 7.5 Appendix

### 7.5.1 Proof of Theorem 1

From (7.23) for $\varphi=H D$, we obtain

$$
\begin{equation*}
O P_{1}^{(H D)}=\underbrace{\operatorname{Pr}\left\{\gamma_{1-x_{2}}^{(H D)}<\gamma_{2}^{(H D)}\right\}}_{Q_{1}}+\underbrace{\operatorname{Pr}\left\{\gamma_{1-x_{2}}^{(H D)} \geq \gamma_{2}^{(H D)}, \gamma_{1-x_{1}}^{(H D)}<\gamma_{1}^{(H D)}\right\}}_{Q_{2}} \tag{7.66}
\end{equation*}
$$

After some algebraic manipulation, we obtain:

$$
\begin{equation*}
Q_{1}=\operatorname{Pr}\left\{\left|h_{1}\right|^{2}<\frac{\gamma_{2}^{(H D)}}{\xi^{(H D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(H D)}\right) \rho}\right\} \tag{7.67}
\end{equation*}
$$

By applying the CDF given by (7.22), the expression (7.67) obtains:

$$
\begin{equation*}
Q_{1}=F_{\left|h_{1}\right|^{2}}(x)=1-\exp \left(-\frac{\gamma_{2}^{(H D)}}{\xi^{(H D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(H D)}\right) \rho \sigma_{1}}\right) \tag{7.68}
\end{equation*}
$$

The expression $Q_{2}$ in (7.66) can be rewritten as:

$$
\begin{equation*}
Q_{2}=\operatorname{Pr}\left\{\left|h_{1}\right|^{2} \geq \frac{\gamma_{2}^{(H D)}}{\xi^{(H D)}\left(\alpha_{2}-\gamma_{2}^{(H D)} \alpha_{1}\right) \rho},\left|h_{1}\right|^{2}<\frac{\gamma_{1}^{(H D)}}{\xi^{(H D)} \alpha_{1} \rho}\right\} \tag{7.69}
\end{equation*}
$$

Similarly, we obtain $Q_{2}$ in closed form by applying the CDF given by (7.21) as follows:

$$
\begin{align*}
Q_{2} & =\int \frac{\gamma_{1}^{(H D)}}{{\frac{\xi^{(H D)} \alpha_{1} \rho}{(H D)}}_{\gamma_{2}^{(H D)}\left(\alpha_{2}-\gamma_{2}^{(H D)} \alpha_{1}\right) \rho}^{\xi_{1}}} \frac{1}{\sigma_{1}} \exp \left(-\frac{y}{\sigma_{1}}\right) d y \\
& =\exp \left(-\frac{\gamma_{2}^{(H D)}}{\xi^{(H D)}\left(\alpha_{2}-\gamma_{2}^{(H D)} \alpha_{1}\right) \rho \sigma_{1}}\right)-\exp \left(-\frac{\gamma_{1}^{(H D)}}{\xi^{(H D)} \alpha_{1} \rho \sigma_{1}}\right) \tag{7.70}
\end{align*}
$$

where $\alpha_{2}-\gamma_{2}^{(H D)} \alpha_{1}>\alpha_{1}$.
By substituting (7.68) and (7.70) into (7.66), we obtain the OP at the near device $D_{1}$ in HD scenario in closed form, as shown in (7.24).

In the FD-IoT model, the near device $D_{1}$ works in FD relaying mode. The near device $D_{1}$ must decode messages $x_{2}$ and $x_{1}$ according to (7.6) and (7.7), respectively, with the effect of the LI channel. From (7.23) for $\varphi=F D$, the OP at the near device $D_{1}$ in the FD-IoT model is expressed as follows:

$$
\begin{equation*}
O P_{1}^{(F D)}=\underbrace{\operatorname{Pr}\left\{\gamma_{1-x_{2}}^{(F D)}<\gamma_{2}^{(F D)}\right\}}_{Q_{3}}+\underbrace{\operatorname{Pr}\left\{\gamma_{1-x_{2}}^{(F D)} \geq \gamma_{2}^{(F D)}, \gamma_{1-x_{1}}^{(F D)}<\gamma_{1}^{(F D)}\right\}}_{Q_{4}} . \tag{7.71}
\end{equation*}
$$

Let $\sigma_{L I}=E\left\{\left|h_{L I}\right|^{2}\right\}=\varpi E\left\{\left|h_{1}\right|^{2}\right\}$. After some algebraic manipulation, we obtain:

$$
\begin{equation*}
Q_{3}=1-\operatorname{Pr}\left\{\left|h_{1}\right|^{2} \geq \frac{\gamma_{2}^{(F D)}\left(\eta^{2}\left|h_{L I}\right|^{2} \varepsilon^{(F D)} \rho+1\right)}{\xi^{(F D)} \rho\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)},\left|h_{L I}\right|^{2} \geq 0\right\} \tag{7.72}
\end{equation*}
$$

By applying the PDF given by (7.21), we obtain

$$
\begin{align*}
Q_{3} & =1-\int_{0}^{\infty} \int_{\frac{\gamma_{2}^{(F D)}\left(\eta^{2} y \varepsilon(F D)^{(F+1)}\right.}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)_{\rho}}}^{\infty} \frac{1}{\varpi \sigma_{1}^{2}} \exp \left(-\frac{x}{\sigma_{1}}-\frac{y}{\varpi \sigma_{1}}\right) d x d y \\
& =1-\exp \left(-\frac{\gamma_{2}^{(F D)}}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right) \rho \sigma_{1}}\right) \frac{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)+\eta^{2} \varpi \varepsilon^{(F D)} \gamma_{2}^{(F D)}}, \tag{7.73}
\end{align*}
$$

where $R_{2}<\frac{1}{2} \log _{2}\left(\frac{\alpha_{2}-\alpha_{1}}{\alpha_{1}}+1\right)$.
The expression $Q_{4}$ in (7.71) is obtained by

$$
\begin{equation*}
Q_{4}=\operatorname{Pr}\left\{\left|h_{1}\right|^{2} \geq \frac{\gamma_{2}^{(F D)}\left(\eta^{2}\left|h_{L I}\right|^{2} \varepsilon^{(F D)} \rho+1\right)}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right) \rho},\left|h_{1}\right|^{2}<\frac{\gamma_{1}^{(F D)}\left(\eta^{2}\left|h_{L I}\right|^{2} \varepsilon^{(F D)} \rho+1\right)}{\xi^{(F D)} \alpha_{1} \rho},\left|h_{L I}\right|^{2} \geq 0\right\} \tag{7.74}
\end{equation*}
$$

Similarly, the expression $Q_{6}$ in (7.67) can be obtained in closed form as follows:

$$
\begin{align*}
Q_{4} & =\int_{0}^{\infty} \int_{\gamma_{1}^{(F D)}\left(\eta^{2} y_{\varepsilon}^{(F D)}{ }_{\rho+1}\right)}^{\frac{\gamma_{1}^{(F D)}\left(\eta^{2} y^{(F D)}{ }_{\rho+1}\right)}{\xi^{(F D)} \alpha_{1} \rho}} \frac{1}{\sigma_{1} \sigma_{L I}} \exp \left(-\frac{x}{\sigma_{1}}-\frac{y}{\sigma_{L I}}\right) d x d y \\
& =\xi^{(F D)}\left(\exp \left(-\frac{\gamma_{2}^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)^{\rho}}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right) \rho \sigma_{1}}\right) \frac{\alpha_{1} \gamma_{2}^{(F D)}}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)+\gamma_{2}^{(F D)} \eta^{2} \varepsilon^{(F D)} \varpi}\right. \\
& \left.-\exp \left(-\frac{\gamma_{1}^{(F D)}}{\xi^{(F D)} \alpha_{1} \rho \sigma_{1}}\right) \frac{\alpha_{1}}{\xi^{(F D)} \alpha_{1}+\gamma_{1}^{(F D)} \eta^{2} \varepsilon^{(F D)} \varpi}\right),
\end{align*}
$$

where $R_{2}<\log _{2}\left(\frac{\alpha_{2}-\alpha_{1}}{\alpha_{1}}+1\right)$.
By substituting (7.73) and (7.75) into (7.71), we obtain the OP at the near device $D_{1}$ in the FD-IoT model in closed form given by (7.25).

### 7.5.2 Proof of Lemma 1:

From (7.27) and (7.28), we obtain min-rate OP at device $D_{1}$ in the HD scenario as follows:

$$
\begin{align*}
M O P_{1}^{(H D)} & =1-\min \left\{\operatorname{Pr}\left\{\left|h_{1}\right|^{2} \geq \frac{\gamma_{2}^{(H D)}}{\xi^{(H D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(H D)}\right) \rho}\right\}, \operatorname{Pr}\left\{\left|h_{1}\right|^{2} \geq \frac{\gamma_{1}^{(H D)}}{\xi^{(H D)} \alpha_{1} \rho}\right\}\right\} \\
& =1-\operatorname{Pr}\left\{\left|h_{1}\right|^{2} \geq \frac{\max \left\{\frac{\gamma_{2}^{(H D)}}{\left.\alpha_{2}-\alpha_{1} \gamma_{2}^{(H D)}, \frac{\gamma_{1}^{(H D)}}{\alpha_{1}}\right\}}\right.}{\xi^{(H D)} \rho}\right\} \\
& =1-f_{\left|h_{1}\right|^{2}}(x) \\
& =1-\exp \left(-\frac{\max \left\{\frac{\gamma_{2}^{(H D)}}{\left.\alpha_{2}-\alpha_{1} \gamma_{2}^{(H D)}, \frac{\gamma_{1}^{(H D)}}{\xi_{1}}\right\}}\right.}{\xi^{(H D)} \rho \sigma_{1}}\right)  \tag{7.76}\\
& =1-\exp \left(-\frac{\gamma^{(H D)}}{\xi^{(H D)} \rho \sigma_{1} \min \left\{\begin{array}{c}
\alpha_{2}-\alpha_{1} \gamma^{(H D)} \\
\alpha_{1}
\end{array}\right\}}\right) \tag{7.77}
\end{align*}
$$

such that $R_{1} \neq R_{2}$ in (7.76) and $R_{1}=R_{2}=R$ in (7.77).
Similarly, from (7.27) and (7.28), where $\varphi=F D$, we obtain the min-rate OP at device $D_{1}$
in the FD scenario as follows:

$$
\begin{align*}
& M O P_{1}^{(F D)}=1-\min \left\{\operatorname{Pr}\left\{\left|h_{1}\right|^{2} \geq \frac{\gamma_{1}^{(F D)}\left(\eta^{2}\left|h_{L I}\right|^{2} \varepsilon^{(F D)} \rho+1\right)}{\xi^{(F D)} \alpha_{1} \rho},\left|h_{L I}\right|^{2} \geq 0\right\},\right. \\
&\left.\operatorname{Pr}\left\{\left|h_{1}\right|^{2} \geq \frac{\gamma_{2}^{(F D)}\left(\eta^{2}\left|h_{L I}\right|^{2} \varepsilon^{(F D)} \rho+1\right)}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right) \rho},\left|h_{L I}\right|^{2} \geq 0\right\}\right\} \tag{7.78}
\end{align*}
$$

We obtain

$$
\begin{align*}
& M O P_{1}^{(F D)}=1-\int_{0}^{\infty} \int_{\frac{\eta^{2} y \varepsilon(F D)_{\rho+1}}{\xi^{(F D)_{\rho}}} \max \left\{\frac{\gamma_{2}^{(F D)}}{\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}}, \frac{\gamma_{1}^{(F D)}}{\alpha_{1}}\right\}}^{\infty} \frac{1}{\varpi \sigma_{1}^{2}} \exp \left(-\frac{x}{\sigma_{1}}-\frac{y}{\varpi \sigma_{1}}\right) d x d y \\
& =1-\exp \left(-\frac{\max \left\{\frac{\gamma_{2}^{(F D)}}{\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}}, \frac{\gamma_{1}^{(F D)}}{\alpha_{1}}\right\}}{\xi^{(F D)} \rho \sigma_{1}}\right) \frac{\xi^{(F D)}}{\xi^{(F D)}+\eta^{2} \varpi \varepsilon^{(F D)} \max \left\{\frac{\gamma_{2}^{(F D)}}{\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}}, \frac{\gamma_{1}^{(F D)}}{\alpha_{1}}\right\}} \\
& =1-\exp \left(\frac{-\gamma^{(F D)}}{\xi^{(F D)} \rho \sigma_{1} \min \left\{\begin{array}{c}
\alpha_{2}-\alpha_{1} \gamma^{(H D)} \\
\alpha_{1}
\end{array}\right\}}\right) \frac{\xi^{(F D)} \min \left\{\alpha_{2}-\alpha_{1} \gamma^{(F D)}, \alpha_{1}\right\}}{\xi^{(F D)} \min \left\{\alpha_{2}-\alpha_{1} \gamma^{(F D)}, \alpha_{1}\right\}+\eta^{2} \varpi \varepsilon^{(F D)} \gamma^{(F D)}}, \tag{7.80}
\end{align*}
$$

such that $R_{1} \neq R_{2}$ in (7.79) and $R_{1}=R_{2}=R$ in (7.80).

### 7.5.3 Proof of Theorem 2:

From (7.39) for $\varpi=H D$, we obtain the OP at the far device $D_{2}$ in the HD-IoT model as follows:

$$
\begin{equation*}
O P_{2}^{(H D)}=\underbrace{\operatorname{Pr}\left\{\gamma_{1-x_{2}}^{(H D)}<\gamma_{2}^{(H D)}\right\}}_{Q_{1}}+\underbrace{\operatorname{Pr}\left\{\gamma_{1-x_{2}}^{(H D)} \geq \gamma_{2}^{(H D)}, \gamma_{2-x_{2}}^{(H D)}<\gamma_{2}^{(H D)}\right\}}_{Q_{5}} \tag{7.81}
\end{equation*}
$$

However, it is important to note that the expression $Q_{5}$ has two randomly independent
variables. By applying the PDF given by (7.21), we obtain

$$
\begin{align*}
Q_{5}^{(H D)} & =1-\operatorname{Pr}\left\{\left|h_{1}\right|^{2} \geq \frac{\gamma_{2}^{(H D)}}{\xi^{(H D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(H D)}\right) \rho},\left|h_{1}\right|^{2}<\frac{\gamma_{2}^{(H D)}}{\eta^{2}\left|h_{2}\right|^{2} \varepsilon^{(H D)} \rho},\left|h_{2}\right|^{2}>0\right\} \\
& =\int_{0}^{\infty} \frac{\gamma_{2}^{(H D)}}{\frac{\gamma_{2}^{(H D)}}{\eta^{2 y \varepsilon} \varepsilon^{(H D)}}} \frac{1}{\xi_{1}^{(H D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(H D)}\right)_{\rho}} \exp \left(-\frac{x}{\sigma_{1}}-\frac{y}{\sigma_{2}}\right) d x d y \\
& =\exp \left(-\frac{\gamma_{2}^{(H D)}}{\xi^{(H D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(H D)}\right) \rho \sigma_{1}}\right)-\frac{2 B_{1}\left\{2 / \sqrt{\frac{\eta^{2} \varepsilon^{(H D)} \rho \sigma_{1} \sigma_{2}}{\gamma_{2}^{(H D)}}}\right\}}{\sqrt{\frac{\eta^{2} \varepsilon^{(H D)} \rho \sigma_{1} \sigma_{2}}{\gamma_{2}^{(H D)}}}} . \tag{7.82}
\end{align*}
$$

By substituting (7.68) and (7.82) into (7.81), we obtain the OP at the far device $D_{2}$ in the HD-IoT model in closed form given by (7.40).

However, the OP at the far device $D_{2}$ in the FD-IoT model can be rewritten as follows:

$$
\begin{equation*}
O P_{2}^{(F D)}=\underbrace{\operatorname{Pr}\left\{\gamma_{1-x_{2}}^{(F D)}<\gamma_{2}^{(F D)}\right\}}_{Q_{4}}+\underbrace{\operatorname{Pr}\left\{\gamma_{1-x_{2}}^{(F D)} \geq \gamma_{2}^{(F D)}, \gamma_{2-x_{2}}^{(F D)}<\gamma_{2}^{(F D)}\right\}}_{Q_{6}}, \tag{7.83}
\end{equation*}
$$

where the expressions $Q_{4}$ is given by (7.75). Then, $Q_{7}^{(F D)}$ is similarly obtained as follows:

$$
\begin{align*}
& Q_{6}=\operatorname{Pr}\left\{\left|h_{1}\right|^{2} \geq \frac{\gamma_{2}^{(F D)}\left(\eta^{2}\left|h_{L I}\right|^{2} \varepsilon^{(F D)} \rho+1\right)}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right) \rho},\left|h_{1}\right|^{2}<\frac{\gamma_{2}^{(F D)}}{\eta^{2}\left|h_{2}\right|^{2} \varepsilon^{(F D) \rho}},\left|h_{L I}\right|^{2} \geq 0,\left|h_{2}\right|^{2}>0\right\} \\
& =\left[\int_{0}^{\infty} \int_{0}^{\infty} \int_{\frac{\gamma_{2}^{(F D)}\left(\eta^{2} z \varepsilon\right.}{\xi^{\left.(F D)^{(F D)}\right)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right)^{\rho}}}^{\frac{\gamma_{2}^{(F D)}}{\eta^{2} y \varepsilon \in(F D)_{\rho}}} \frac{1}{\sigma_{1} \sigma_{2} \sigma_{L I}} \times \exp \left(-\frac{x}{\sigma_{1}}-\frac{y}{\sigma_{2}}-\frac{z}{\sigma_{L I}}\right) d x d y d z\right]^{+} \\
& =\left[\exp \left(-\frac{\gamma_{2}^{(F D)}}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right) \rho \sigma_{1}}\right) \frac{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right) \sigma_{1}}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} \gamma_{2}^{(F D)}\right) \rho \sigma_{1}+\gamma_{2}^{(F D)} \eta^{2} \varepsilon^{(F D)} \sigma_{L I}}\right. \\
& \left.-\frac{2 B_{1}\left\{2 / \sqrt{\frac{\eta^{2} \varepsilon^{(F D)} \rho \sigma_{1} \sigma_{2}}{\gamma_{2}^{(F D)}}}\right\}}{\sqrt{\frac{\eta^{2} \varepsilon^{(F D)_{\rho \sigma_{1}} \sigma_{2}}}{\gamma_{2}^{(F D)}}}}\right]^{+} . \tag{7.84}
\end{align*}
$$

By substituting (7.75) and (7.84) into (7.83), we obtain the OP at the far device $D_{2}$ in the FD-IoT model in closed form given by (7.41).

### 7.5.4 Proof of Theorem 3

The SOP performance at device $D_{1}$ is given by (7.48) and (7.49), where $\varphi=H D$.

From $Q_{3}$ and $Q_{1}$ in (7.73) and (7.68), we obtain the CDF of devices $D_{1}$ and eavesdropper $E_{1}$ when they decode the data symbols $x_{1}$ and $x_{2}$, respectively, as follows:

$$
\begin{equation*}
F_{\gamma_{d-x_{1}}^{(H D)}}(x)=1-\exp \left(-\frac{x}{\xi^{(H D)} \alpha_{1} \rho \sigma_{d}}\right), \tag{7.85}
\end{equation*}
$$

and

$$
F_{\gamma_{d-x_{2}}^{(H D)}}(x)= \begin{cases}1-\exp \left(-\frac{x}{\xi^{(H D)}\left(\alpha_{2}-\alpha_{1} x\right) \rho \sigma_{d}}\right), & x<\frac{\alpha_{2}}{\alpha_{1}},  \tag{7.86}\\ 1, & x \geq \frac{\alpha_{2}}{\alpha_{1}},\end{cases}
$$

where $d=\{1,3\}$.
We obtain the PDF of devices $D_{1}$ and eavesdropper $E_{1}$ when they decode the $x_{2}$ and $x_{1}$ data symbols, respectively, as follows:

$$
\begin{equation*}
f_{\gamma_{d-x_{1}}^{(H D)}}(x)=\frac{\exp \left(-\frac{x}{\xi^{(H D)} \alpha_{1} \rho \sigma_{d}}\right)}{\xi^{(H D)} \alpha_{1} \rho \sigma_{d}}, \tag{7.87}
\end{equation*}
$$

and

$$
f_{\gamma_{d-x_{2}}^{(H D)}}(x)=\left\{\begin{array}{l}
\frac{\alpha_{2} \exp \left(-\frac{x}{\xi^{(H D)}\left(\alpha_{2}-\alpha_{1} x\right) \rho \sigma_{d}}\right)}{\xi^{(H D)}\left(\alpha_{2}-\alpha_{1} x\right)^{2} \rho \sigma_{d}}, x<\frac{\alpha_{2}}{\alpha_{1}}  \tag{7.88}\\
0, x \geq \frac{\alpha_{2}}{\alpha_{1}},
\end{array}\right.
$$

Let $Q_{7}=\operatorname{Pr}\left\{\left[R_{1-x_{1}}^{(H D)}-R_{3-x_{1}}^{(H D)}\right]^{+} \geq R_{1}\right\}$. From [32, Eq. (9)], the expression $Q_{7}$ can be obtained as follows:

$$
\begin{equation*}
Q_{7}=1-\int_{0}^{\infty} F_{\gamma_{1-x_{1}}^{(H D)}}\left(\tilde{\gamma}_{1}^{(H D)} y+\gamma_{1}^{(H D)}\right) f_{\gamma_{3-x_{1}}^{(H D)}}(y) d y . \tag{7.89}
\end{equation*}
$$

By substituting (7.85) and (7.87) into (7.89), we obtain

$$
\begin{equation*}
Q_{7}=\frac{\sigma_{1}}{\sigma_{1}+\tilde{\gamma}_{1}^{(H D)} \sigma_{3}} \exp \left(-\frac{\gamma_{1}^{(H D)}}{\xi^{(H D)} \alpha_{1} \rho \sigma_{1}}\right) . \tag{7.90}
\end{equation*}
$$

Let $Q_{8}=\operatorname{Pr}\left\{\left[R_{1-x_{2}}^{(H D)}-R_{3-x_{2}}^{(H D)}\right]^{+} \geq R_{2}\right\}$.

We then obtain

$$
\begin{align*}
& Q_{8}=1-\int_{0}^{\psi} F_{\gamma_{1-x_{2}}^{(H D)}}\left(\tilde{\gamma}_{2}^{(H D)} y+\gamma_{2}^{(H D)}\right) f_{\gamma_{3-x_{2}}^{(H D)}}(y) d y+\int_{\psi}^{\alpha_{2} / \alpha_{1}} f_{\gamma_{3-x_{2}}^{(H D D}}(y) d y \\
&=\frac{\alpha_{2} \psi \pi}{2 K \xi^{(H D)} \rho \sigma_{3}} \sum_{k=1}^{K}\left(\frac{\sqrt{1-(2 \Omega-1)^{2}}}{\left(\alpha_{2}-\alpha_{1} \psi \Omega\right)^{2}} \exp \left(-\frac{\psi \Omega}{\xi^{(H D)}\left(\alpha_{2}-\alpha_{1} \psi \Omega\right) \rho \sigma_{3}}\right)\right. \\
&\left.\times \exp \left(-\frac{\tilde{\gamma}_{2}^{(H D)} \psi \Omega-1}{\xi^{(H D)}\left(\alpha_{2}-\alpha_{1}\left(\tilde{\gamma}_{2}^{(H D)} \Omega-1\right)\right) \rho \sigma_{1}}\right)\right) . \tag{7.91}
\end{align*}
$$

By substituting (7.89) and (7.91) into (7.49), we obtain the SOP at device $D_{1}$ in closed form given by (7.50).

In the FD-IoT network model shown Figure 7.2a, the SOP performance at device $D_{1}$ is given by (7.48), where $\varphi=F D$. Let $Q_{9}=\operatorname{Pr}\left\{\left[R_{1-x_{1}}^{(F D)}-R_{3-x_{1}}^{(F D)}\right]^{+} \geq R_{1}\right\}$.

We then obtain

$$
\begin{align*}
Q_{9} & =1-\int_{0}^{\infty} F_{\gamma_{1-x_{1}}^{(F D)}}\left(\tilde{\gamma}_{1}^{(F D)} y+\gamma_{1}^{(F D)}\right) f_{\gamma_{3-x_{1}}^{(F D)}}(y) d y \\
& =-\frac{1}{\eta^{2} \varepsilon^{(F D)} \varpi \rho \tilde{\gamma}_{1}^{(F D)} \sigma_{3}} \exp \left(-\frac{\gamma_{1}^{(F D)}}{\xi^{(F D)} \alpha_{1} \rho \sigma_{1}}\right)\left(\exp \left(-\frac{\left(\xi^{(F D)} \alpha_{1}+\eta^{2} \varepsilon^{(F D)} \varpi \gamma_{1}^{(F D)}\right) \chi}{\xi^{(F D)} \alpha_{1} \eta^{2} \varepsilon^{(F D)} \varpi \gamma_{1}^{(F D)} \rho \sigma_{1} \sigma_{3}}\right)\right. \\
& \times\left(\lim _{\Gamma \rightarrow \infty}\left(\sum_{\gamma=1}^{\Gamma} \frac{1}{\gamma}-\ln \Gamma\right)+\ln \frac{\chi}{\xi^{(F D)} \alpha_{1} \rho \sigma_{1} \sigma_{3}}-\ln \frac{\eta^{2} \varepsilon^{(F D)} \varpi \tilde{\gamma}_{1}^{(F D)}}{\xi^{(F D)} \alpha_{1}+\eta^{2} \varepsilon^{(F D)} \varpi \gamma_{1}^{(F D)}}\right) \\
& \left.-U\left\{1 ; 1 ; \frac{\left(\xi^{(F D)} \alpha_{1}+\eta^{2} \varepsilon^{(F D)} \varpi \gamma_{1}^{(F D)}\right) \chi}{\xi^{(F D)} \alpha_{1} \eta^{2} \varepsilon^{(F D)} \varpi \gamma_{1}^{(F D)} \rho \sigma_{1} \sigma_{3}}\right\}\right), \tag{7.92}
\end{align*}
$$

where $U\{. ; . ;$.$\} is Kummer's confluent hypergeometric function, and F_{\gamma_{1-x_{1}}^{(F D)}}(x)$ is given as follows:

$$
\begin{equation*}
F_{\gamma_{1-x_{1}}^{(F D)}}(x)=1-\frac{\xi^{(F D)} \alpha_{1}}{\xi^{(F D)} \alpha_{1}+\eta^{2} \varepsilon^{(F D)} \varpi x} \exp \left(-\frac{x}{\xi^{(F D)} \alpha_{1} \rho \sigma_{1}}\right) . \tag{7.93}
\end{equation*}
$$

Then, let $Q_{10}=\operatorname{Pr}\left\{\left[R_{1-x_{2}}^{(F D)}-R_{3-x_{2}}^{(F D)}\right]^{+} \geq R_{2}\right\}$.

We then obtain

$$
\begin{align*}
Q_{10} & =1-\int_{0}^{\delta} F_{\gamma_{1-x_{2}}^{(F D)}}\left(\tilde{\gamma}_{2}^{(F D)} y+\gamma_{2}^{(F D)}\right) f_{\gamma_{3-x_{2}}^{(F D)}}(y) d y+\int_{\delta}^{\alpha_{2} \alpha_{1}} f_{\gamma_{3-x_{2}}^{(F D)}}(y) d y \\
& =\frac{\alpha_{2} \delta \pi}{2 K \xi^{(F D)} \rho \sigma_{3}+\eta^{2} \varepsilon^{(F D)} \varpi \tilde{\gamma}_{2}^{(F D)}} \sum_{k=1}^{K}\left(\frac{\sqrt{1-(2 \Omega-1)^{2}}}{\left(\alpha_{2}-\alpha_{1} \delta \Omega\right)^{2}+\eta^{2} \varepsilon^{(F D)} \varpi \tilde{\gamma}_{2}^{(F D)}}\right. \\
& \left.\times \exp \left(-\frac{\delta \Omega}{(1-\varepsilon)\left(\alpha_{2}-\alpha_{1} \delta \Omega\right) \rho \sigma_{3}}\right) \exp \left(-\frac{\tilde{\gamma}_{2}^{(F D)} \delta \Omega-1}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1}\left(\tilde{\gamma}_{2}^{(F D)} \Omega-1\right)\right) \rho \sigma_{3}}\right)\right) \tag{7.94}
\end{align*}
$$

where $\delta=\frac{1}{\tilde{\gamma}_{2}^{(F D)}\left(\alpha_{1}+\eta^{2} \varepsilon^{(F D)} \varpi\right)}-1<\frac{\alpha_{2}}{\alpha_{1}}$, and $F_{\gamma_{1-x_{2}}^{(F D)}}(x)$ is given as follows:.

$$
\begin{equation*}
F_{\gamma_{1-x_{2}}^{(F D)}}(x)=1-\frac{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} x\right)}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} x\right)+\eta^{2} \xi^{(F D)} \varpi x} \exp \left(-\frac{x}{\xi^{(F D)}\left(\alpha_{2}-\alpha_{1} x\right) \rho \sigma_{1}}\right) \tag{7.95}
\end{equation*}
$$

By substituting (7.92) and (7.94) into (7.49), we obtain the SOP at device $D_{1}$ in the FD scenario in closed form given by (7.51).

### 7.5.5 Proof of Theorem 4

From (7.53), let $Q_{11}^{(\varphi)}=\operatorname{Pr}\left\{\left[R_{2-x_{2}}^{(\varphi)}-R_{4-x_{2}}^{(\varphi)}\right]^{+}<R_{2}\right\}$.
After some algebraic manipulation, we then obtain

$$
\begin{align*}
Q_{11}^{(\varphi)} & =1-\operatorname{Pr}\left\{\left|h_{2}\right|^{2} \geq \frac{\gamma_{2}^{(\varphi)}+\left(\gamma_{2}^{(\varphi)}+1\right) \eta^{2} \varepsilon^{(\varphi)} \rho\left|h_{1}\right|^{2}\left|h_{4}\right|^{2}}{\eta^{2} \varepsilon^{(\varphi)} \rho\left|h_{1}\right|^{2}},\left|h_{4}\right|^{2} \geq 0,\left|h_{1}\right|^{2} \geq 0\right\} \\
& =1-\int_{0}^{\infty} \int_{0}^{\infty} \frac{1}{\sigma_{1} \sigma_{2} \sigma_{4}} \exp \left(-\frac{x}{\sigma_{2}}-\frac{y}{\sigma_{4}}-\frac{z}{\left.\sigma_{1}^{(\varphi)}+\left(\gamma_{2}^{(\varphi)}+1\right) \eta^{2} \varepsilon^{(\varphi)}\right) d x d y d z} \begin{array}{rl}
\eta^{2} \varepsilon^{(\varphi)} \rho z \\
& \sqrt{\frac{2 \sigma_{2} B_{1}(2}{\frac{\eta^{2} \varepsilon^{(\varphi)} \rho \prod_{i} \sigma_{i}}{\gamma_{2}^{(\varphi)}}}\left(\sigma_{2}+\sigma_{4}+\gamma_{2}^{(\varphi)} \sigma_{4}\right)}
\end{array}\right. \\
& \left.=1-\frac{\eta^{2} \varepsilon^{(\varphi)} \rho \prod_{i} \sigma_{i}}{\gamma_{2}^{(\varphi)}}\right) \tag{7.96}
\end{align*}
$$

By substituting (7.68) and (7.96) into (7.53), we obtain the SOP at device $D_{2}$ in the HD scenario given by (7.54). Then, by substituting (7.73) and (7.96) into (7.53), we obtain the SOP at device $D_{2}$ in the FD scenario without eavesdropper $E_{1}$ given by (7.55).

## Part II - A Combination of the SWIPT, Massive MIMO and TAS Techniques

THE dissertation proposes a new switchable coupled relay model for massive MIMO-NOMA networks. The model equips more antennas on the coupled relays to dramatically improve capacity and EE. Each relay in a coupled relay is selected and delivered into a single transmission block to serve multiple devices. This dissertation also plots a new diagram of two transmission blocks to illustrate EH and signal processing. To optimize the system performance of a massive MIMO-NOMA network, i.e., OP and system throughput, this dissertation deployed a TAS protocol to select the best received signals from the pre-coding channel matrices. In addition, to achieve better EE, the dissertation implemented SWIPT. Specifically, the dissertation derived the novel theoretical analysis in closed form expressions, i.e., OP, system throughput and EE from a massive MIMO-NOMA network aided by switchable coupled relays. The theoretical results obtained from the closed form expressions showed that a massive MIMO-NOMA network achieves better OP and larger capacity and expends less energy than the MIMO technique. Finally, independent Monte Carlo simulations verified the theoretical results.

I briefly describe the contributions of the third aim:

- A new design for a switchable coupled relay model to assist massive MIMO-NOMA wireless networks. Each relay in a coupled relay is selected and delivered into odd transmission block (OTB)/even transmission block (ETB). The selected relay is used to forward signals to multiple devices while another relay maintains EH.
- A new proposed design for a diagram of two transmission blocks to calculate the propagation of SWIPT.
- Maximization of system throughput in a massive MIMO-NOMA network. The dissertation deploys a TAS protocol which selects the best received signals from the pre-coding channel matrices.
- The dissertation delivers novel expressions for OP, system throughput and EE in closed form. I apply Monte Carlo simulation results to verify the analysis results.

Note that the outcomes in the Chapter 7 (Part II) have been published in the paper [TTNam07] entitled "Switchable Coupled Relays Aid Massive Non-Orthogonal Multiple Access Networks with Transmit Antenna Selection and Energy Harvesting", in (MDPI) Sensors, 21 (4), art. no. 1101 (2021). DOI: 10.3390/s21041101. IF 3.031

### 7.6 System Models

The dissertation examines a new cooperative MIMO-NOMA model for emerging 5G wireless networks and networks beyond. Figure 7.12 depicts a system model containing a BS, coupled
relay $\mathcal{R}=\left\{R_{1}, R_{2}\right\}$, and multiple devices $D_{n}=\left\{D_{1}, \ldots, D_{N}\right\}$. To benefit a massive MIMONOMA network, a large number of antennas $A_{0}, A_{1}$ and $A_{2}$ are equipped at the network nodes and BS, coupled relays, and devices, respectively. I also assume that the BS has full knowledge of the CSI [34]. As with the system models in previous major studies [35, 77, 92, 95], the massive MIMO underlay C-NOMA model shown in Figure 7.12 contains two time slots to complete a transmission block. It is important to illustrate the difference to these studies. In studies [66, $82,98,99]$, the authors verified that relays are a good solution which assist in combating channel fading. In other major studies, the authors deployed a SISO relay to aid a multi-destination [92] or a multiple SISO relay to aid a single destination [77]. The authors also proposed RS strategies to select the best nearest relay [98] and max-instantaneous data rate [99, Eq. (16)] to assist the destinations. The dissertation deploys coupled relays to assist massive MIMO-NOMA networks, but only the relay with better power capacity among the coupled relays is selected for cooperation with devices in OTB/ETB, i.e., while one relay is selected to forward the signal to devices, another relay has to maintain EH from the BS.


Figure 7.12: Coupled relays in a cooperative MIMO-NOMA network with the application of TAS and SWIPT.

Note that the model in the dissertation is designed to serve multiple devices simultaneously. The coupled relays must first have the device CSI and report this information to the BS. Based on the devices' CSI, the BS allocates PS factors whereas the coupled relays feed back their own CSI to the BS and other devices. Based on the energy capacity information, the BS selects the best powered relay to forward the signal. The devices then wait to receive the signal from the strongest powered relay. In the case of insufficient CSI, the BS may select the poorest powered relay to forward the signal, leading to a reduced lifespan of the relay. This may interrupt signal propagation because the devices are waiting for a non-cooperative relay.

### 7.7 Propagation and formulations

From the model depicted in Figure 7.12, I designed a new propagation diagram, shown in Figure 7.13. The coupled relays feed back data to the BS about their energy capacities. The BS decides which relay has more energy to forward the superimposed signal, while the remaining relay has less energy to maintain EH. Two main phases take place: EH and data transmission (DT). To illustrate, Figure 7.13 depicts two transmission blocks: an OTB $T^{(o d d)}$ and an ETB $T^{(\text {even })}$. Each transmission block $T^{(\theta)}$ for $\theta=\{o d d$, even $\}$ is separated into two equal time slots. The FTS $T_{1}^{(o d d)}=T^{(o d d)} / 2$ in the OTB $T^{(o d d)}$ is used by the BS to transmit wireless energy and superimposed information to coupled relays $\mathcal{R}=\left\{R_{1}, R_{2}\right\}$. In terms of the SWIPT technique with the PS protocol, during the FTS $T_{1}^{(o d d)}$, a fraction $\lambda$ of the power domain $P_{S}$ is used for EH while the remaining fraction $(1-\lambda)$ is used to superimpose data from the BS. The STS $T_{2}^{(o d d)}=T^{(o d d)} / 2$ in the OTB $T^{(o d d)}$ is used by the best powered relay to forward the superimposed signal to devices, while the worse powered relay applies EH from the BS, where the PS factor $\lambda=1$. The dissertation assumes that relay $R_{1}$ is selected in the OTB because relay $R_{1}$ has more energy than relay $R_{2}$. Therefore, relay $R_{2}$ maintains EH from the BS. Similarly, the ETB $T^{(\text {even })}$ is also separated into two equal time slots. The FTS $T_{1}^{(\text {even })}=T^{(\text {even })} / 2$ in the ETB $T^{(\text {even })}$ is also used by the BS to simultaneously transmit wireless energy and the superimposed signal to the coupled relay $\mathcal{R}=\left\{R_{1}, R_{2}\right\}$. However, in the $\operatorname{STS} T_{2}^{(\text {even })}=T^{(\text {even })} / 2$ in the ETB $T^{(\text {even })}$, relay $R_{2}$ is selected to forward the superimposed signal to devices instead of relay $R_{1}$ because relay $R_{2}$ harvests energy from the BS , where $\lambda=1$ during $T_{2}^{(o d d)}$. Relay $R_{2}$ then contains more energy than relay $R_{1}$. As a result, relay $R_{1}$ maintains EH from the BS with PS factor $\lambda=1$ during $T_{2}^{(e v e n)}$. Although the network model shown in Figure 7.12 is complex, it requires two time slots for signals to propagate through the network, as in studies [35, 77, 92]. Specifically, the dissertation examines how multiple devices are served simultaneously. I therefore apply the emerging NOMA technique. The BS also superimposes the information of all devices in the same signal by sharing the spectrum. The devices may be thus served simultaneously. As a result, the massive MIMO-NOMA network in the dissertation are low latency.

### 7.7.1 Odd transmission block

Fig. 7.12 shows that both the BS and coupled relays ( $R_{1}$ and $R_{2}$ ) are equipped with multiple antennas, where $A_{0}>1$ and $A_{1}>1 A_{0}$ and $A_{1}$ are the number of antennas at the BS and coupled relays, respectively. In the study [TTNam06], I designed a pre-coding channel matrix size according to [number of transmitting antennas $\times$ number of receiving antennas]. Therefore, the pre-coding channel matrices from the $A_{0}$ transmitting antennas at the BS to the $A_{1}$ receiving antennas on the coupled relays $R_{1}$ and $R_{2}$ can be expressed as follows:

$$
\mathbf{H}_{0}=\left[\begin{array}{ccc}
h_{0}^{(1,1)} & \cdots & h_{0}^{\left(1, A_{1}\right)}  \tag{7.97a}\\
\vdots & \ddots & \vdots \\
h_{0}^{\left(A_{0}, 1\right)} & \cdots & h_{0}^{\left(A_{0}, A_{1}\right)}
\end{array}\right]
$$

| $\underset{\mathrm{S} \rightarrow \mathrm{R}_{1}}{\mathrm{EH}}$ |  | $\begin{gathered} \mathrm{DT} \\ \mathrm{R}_{1} \rightarrow \mathrm{D}_{\mathrm{n}} \end{gathered}$ |  | $\underset{\mathrm{S} \rightarrow \mathrm{R}_{1}}{\mathrm{EH}}$ |  | $\underset{\mathrm{S} \rightarrow \mathrm{R}_{1}}{\mathrm{EH}}$ |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $\underset{\mathrm{S} \rightarrow \mathrm{R}_{1}}{\mathrm{DT}}$ | $\alpha_{1}$ |  | $\alpha_{N}$ | $\begin{array}{\|c} \hline \mathrm{DT} \\ \mathrm{~S} \rightarrow \mathrm{R}_{1} \end{array}$ | $\alpha_{1}$ |  |  |
|  | $\alpha_{N}$ |  |  |  | $\alpha_{N}$ |  |  |
| $\underset{\mathrm{S} \rightarrow \mathrm{R}_{2}}{\mathrm{EH}}$ |  | $\underset{\mathrm{S} \rightarrow \mathrm{R}_{2}}{\mathrm{EH}}$ |  | $\underset{\mathrm{S} \rightarrow \mathrm{R}_{2}}{\mathrm{EH}}$ |  | $\begin{gathered} \mathrm{DT} \\ \mathrm{R}_{2} \rightarrow \mathrm{D}_{\mathrm{n}} \end{gathered}$ | $\alpha_{1}$ |
| $\begin{gathered} \mathrm{DT} \\ \mathrm{~S} \rightarrow \mathrm{R}_{2} \end{gathered}$ | $\alpha_{1}$ |  |  | $\underset{\mathrm{S} \rightarrow \mathrm{R}_{2}}{\substack{\mathrm{DT}}}$ | $\alpha_{1}$ |  | $\ldots$ |
|  | $\alpha_{N}$ |  |  | $\alpha_{N}$ | $\alpha_{N}$ |  |



Figure 7.13: Diagram of two transmission blocks.

$$
\mathbf{G}_{0}=\left[\begin{array}{ccc}
g_{0}^{(1,1)} & \cdots & g_{0}^{\left(1, A_{1}\right)}  \tag{7.97b}\\
\vdots & \ddots & \vdots \\
g_{0}^{\left(A_{0}, 1\right)} & \cdots & g_{0}^{\left(A_{0}, A_{1}\right)}
\end{array}\right],
$$

where $h_{0}^{\left(a_{0}, a_{1}\right)} \in \mathbf{H}_{0}$ and $g_{0}^{\left(a_{0}, a_{1}\right)} \in \mathbf{G}_{0}$ for $a_{0} \in A_{0}$ and $a_{1} \in A_{1}$ are channels from a transmitting antenna $a_{0}$ at the BS to a receiving antenna $a_{1}$ at the coupled relays $R_{1}$ and $R_{2}$. In addition, the fading channels are modeled over Rayleigh distributions with $h_{0}^{(., .)}$and $g_{0}^{(., .)}$following $h_{0}^{(., .)}=d_{R_{1}}^{-\omega}$ and $g_{0}^{(. .,)}=d_{R_{2}}^{-\omega}$, where $d_{R_{1}}$ and $d_{R_{2}}$ are the distances from the BS to the coupled relays $R_{1}$ and $R_{2}$, respectively, and the coefficient $\omega$ is the path-loss exponent factor.

By applying the PS protocol, the FTS in the OTB $T_{1}^{(o d d)}$ is used by the BS to transmit wireless energy and superimposed information simultaneously. To illustrate, two phases take place. In the first phase, the BS sends wireless energy to the coupled relay with the PS factor $\lambda$. Therefore, the EH from the best channel in the pre-coding channel matrices given by (7.97a) and (7.97b) in the FTS $T_{1}^{(o d d)}$ in the OTB $T^{(o d d)}$ at coupled relays $R_{1}$ and $R_{2}$ is expressed as follows:

$$
\begin{align*}
& E_{R_{1}}^{\left(T_{1}^{(o d d)}\right)}=\eta \lambda P_{S} \max _{\left[A_{0} \times A_{1}\right]}\left\{\left|\mathbf{H}_{0}\right|^{2}\right\},  \tag{7.98a}\\
& E_{R_{2}}^{\left(T_{1}^{(\text {odd })}\right)}=\eta \lambda P_{S} \max _{\left[A_{0} \times A_{1}\right]}\left\{\left|\mathbf{G}_{0}\right|^{2}\right\}, \tag{7.98b}
\end{align*}
$$

where $\eta$ is the collection factor, $\lambda$ is the PS factor, and $P_{S}$ is the transmission power at the BS.
In the second phase of the FTS $T_{1}^{(o d d)}$ in the OTB $T^{(o d d)}$, in a major advantage of NOMA theory, the BS broadcasts a superimposed signal by superimposing the messages $x_{i}$ of devices $D_{i}$, for $i=\{1, \ldots, N\}$, to the coupled relays $R_{1}$ and $R_{2}$. I assume that no direct down-link exists
from the BS to the devices. The received signal at the coupled relays is expressed as follows:

$$
\begin{align*}
& \max _{\left[A_{0} \times A_{1}\right]}\left\{\mathbf{Y}_{\mathrm{R}_{1}}^{\left(T_{1}^{(\text {odd })}\right)}\right\}=\sqrt{1-\lambda} \max _{\left[A_{0} \times A_{1}\right]}\left\{\left|\mathbf{H}_{0}\right|\right\} \sum_{i=N}^{1} \sqrt{\alpha_{\mathrm{i}} P_{S}} x_{i}+n_{R_{1}},  \tag{7.99a}\\
& \max _{\left[A_{0} \times A_{1}\right]}\left\{\mathbf{Y}_{\mathrm{R}_{2}}^{\left(T_{1}^{(o d d)}\right)}\right\}=\sqrt{1-\lambda} \max _{\left[A_{0} \times A_{1}\right]}\left\{\left|\mathbf{G}_{0}\right|\right\} \sum_{i=N}^{1} \sqrt{\alpha_{\mathrm{i}} P_{S}} x_{i}+n_{R_{2}}, \tag{7.99b}
\end{align*}
$$

where $n_{\mathcal{R}} \sim C N\left(0, N_{0}\right)$ is the AWGN at the coupled relays $\mathcal{R}=\left\{R_{1}, R_{2}\right\}$ with zero mean and variance $N_{0}$. The PA factors for devices $D_{i}$, for $i=\{N, \ldots, 1\}$, are respectively denoted by $\alpha_{i}$ and constrained to $\alpha_{1}<\ldots<\alpha_{N}, \alpha_{1}+\ldots+\alpha_{N}=1$ and given by:

$$
\begin{equation*}
\alpha_{i}=i / \sum_{n=1}^{N} n . \tag{7.100}
\end{equation*}
$$

Note that expression (7.100) is derived from the feature study [6]. However, the devices in study [6] were ordered where $D_{1}$ was the farthest device. However, the system model shown Figure 7.12 indicates that device $D_{N}$ has the farthest distance from the coupled relays. According to NOMA theory, the farthest device must be allocated the biggest PA factor. As a result, the PA factor $\alpha_{N}$ for device $D_{N}$ is the largest value among the PA factors, whereas device $D_{1}$ is the nearest distance from the coupled relays. Therefore, device $D_{1}$ is allocated the smallest PA factor.

SIC is another NOMA feature which is implemented at the user. The user therefore executes SIC to detect messages in the received signal. In [6] and [TTNam03], the authors investigated NOMA networks with a random number $N$ of users. The users repeated the SIC phases until their own messages were successfully detected in the received signal. It is important to note that $N$ devices exist in my model (Fig. 7.12), and therefore, $N$ SIC phases at the relay $R_{1}$. After selecting the received signal given by (7.99a), relay $R_{1}$ detects the message $x_{N}$ of device $D_{N}$ in the first SIC phase as a result of the constraint of the PA factors $\alpha_{N}>\ldots>\alpha_{1}$. In the second SIC phase, relay $R_{1}$ detects the message $x_{N-1}$ of device $D_{N-1}$ after removing the $x_{N}$ symbol from the received signals. The relay $R_{1}$ repeats SIC until it successfully detects the last symbol $x_{1}$.

However, the dissertation examines a massive MIMO underlay C-NOMA network in contrast to the schemes presented in [77, 92], where the authors studied cooperative SISO-NOMA schemes. Fortunately, the authors in [32] and [TTNam06] also investigated a MIMO-NOMA network with TAS and obtained the SINR, where the devices detected information by applying SIC. To optimize system performance, the dissertation considers the massive MIMO technique in combination with the TAS protocol, where relay $R_{1}$ selects the best received signal $\max \left\{\left|\mathbf{Y}_{R_{1}}^{\left(T_{1}^{(o d d)}\right)}\right|\right\}$ for SIC. In the first SIC phase, relay $R_{1}$ decodes the $x_{N}$ symbol from the
best received signal max $\left\{\left|\mathbf{Y}_{R_{1}}^{\left(T_{1}^{(\text {odd })}\right)}\right|\right\}$ by treating the data symbols $x_{j}=\left\{x_{1}, \ldots, x_{N-1}\right\}$ and AWGN $n_{R_{1}}$ as interference. The SINR is therefore obtained when relay $R_{1}$ decodes the $x_{i}$ symbol, as follows:

$$
\begin{align*}
\max _{\left[A_{0} \times A_{1}\right]}\left\{\begin{array}{c}
\left.\gamma_{R_{1}-x_{i}}^{\left(T_{1}^{(o d}\right)}\right) \\
i=\{N, \ldots, 1\}
\end{array}\right\} & =\frac{(1-\lambda) \max _{\left[A_{0} \times A_{1}\right]}\left\{\left|\mathbf{H}_{0}\right|^{2}\right\} \alpha_{i} \rho_{S}}{(1-\lambda) \max _{\left[A_{0} \times A_{1}\right]}\left\{\left|\mathbf{H}_{0}\right|^{2}\right\} \rho_{S} \sum_{j=1}^{i-1} \alpha_{j}+1}, \text { where } i>1,  \tag{7.101a}\\
& =(1-\lambda) \max _{\left[A_{0} \times A_{1}\right]}\left\{\left|\mathbf{H}_{0}\right|^{2}\right\} \alpha_{i} \rho_{S}, \quad \text { where } i=n=1, \tag{7.101b}
\end{align*}
$$

where $\rho_{S}$ is the transmission SNR and $\rho_{0}=P_{S} / N_{0}$.
Maximization of the instantaneous bit rate threshold is achieved at relay $R_{1}$ when relay $R_{1}$ decodes the message $x_{i}$, where $i=\{N, \ldots, 1\}$, as follows:

$$
\max _{\left[A_{0} \times A_{1}\right]}\left\{\begin{array}{c}
\left.\mathbf{R}_{R_{1}-x_{i}}^{\left(T_{1}^{(o d d)}\right.}\right)  \tag{7.102}\\
i=\{N, \ldots, 1\}
\end{array}\right\}=\frac{1}{2} \log _{2}\left(1+\max _{\left[A_{0} \times A_{1}\right]}\left\{\begin{array}{c}
\left(\begin{array}{c}
\left(T_{1}^{(\text {odd })}\right) \\
\gamma_{R_{1}}-x_{i} \\
i=\{N, \ldots, 1\}
\end{array}\right\}
\end{array}\right\}\right) .
$$

In the STS $T_{2}^{(o d d)}$ in the OTB $T^{(o d d)}$, the relay $R_{1}$ retrieves the messages $x_{i}=\left\{x_{N}, \ldots, x_{1}\right\}$ and forwards the messages to the devices in the superimposed signal while the relay $R_{2}$ continues to harvest energy from the BS. Therefore, the received signal at devices $D_{n}$, where $n=\{1, \ldots, N\}$, and the EH at relay $R_{2}$ are expressed, respectively, as follows:

$$
\begin{align*}
\max _{\left[A_{1} \times A_{2}\right]}\left\{\mathbf{Y}_{n \in N}^{\left(T_{2}^{(o d d)}\right)}\right\} & =\max _{\left[A_{1} \times A_{2}\right]}\left\{\left|\mathbf{H}_{n}\right|\right\} \sum_{i=N}^{1} \sqrt{\alpha_{\mathbf{1}} P_{R_{1}}} x_{i}+n_{n},  \tag{7.103a}\\
E_{R_{2}}^{\left(T_{2}^{(o d d)}\right)} & =\eta \lambda P_{S} \max _{\left[A_{0} \times A_{1}\right]}\left\{\left|\mathbf{G}_{\mathbf{0}}\right|^{2}\right\}, \tag{7.103b}
\end{align*}
$$

where $P_{R_{1}}$ is the transmission power at relay $R_{1}$ and $n_{n} \sim C N\left(0, N_{0}\right)$ is the AWGN at device $D_{n}$, where $n=\{1, \ldots, N\}$, which follows zero mean and variance $N_{0}$.

Note that the pre-coding channel matrix $\mathbf{H}_{\mathbf{n}}$ is given by:

$$
\underset{n=\{1, \ldots, N\}}{\mathbf{H}_{n}}=\left[\begin{array}{ccc}
h_{n}^{(1,1)} & \cdots & h_{n}^{\left(1, A_{2}\right)}  \tag{7.104}\\
\vdots & \ddots & \vdots \\
h_{n}^{\left(A_{1}, 1\right)} & \cdots & h_{n}^{\left(A_{1}, A_{2}\right)}
\end{array}\right]
$$

where the channel $h_{n}^{\left(a_{1}, a_{2}\right)}$ in the pre-coding channel matrix $\mathbf{H}_{n}$, where $a_{1} \in A_{1}$ and $a_{2} \in A_{2}$, is a channel from the transmitting antenna $a_{1}$ at relay $R_{1}$ to the receiving antenna $a_{2}$ at device $D_{n}$, also applying Rayleigh distribution for propagation. Each fading channel gain is given by $h_{n}^{(\ldots .)}=d_{n}^{-\omega}$, where $d_{n}$ is the distance from relay $R_{1}$ to device $D_{n}$.

As a result of the combination of TAS and SIC, the SINR is obtained at devices $D_{n}$, where $n=\{1, \ldots, N\}$, when the devices decode the data symbols $x_{i}$, where $i=\{N, \ldots, n\}$, from the best received signal max $\left\{\left|\mathbf{Y}_{\mathbf{2}}\right|\right\}_{\mathcal{A}_{1} \times \mathcal{A}_{2}}$ by treating the data symbols $x_{j}$, where $j=\{1, \ldots, i-1\}$, and the AWGN $n_{n}$ as interference:

$$
\begin{align*}
\max _{\left[A_{1} \times A_{2}\right]}\left\{\underset{n}{\gamma_{n \in N}^{n}-} \underset{i=\left\{x_{i}, \ldots, n\right\}}{\left(T_{2}^{(o d d)}\right)}\right\} & =\frac{\max _{\left[A_{1} \times A_{2}\right]}\left\{\left|\mathbf{H}_{n}\right|^{2}\right\} \alpha_{i} \rho_{R_{1}}}{\max _{\left[A_{1} \times A_{2}\right]}\left\{\left|\mathbf{H}_{n}\right|^{2}\right\} \sum_{j=1}^{i-1} \alpha_{j} \rho_{R_{1}}+1}, \text { where } i>1,  \tag{7.105a}\\
& =\max _{\left[A_{1} \times A_{2}\right]}\left\{\left|\mathbf{H}_{n}\right|^{2}\right\} \alpha_{i} \rho_{R_{1}}, \quad \text { where } i=n=1, \tag{7.105b}
\end{align*}
$$

where SNR $\rho_{R_{1}}=P_{R_{1}} / N_{0}$.
The achievable bit rate reached at device $D_{n}$ when it decodes the data symbol $x_{i}$, where $i=\{N, \ldots, n\}$, from the best received signal $\max \left\{\left|\mathbf{Y}_{\mathbf{n}}\right|\right\}$ is expressed as follows:

### 7.7.2 Even transmission block

In the same manner as the FTS in the OTB, by applying the PS protocol, the BS uses the FTS in the ETB $T_{1}^{(e v e n)}$ to transmit wireless energy and superimposed information simultaneously to coupled relays. The EH from the best channel in the pre-coding channel matrix at coupled relays $R_{1}$ and $R_{2}$ is expressed as follows:

$$
\begin{align*}
& E_{R_{1}}^{T_{1}^{(e v e n)}}=\eta \lambda P_{S} \max _{\left[A_{0} \times A_{1}\right]}\left\{\left|\mathbf{H}_{0}\right|^{2}\right\},  \tag{7.107a}\\
& E_{R_{2}}^{T_{1}^{(e v e n)}}=\eta \lambda P_{S} \max _{\left[A_{0} \times A_{1}\right]}\left\{\left|\mathbf{G}_{0}\right|^{2}\right\},
\end{align*}
$$

where $T_{1}^{(o d d)}=T^{(o d d)} / 2$.
The BS broadcasts a beamforming superimposed signal by combining the independent messages $x_{i}$ of devices $D_{i}$, where $i=\{N, \ldots, 1\}$. Therefore, the received signal at the coupled relays is expressed as:

$$
\begin{align*}
& \max _{\left[A_{0} \times A_{1}\right]}\left\{\mathbf{Y}_{\mathrm{R}_{1}}^{\left(T_{1}^{(\text {even })}\right)}\right\}=\sqrt{1-\lambda} \max _{\left[A_{0} \times A_{1}\right]}\left\{\left|\mathbf{H}_{0}\right|\right\} \sum_{i=N}^{1} \sqrt{\alpha_{\mathrm{i}} P_{S}} x_{i}+n_{R_{1}},  \tag{7.108a}\\
& \max _{\left[A_{0} \times A_{1}\right]}\left\{\mathbf{Y}_{\mathrm{R}_{2}}^{\left(T_{1}^{(\text {even })}\right)}\right\}=\sqrt{1-\lambda} \max _{\left[A_{0} \times A_{1}\right]}\left\{\left|\mathbf{G}_{0}\right|\right\} \sum_{i=N}^{1} \sqrt{\alpha_{\mathrm{i}} P_{S}} x_{i}+n_{R_{2}} . \tag{7.108b}
\end{align*}
$$

In the second transmission block, SIC is executed at relay $R_{2}$. In the same manner as SIC in the OTB, relay $R_{2}$ must repeat SIC until it detects all data symbols $x_{i}$, where $i=\{N, \ldots, 1\}$, in the best received signal given by (7.108b). The SINR is obtained when relay $R_{2}$ decodes the data symbols $x_{i}=\left\{x_{N}, \ldots, x_{1}\right\}$ as follows:

$$
\begin{align*}
\max _{\left[A_{0} \times A_{1}\right]}\left\{\begin{array}{c}
(1-\lambda) \max _{\left[A_{0} \times A_{1}\right]}^{\left(T_{1}^{(\text {even })}\right)}\left\{\left|\mathbf{G}_{0}\right|^{2}\right\} \alpha_{i} \rho_{S} \\
i=\{N, \ldots, 1\}
\end{array}\right\} & =\frac{(1-\lambda) \max _{\left[A_{0} \times A_{1}\right]}\left\{\left|\mathbf{G}_{0}\right|^{2}\right\} \rho_{S} \sum_{j=1}^{i-1} \alpha_{j}+1}{(1-\text { where } i>1},  \tag{7.109a}\\
& =(1-\lambda) \max _{\left[A_{0} \times A_{1}\right]}\left\{\left|\mathbf{G}_{0}\right|^{2}\right\} \alpha_{i} \rho_{S}, \quad \text { where } i=n=1 . \tag{7.109b}
\end{align*}
$$

Similarly (7.101a) and (7.101b), maximization of the instantaneous bit rate threshold achieved at relay $R_{2}$ when relay $R_{2}$ decodes data symbols $x_{i}$, where $i=\{N, \ldots, 1\}$, is expressed as follows:

$$
\max _{\left[A_{0} \times A_{1}\right]}\left\{\begin{array}{c}
\left.\mathbf{R}_{R_{2}-x_{i}}^{\left(T_{1}^{(\text {even })}\right.}\right)  \tag{7.110}\\
i=\{N, \ldots, 1\}
\end{array}\right\}=\frac{1}{2} \log _{2}\left(1+\max _{\left[A_{0} \times A_{1}\right]}\left\{\begin{array}{c}
\left.\gamma_{R_{2}-x_{i}}^{\left(T_{1}^{(\text {even })}\right.}\right) \\
i=\{N, \ldots, 1\}
\end{array}\right\}\right) .
$$

By applying the DF protocol, relay $R_{2}$ recovers the decoded data symbols $x_{i}$, where $i=$ $\{N, \ldots, 1\}$, and forwards a beamforming superimposed signal to devices $D_{n}$, where $n=\{1, \ldots, N\}$. The received signals in the STS $T_{2}^{(\text {even })}$ in the ETB $T^{(\text {even })}$ at devices $D_{n}$ while relay $R_{1}$ harvests energy are expressed, respectively, as follows:

$$
\begin{align*}
\max _{\left[A_{1} \times A_{2}\right]}\left\{\mathbf{Y}_{n \in N}^{\left(T_{2}^{(\text {even })}\right)}\right\} & =\max _{\left[A_{1} \times A_{2}\right]}\left\{\left|\mathbf{G}_{n}\right|\right\} \sum_{i=N}^{1} \sqrt{\alpha_{\mathrm{i}} P_{R_{2}}} x_{i}+n_{n}  \tag{7.111a}\\
E_{R_{1}}^{\left(T_{2}^{(\text {even })}\right)} & =\eta \lambda P_{S} \max _{\left[A_{0} \times A_{1}\right]}\left\{\left|\mathbf{H}_{\mathbf{0}}\right|^{2}\right\}, \tag{7.111b}
\end{align*}
$$

where $P_{R_{2}}$ is the transmission power at relay $R_{2}$, and the pre-coding channel matrix $\mathbf{G}_{n}$ is given by:

$$
\underset{n=\{1, \ldots, N\}}{\mathbf{G}_{n}}=\left[\begin{array}{ccc}
g_{n}^{(1,1)} & \cdots & g_{n}^{\left(1, A_{2}\right)}  \tag{7.112}\\
\vdots & \ddots & \vdots \\
g_{n}^{\left(A_{1}, 1\right)} & \cdots & g_{n}^{\left(A_{1}, A_{2}\right)}
\end{array}\right]
$$

where the channel $g_{n}^{\left(a_{1}, a_{2}\right)}$ in the pre-coding matrix channel $\mathbf{G}_{n}$, where $a_{1} \in \mathcal{A}_{1}$ and $a_{2} \in \mathcal{A}_{2}$, is a channel from the transmitting antenna $a_{1}$ at relay $R_{2}$ to the receiving antenna $a_{2}$ at device $D_{n}$, applying Rayleigh distributions for propagation. Each fading channel is represented by $g_{n}^{(., .)}$ where $g_{n}^{(., .)}=v_{n}^{-\omega}$ and $v_{n}$ is the distance from relay $R_{2}$ to device $D_{n}$.

The SINR obtained at devices $D_{n}$, where $n=\{1, \ldots, N\}$, when they decode the data symbols $x_{i}$, where $i=\{N, \ldots, n\}$, from the best received signal $\max _{\left[A_{1} \times A_{2}\right]}\left\{\left|\mathbf{Y}_{n}^{\left(T_{2}^{(\text {even })}\right)}\right|\right\}$ is expressed as
follows:

$$
\begin{align*}
& \left.\max _{\left[A_{1} \times A_{2}\right]}\left\{\underset{\substack{n \\
n \in N}}{\left(T_{2}^{(\text {even })}\right.}\right)_{\substack{x_{i} \\
i=\{N, \ldots, n\}}}\right\}=\frac{\max _{\left[A_{1} \times A_{2}\right]}\left\{\left|\mathbf{G}_{n}\right|^{2}\right\} \alpha_{i} \rho_{R_{2}}}{\max _{\left[A_{1} \times A_{2}\right]}\left\{\left|\mathbf{G}_{n}\right|^{2}\right\} \sum_{j=1}^{i-1} \alpha_{j} \rho_{R_{2}}+1} \text {, where } i>1 \text {, }  \tag{7.113a}\\
& =\max _{\left[A_{1} \times A_{2}\right]}\left\{\left|\mathbf{G}_{n}\right|^{2}\right\} \alpha_{i} \rho_{R_{2}}, \quad \text { where } i=n=1, \tag{7.113b}
\end{align*}
$$

where SNR $\rho_{R_{2}}=P_{R_{2}} / N_{0}$.
Maximization of the achievable bit rate thresholds achieved at devices $D_{n}$ when they decode the data symbols $x_{i}$, where $i=\{N, \ldots, n\}$, from the best received signal $\max _{\left[A_{1} \times A_{2}\right]}\left\{\left|\mathbf{Y}_{n}^{\left(T_{2}^{(\text {even })}\right)}\right|\right\}$ is expressed as follows:

### 7.8 System Performance Analysis

The downlink MIMO-NOMA model, with superposition transmission at the BS and SIC at the terminal devices, adopts SIC processing at the receivers [33]. The dissertation therefore considers OP at the receivers when the receivers cannot successfully decode messages in the received signals. I analyzed the system performance of the network model depicted in Figure 7.12 and deliver novel closed form expressions of OP, system throughput and EE at the coupled relays $\mathcal{R}=\left\{R_{1}, R_{2}\right\}$ and devices $D_{n}$, where $n=\{1, \ldots, N\}$.

### 7.8.1 Outage probability at the coupled relays $\mathcal{R}$

Theorem 1: The outage event at a relay in the coupled relays $\mathcal{R}$ occurs when the relay cannot successfully decode at least the data symbol $x_{i} \in\left\{x_{N}, \ldots, x_{1}\right\}$ from the best received signal $\max _{\left[A_{0} \times A_{1}\right]}\left\{\left|\mathbf{Y}_{R_{1}}^{\left(T_{1}^{(\text {odd })}\right)}\right|\right\}$ for the OTB or $\left.\max _{\left[A_{0} \times A_{1}\right]}\left\{\mid \mathbf{Y}_{R_{2}}^{\left(T_{1}^{(\text {even })}\right)}\right) \mid\right\}$ for the ETB, which is the best signal after TAS. Therefore, the coupled relays $\mathcal{R}$ receive the best superimposed signal $\max _{\left[A_{0} \times A_{1}\right]}\left\{\left|\mathbf{Y}_{\mathcal{R}}^{\left(T_{1}^{(\theta)}\right)}\right|\right\}$ by applying the TAS protocol to select the best signal from the precoding channel matrix $\mathbf{H}_{\mathbf{0}}$ for the OTB or $\mathbf{G}_{0}$ for the ETB to maximize the $\operatorname{SINR} \gamma_{\mathcal{R}-x_{i}}^{\left(T_{1}^{(\theta)}\right)}$ given by (7.101a), (7.101b), (7.109a) and (7.109a) and to maximize the instantaneous bit rate threshold $\max _{\left[A_{0} \times A_{1}\right]}\left\{\begin{array}{c}\left(T_{1}^{(\theta)}\right) \\ \left.\mathbf{R}_{\mathcal{R}-x_{i}}^{i=\{N, \ldots, 1\}}\right\}\end{array}\right\}$ given by (7.102) or (7.110). Maximization of the instantaneous bit rate threshold $\max _{\left[A_{0} \times A_{1}\right]}\left\{\begin{array}{c}\mathbf{R}_{\mathcal{R}}\left(T_{1}^{(\theta)}\right) \\ i=\{N, \ldots, 1\}\end{array}\right\}$ is then compared to a device's predefined bit rate threshold $R_{i}^{*}$, where $i=\{N, \ldots, 1\}$. If maximization of the instantaneous bit rate threshold
$\max _{\left[A_{0} \times A_{1}\right]}\left\{\begin{array}{c}\mathbf{R}_{\mathcal{R}-x_{i}}^{\left(T_{1}^{(\theta)}\right)} \\ i=\{N, \ldots, 1\}\end{array}\right\}$ is less than a device's predefined bit rate threshold $R_{i}^{*}$, an outage event will occur, i.e, the OP at coupled relays $\mathcal{R}$ is expressed as follows:

$$
\begin{align*}
O P_{\mathcal{R}}^{\left(T_{1}^{(\theta)}\right)} & =\operatorname{Pr}\left\{\max _{\left[A_{0} \times A_{1}\right]}\left\{\mathbf{R}_{\mathcal{R}-x_{N}}^{\left(T_{1}^{(\theta)}\right)}\right\}<R_{N}^{*}\right\} \\
& +\operatorname{Pr}\left\{\max _{\left[A_{0} \times A_{1}\right]}\left\{\mathbf{R}_{\mathcal{R}-x_{N}}^{\left(T_{1}^{(\theta)}\right)}\right\} \geq R_{N}^{*}, \max _{\left[A_{0} \times A_{1}\right]}\left\{\mathbf{R}_{\mathcal{R}-x_{N-1}}^{\left(T_{1}^{(\theta)}\right)}\right\}<R_{N-1}^{*}\right\} \\
& + \\
& \vdots \\
& +\operatorname{Pr}\left\{\begin{array}{c}
\max _{\left.A_{0} \times A_{1}\right]}\left\{\mathbf{R}_{\mathcal{R}-x_{N}}^{\left(T_{1}^{(\theta)}\right)}\right\} \geq R_{N}^{*}, \max _{\left[A_{0} \times A_{1}\right]}\left\{\mathbf{R}_{\mathcal{R}-x_{N-1}}^{\left(T_{1}^{(\theta)}\right)}\right\} \geq R_{N-1}^{*}, \ldots, \\
\max _{\left[A_{0} \times A_{1}\right]}\left\{\mathbf{R}_{\mathcal{R}-x_{2}}^{\left(T_{1}^{(\theta)}\right)}\right\} \geq R_{2}^{*}, \max _{\left[A_{0} \times A_{1}\right]}\left\{\mathbf{R}_{\mathcal{R}-x_{1}}^{\left(T_{1}^{(\theta)}\right)}\right\}<R_{1}^{*}
\end{array}\right\} \tag{7.115}
\end{align*}
$$

We obtain the OP at coupled relays $\mathcal{R}=\left\{R_{1}, R_{2}\right\}$ in novel closed form as follows:

$$
\begin{align*}
O P_{\mathcal{R}}^{\left(T_{1}^{(\theta)}\right)} & =\sum_{i=N}^{1}\left(\prod_{a_{0}=0}^{A_{0}} \prod_{a_{1}=1}^{A_{1}}\left(1-\exp \left(-\frac{\gamma_{i}^{*}}{(1-\lambda) \beta_{i} \rho_{S} \sigma_{\mathcal{R}}^{2}}\right)\right)\right. \\
& \times \underbrace{\prod_{k=N}^{i+1}\left(1-\prod_{a_{0}=1}^{A_{1}} \prod_{a_{1}=1}^{A_{1}}\left(1-\exp \left(-\frac{\gamma_{k}^{*}}{(1-\lambda)\left(\alpha_{k}-\gamma_{k}^{*} \sum_{j=1}^{k-1} \alpha_{j}\right) \rho_{S} \sigma_{\mathcal{R}}^{2}}\right)\right)\right.}_{\text {where } i<N}) \tag{7.116}
\end{align*}
$$

where $\beta_{i}$ is given by

$$
\begin{array}{lr}
\beta_{i}=\alpha_{i}-\gamma_{i}^{*} \sum_{j=1}^{i-1} \alpha_{j}, & \text { where } i>1 \\
\beta_{i}=\alpha_{i}, & \text { where } i=1 \tag{7.117b}
\end{array}
$$

Remark 1: If the network has a large number of devices, it is difficult to apply the expression (7.115) in Monte Carlo simulations. However, in the study [TTNam03], I analyzed a network model with multiple relays and multiple devices. I presented the expressions for OP at the relays as [TTNam03, Eq. (33)]. It is important to mention that this chapter extends the work of the previous study [TTNam03] by deploying massive MIMO and TAS techniques. From [TTNam03,

Eq. (33)], the OP expression at the coupled relay $\mathcal{R}$ in (7.115) can be rewritten as follows:

$$
\begin{equation*}
O P_{\mathcal{R}}^{\left(T_{1}^{(\theta)}\right)}=1-\prod_{i=N}^{1} \underbrace{\operatorname{Pr}\left\{\max \left\{\mathbf{R}_{\mathcal{R}-x_{i}}^{\left(T_{1}^{(\theta)}\right)}\right\} \geq R_{i}^{*}\right\}}_{Q_{i}} . \tag{7.118}
\end{equation*}
$$

From (7.118), we obtain a novel expression of OP at the coupled relay $\mathcal{R}$ in closed form by applying the Cumulative Density Function (CDF) as defined in [TTNam04Eq. (71)]:

$$
\begin{equation*}
O P_{\mathcal{R}}^{\left(T_{1}^{(\theta)}\right)}=1-\prod_{i=N}^{1}\left(1-\sum_{\psi=0}^{A_{0} A_{1}} \frac{(-1)^{\psi}\left(A_{0} A_{1}\right)!}{\psi!\left(A_{0} A_{1}-\psi\right)!} \exp \left(-\frac{\psi \gamma_{i}^{*}}{(1-\lambda) \beta_{i} \rho_{S} \sigma_{\mathcal{R}}^{2}}\right)\right) . \tag{7.119}
\end{equation*}
$$

See Appendix A (section 7.11.1) for proof.

### 7.8.2 Outage probability at device $D_{n}$

Theorem 2: The outage event in an OTB or ETB at devices $D_{n}$, where $n=\{1, \ldots, N\}$, occurs when, in one case, the relays $R_{1}$ and $R_{2}$ for the OTB and ETB, respectively, cannot successfully decode at least data symbol $x_{i}$, where $i=\{N, \ldots, n\}$, from the best received signal $\max _{\left[A_{0} \times A_{1}\right]}\left\{\left|\mathbf{Y}_{R_{1}}^{\left(T_{1}^{(\text {odd })}\right)}\right|\right\}$ given by (7.99a) or $\max _{\left[A_{0} \times A_{1}\right]}\left\{\left|\mathbf{Y}_{R_{2}}^{\left(T_{1}^{(\text {even })}\right)}\right|\right\}$ given by (7.108b), and in the other case, the coupled relays can successfully decode all data symbol $x_{i}$, where $i=\{N, \ldots, n\}$, but device $D_{n}$ cannot successfully decode at least data symbols $x_{i}$, where $i=\{N, \ldots, n\}$, from the best received signal $\max _{\left[A_{1} \times A_{2}\right]}\left\{\left|\mathbf{Y}_{n}^{\left(T_{2}^{(\text {odd })}\right)}\right|\right\}$ as (7.103a) for the OTB or $\max _{\left[A_{1} \times A_{2}\right]}\left\{\left|\mathbf{Y}_{n}^{\left(T_{2}^{(\text {even })}\right)}\right|\right\}$ given by (7.111a) for the ETB.

Therefore, the device OP in an OTB/ETB is expressed as follows:

$$
\left.\begin{array}{rl}
O P_{n}^{(\theta)}= & \sum_{i=N}^{n}\left\{\operatorname { P r } \left\{\max _{\left[A_{0} \times A_{1}\right]}\left\{\mathbf{R}_{\mathcal{R}-x_{i}}^{\left(T_{1}^{(\theta)}\right)}\right\}<R_{i}^{*}\right.\right.
\end{array}\right\} \underbrace{\prod_{k=N}^{i+1} \operatorname{Pr}\left\{\max _{\left[A_{0} \times A_{1}\right]}\left\{\mathbf{R}_{\mathcal{R}-x_{k}}^{\left(T_{1}^{(\theta)}\right)}\right\} \geq R_{k}^{*}\right\}}_{\text {where } i<N}\} .
$$

From (7.120), the OP at user $D_{n}$ is obtained in closed form as follows:

$$
\begin{align*}
O P_{n \in N}^{(\theta)} & =\sum_{i=N}^{n}(\underbrace{\prod_{a_{0}}^{A_{0}} \prod_{a_{1}}^{A_{1}}\left(1-\exp \left(-\frac{\gamma_{i}^{*}}{(1-\lambda) \beta_{i} \rho_{S} \sigma_{\mathcal{R}}^{2}}\right)\right)}_{Q_{i}} \underbrace{\prod_{k=N}^{i+1}\left(1-Q_{k}\right)}_{\text {where } i<N}) \\
& +\sum_{i=N}^{n}(\underbrace{\prod_{a_{1}}^{A_{1}} \prod_{a_{2}}^{A_{2}}\left(1-\exp \left(-\frac{\gamma_{i}^{*}}{\beta_{i} \rho_{\mathcal{R}} \sigma_{n}^{2}}\right)\right.}_{K_{i}}) \underbrace{\prod_{k=N}^{i+1}\left(1-K_{k}\right)}_{\text {where } i<N} \prod_{t=N}^{n}\left(1-Q_{t}\right)) . \tag{7.121}
\end{align*}
$$

where $\sigma_{n}^{2}=E\left\{\left|\mathbf{H}_{n}\right|^{2}\right\}$. Note that $\theta=$ odd and $\mathcal{R}=R_{1}$, or $\theta=$ even and $\mathcal{R}=R_{2}$.
Remark 2: Similarly (7.115), note that the expression (7.120) is difficult in Monte Carlo simulations if the network has a large number of devices. Therefore, the OP at devices $D_{n}$ can be rewritten as:

$$
\begin{equation*}
O P_{n}^{(\theta)}=1-\prod_{i=N}^{n} \operatorname{Pr}\left\{\max _{\left[A_{0} \times A_{1}\right]}\left\{\mathbf{R}_{\mathcal{R}-x_{i}}^{\left(T_{1}^{(\theta)}\right)}\right\} \geq R_{i}, \max _{\left[A_{1} \times A_{2}\right]}\left\{\mathbf{R}_{n-x_{i}}^{\left(T_{2}^{(\theta)}\right)}\right\} \geq R_{i}\right\} . \tag{7.122}
\end{equation*}
$$

From (7.122), the OP at devices $D_{n}$ is expressed in closed form as:

$$
\begin{align*}
& O P_{n}^{(\theta)}=1-\prod_{i=N}^{n}( \\
&\left(1-\sum_{\psi=0}^{A_{0} A_{1}} \frac{(-1)^{\psi}\left(A_{0} A_{1}\right)!}{\psi!\left(A_{0} A_{1}-\psi\right)!} \exp \left(-\frac{\psi \gamma_{i}^{*}}{(1-\lambda) \beta_{i} \rho_{S} \sigma_{\mathcal{R}}^{2}}\right)\right)  \tag{7.123}\\
&\left.\times\left(1-\sum_{\mu=0}^{A_{1} A_{2}} \frac{(-1)^{\mu}\left(A_{1} A_{2}\right)!}{\mu!\left(A_{1} A_{2}-\mu\right)!} \exp \left(-\frac{\mu \gamma_{i}^{*}}{\beta_{i} \rho_{\mathcal{R}} \sigma_{n}^{2}}\right)\right)\right)
\end{align*}
$$

See Appendix B (section 7.11.2) for the proof.

### 7.8.3 System throughput

From Figures 7.12 and 7.13 , the individual system model has two transmission blocks. Each OTB/ETB is separated into two time slots. The achievable system throughput in an OTB/ETB is the sum of the minimal device throughput at the relay and device in the same transmission block. Therefore, the system throughput is expressed as:

$$
\begin{equation*}
T P^{(\theta)}=\sum_{n=1}^{N}\left(1-\max \left\{O P_{\mathcal{R}-x_{n}}^{\left(T_{1}^{(\theta)}\right)}, O P_{n-x_{n}}^{\left(T_{2}^{(\theta)}\right)}\right\}\right) R_{n}^{*} \tag{7.124}
\end{equation*}
$$

### 7.8.4 Energy efficiency

G-WNs require higher throughput but use less energy. To achieve this aim, the dissertation deploys a massive MIMO technique and SWIPT protocol. As a result, the EE performance indicates the sum of the device throughput and sum of the transmission power at the BS and
coupled relay ratio in the same transmission block. Therefore, the EE performance of an individual network model given by Figure 7.12 is expressed as:

$$
\begin{equation*}
E E^{(\theta)}=\frac{\sum_{n=1}^{N}\left(1-\max \left\{O P_{\mathcal{R}-x_{n}}^{\left(T_{1}^{(\theta)}\right)}, O P_{n-x_{n}}^{\left(T_{2}^{(\theta)}\right)}\right\}\right) R_{n}^{*}}{(1-\lambda) \rho_{S}+\rho_{R}} \tag{7.125}
\end{equation*}
$$

### 7.9 Numerical Results and Discussion

To investigate the system performance of the massive MIMO-NOMA network model shown in Figure 7.12, I propose the parameters for both theoretical analysis and Monte Carlo simulations shown in Table 8.

Let a wireless network contain coupled relays and three devices $(N=3)$. The coupled relays are allocated nearby. The distances from the BS to the coupled relays are $d_{R_{1}}=d_{R_{2}}=10 \mathrm{~m}$, and the distances from the coupled relays to devices $D_{1}, D_{2}$ and $D_{3}$ are $d_{1}=v_{1}=5 \mathrm{~m}, d_{2}=v_{2}=7 \mathrm{~m}$ and $d_{3}=v_{3}=10 \mathrm{~m}$, respectively. The path-loss exponent refers to an indoor environment where $\lambda=4$. By modeling the more challenging indoor environment, the performance bound of the less difficult outdoor scenario is therefore also covered. In 4G Long Term Evolution (LTE) release 8, the maximum number of antennas at the BS and user equipment are 4 T 4 R and $1 T 2 \mathrm{R}$, respectively. In 4G LTE-Advanced (LTE-A), the number of antennas is greater to allow the use of 8 T 8 R at BSs and 2T2R at devices in LTE-A schemes. Therefore, massive MIMO networks need at least an 8 T 8 R antenna array at the BS . However, the dissertation assumes a certain number of antennas equipped at the $\mathrm{BS}\left(A_{0}=4\right)$, coupled relays $R_{1}\left(A_{1}=4\right)$, $R_{2}\left(A_{1}=16\right)$ and devices $\left(A_{2}=2\right)$ to prove the the benefits of massive MIMO (for ETB) over MIMO (for OTB). The fading channel from the transmitting antennas at the BS to the receiving antennas at the coupled relays are distributed over Rayleigh fading channels. Based on distances and the path-loss exponent, the expected channel gains from the BS to coupled relays are $\sigma_{R_{1}}^{2}=\sigma_{R_{2}}^{2}=1 e-4$ and from the coupled relays to devices $D_{1}, D_{2}$ and $D_{3}$ are $\sigma_{1}^{2}=16 e-4$, $\sigma_{2}^{2}=4.1649 e-4$ and $\sigma_{3}^{2}=1 e-4$. Each fading channel randomly generates $1 e 6$ experiments. To simplify, the devices require the same bit rate thresholds $R_{1}^{*}=R_{2}^{*}=R_{3}^{*}=0.1 \mathrm{bps} / \mathrm{Hz}$ and SNR $\rho_{S}=\rho_{\mathcal{R}}=\{0, \ldots, 30\} d B$. By applying (7.100), the PA factors for devices $D_{1}, D_{2}$ and $D_{3}$ are $\alpha_{1}=0.1667, \alpha_{2}=0.3333$ and $\alpha_{3}=0.5$, respectively. The dissertation assumes that coupled relays may fully collect EH ( $\eta=1$ ). The PS factor in an OTB is $\lambda=0.4$. Therefore, $0.4 P_{S}$ and $0.6 P_{S}$ are applied to EH and DT processing, respectively, whereas the PS factor in the ETB is reduced ( $\lambda=0.4$ ) since the relay $R_{2}$ in this block is equipped with more antennas than relay $R_{1}$ in the OTB.

Figure 7.14 plots the OP performance at relay $R_{1}$ and devices in the OTBs. Note the various markers and line plot analysis (Ana) and simulation (Sim) results. The analysis results of OP performance at relay $R_{1}$ are given by (7.115) or (7.118) and for devices $D_{n}$ by (7.120) or (7.122). The analysis results were verified with Monte Carlo simulations for relay $R_{1}$ given by (7.116) or (7.119) and for devices by (7.121) or (7.123), where $\mathcal{R}=R_{1}$ and $\theta=o d d$. Figure 7.14 illustrates

Table 8: Table of parameters.

| Variables | Values | Units |
| :--- | :--- | :--- |
| N | 3 |  |
| $d_{R_{1}}=d_{R_{2}}$ | 10 | metres |
| $d_{1}=v_{1}$ | 5 | metres |
| $d_{2}=v_{2}$ | 7 | metres |
| $d_{3}=v_{3}$ | 10 | metres |
| $\alpha_{1}$ | 0.1667 |  |
| $\alpha_{2}$ | 0.3333 |  |
| $\alpha_{3}$ | 0.5 |  |
| $\omega$ | 4 |  |
| $\sigma_{R_{1}}^{2}=\sigma_{R_{2}}^{2}$ | $1 e-4$ |  |
| $\sigma_{1}^{2}$ | 0.0016 |  |
| $\sigma_{2}^{2}$ | $4.1649 e-4$ |  |
| $\sigma_{3}^{2}$ | $1 \mathrm{e}-4$ |  |
| $R_{1}^{*}=R_{2}^{*}=R_{3}^{*}$ | 0.1 | $b p s / H z$ |
| $\rho_{S}=\rho_{R_{1}}=\rho_{R_{2}}$ | $\{0, \ldots, 30\}$ | $d B$ |
| $\eta$ | 1 |  |
| $A_{0}$ | 4 |  |
| $A_{2}$ | 2 |  |
|  | OTB |  |
| $A_{1}$ | 4 |  |
| $\lambda$ | 0.4 |  |
|  | 16 |  |
| $A_{1}$ | 0.6 |  |



Figure 7.14: OP at relay $R_{1}$ and devices $D_{n}$, where $n=\{1, \ldots, N\}$ in an odd transmission block, where the number of antennas equipped at the BS , relay $R_{1}$ and devices $D_{n}$ are $A_{0}=4$, $A_{1}=4$ and $A_{2}=2$, respectively, and the PS factor $\lambda=0.4$.
that device $D_{3}$ achieved the best OP results, even though device $D_{3}$ was the farthest device and therefore allocated the biggest PA factor $\alpha_{3}=0.5$. When SRN $\rho \rightarrow \infty$, the OP results of relay $R_{1}$ and devices tend to zero.

Figure 7.15 plots the OP performance at relay $R_{2}$ and devices in the ETBs. To improve the networking capacity and energy, I equipped a large number of antennas at relay $R_{2}$ and increased the PS factor to $\lambda=0.6$. By increasing the PS factor, relay $R_{1}$ was able to harvest more energy, but relay $R_{2}$ could only receive weak signals. However, I may observe that the OP performance at relay $R_{2}$ and devices in the ETBs (Fig. 7.15) achieved better results than the OP performance at relay $R_{1}$ and devices in the OTBs (Fig. 7.14). The analysis results of the OP performance for relay $R_{2}$ are given by (7.115) or (7.118) and for the devices $D_{n}$ by (7.120) or (7.122), where $\mathcal{R}=R_{2}$ and $\theta=$ even. The analysis results were verified with Monte Carlo simulations for relay $R_{2}$ given by (7.116) or (7.119) and for the devices by (7.121) or (7.123), where $\mathcal{R}=R_{2}$ and $\theta=$ even.

We may observe that the OP performances at relay $R_{2}$ and the devices in ETBs outperform those at relay $R_{1}$ and the devices in OTBs at high SNR such as $\rho_{S}=\rho_{\mathcal{R}}=20 d B$. The dissertation thus exploits the advantages of a massive MIMO-NOMA network compared to a MIMO-NOMA network. I equipped more antennas at relay $R_{2}\left(A_{1}=16\right)$ than at relay $R_{1}$ $\left(A_{1}=4\right)$. As a result, I obtained the respective pre-coding channel matrix sizes of $[4 \times 16]$ and $[16 \times 2]$ for $\mathbf{G}_{0}$ and $\mathbf{G}_{n}$, which, in the ETBs, were much larger than the pre-coding channel matrix sizes of $[4 \times 4]$ and $[4 \times 2]$ for $\mathbf{H}_{0}$ and $\mathbf{H}_{n}$ in the OTBs. From the expressions (7.101a), (7.101b), (7.105a), (7.105b), (7.109a), (7.109b), (7.113a) and (7.113b) and by applying the TAS


Figure 7.15: OP at relay $R_{2}$ and devices $D_{n}$, where $n=\{1, \ldots, N\}$, in the even transmision block, where the number of antennas equipped at the BS , relay $R_{2}$ and devices $D_{n}$ are $A_{0}=4$, $A_{1}=16$ and $A_{2}=2$, respectively, and the PS factor is $\lambda=0.6$.
protocol, only the best channels from the pre-coding channel matrices are selected for data decoding. Therefore, the relay $R_{2}$ and devices in ETBs have better OP performance than relay $R_{1}$ and devices in OTBs under the same simulation parameters.

Figures 7.16 and 7.17 plot the system throughput performance at devices in OTB and ETB, respectively. Even though device $D_{3}$ has the farthest distance from coupled relays ( $d_{3}=v_{3}=$ 10 m ), device $D_{3}$ always achieved the best throughput performance than other devices. It is interesting that the system throughput results of relay $R_{1}$ and devices in the OTBs (Fig. 7.16) are similar to the system throughput results of relay $R_{2}$ and devices in the ETBs (Fig. 7.17) at the same SNR.

To illustrate, I extracted the investigated results from Matlab software. At a SNR range $\rho_{S}=\rho_{\mathcal{R}}=\{15, \ldots, 21\} d B$, device throughput in the OTB and ETB achieved $T P^{(o d d)}=$ $\{0.0051,0.0435,0.1338,0.2204,0.279,0.2983,0.3\}$ and $T P^{(\text {even })}=\{0.0011,0.0261,0.1287,0.2169,0.2849,0.2999$ respectively. We may observe that device throughput in the OTBs outperformed device throughput in the ETBs at low SNR, i.e., $\rho_{S}=\rho_{\mathcal{R}}=\{15, \ldots, 18\} d B$. However, device throughput in the ETBs improved and outperformed device throughput in the OTBs at high SNR, i.e., $\rho_{S}=\rho_{\mathcal{R}}=\{19,20\} d B$. Device throughput also tended to their data rate thresholds, i.e., $R_{1}^{*}=R_{2}^{*}=R_{3}^{*}=0.1 \mathrm{~b} / \mathrm{s} / \mathrm{Hz}$ when the SNR $\rho_{S}=\rho_{\mathcal{R}} \rightarrow \infty$. As a result, system throughput in both OTB and ETB $T P^{(o d d)}=T P^{(\text {even })}=R_{1}^{*}+R_{2}^{*}+R_{3}^{*}=0.3$ at high SNR $\rho_{S}=\rho_{\mathcal{R}} \geq 20 d B$. It is important to note that the PS factor in ETBs $(\lambda=0.6)$ was greater than the PS factor in OTBs $(\lambda=0.4)$. Therefore, the relay $R_{1}$ in the ETBs harvested more energy than relay $R_{2}$ in the OTBs. Certainly, the ETBs achieved better EE performance than OTBs.


Figure 7.16: System throughput in odd transmission blocks.


Figure 7.17: System throughput in even transmission blocks.

Figure 7.18 plots the EE performance of the odd and ETBs. We may observe that the EE performance in the ETB with massive MIMO had a higher peak than the OTB. The massive MIMO technique therefore not only provided greater throughput but also consumed less energy.


Figure 7.18: EE of a MIMO network (odd transmission block) compared to a massive MIMO network (even transmission block).

### 7.10 Conclusion

Chapter 7 (Part II) in the dissertation plotted a design for a switchable coupled relay model to assist a massive MIMO-NOMA wireless network in serving multiple devices and extending a network's lifespan [TTNam07]. A diagram of two transmission blocks illustrated signal propagation and EH processing. Propagation and formulations were analyzed. I derived novel closed form expressions for OP at the coupled relays and devices. The theoretical results showed that the massive MIMO technique in combination with the TAS and SWIPT protocols in an underlay C-NOMA network provides higher throughput and consumes less energy. The obtained results verified the massive MIMO technique as an effective technology for 5 G wireless networks. The dissertation offers the potential for the practical application of a massive MIMO-NOMA network model assisted by switchable coupled relays, for example, in a water environment where relays and devices are barely powered. The massive MIMO-NOMA network assisted by switchable coupled relays in combination with the TAS and EH protocols not only improve OP and system throughput performance but also extend the network's lifespan. Specifically, EH at the relay may be used to forward signals without consuming the relay's own energy. This is promising as a potential solution in extending a network's lifespan.

### 7.11 Appendix

### 7.11.1 Appendix A

From (7.115), let

$$
\begin{equation*}
{\underset{c}{L}}_{L_{i=\{N, \ldots, 1\}}^{\left(T_{1}^{(\theta)}\right)}}^{R-\operatorname{Pr}\left\{\max _{\left[A_{0} \times A_{1}\right]}\left\{\mathbf{R}_{\mathcal{R}-x_{i}}^{\left(T_{1}^{(\theta)}\right)}\right\}<R_{i}^{*}\right\} \underbrace{\prod_{k=N}^{i+1} \operatorname{Pr}\left\{\max _{\left[A_{0} \times A_{1}\right]}\left\{\mathbf{R}_{\mathcal{R}-x_{i}}^{\left(T_{1}^{(\theta)}\right)}\right\} \geq R_{i}^{*}\right\}}_{\text {where } i<N}} \tag{7.126}
\end{equation*}
$$

After some algebraic manipulation, we obtain

$$
\begin{equation*}
\underset{i=\{N, \ldots, 1\}}{L_{R-x_{i}}^{\left(T_{1}^{(\theta)}\right)}}=\operatorname{Pr}\left\{\max _{\left[A_{0} \times A_{1}\right]}\left\{\left|\mathbf{H}_{0}\right|^{2}\right\}<\frac{\gamma_{i}^{*}}{(1-\lambda) \beta_{i} \rho_{S}}\right\} \underbrace{\prod_{k=N}^{i+1} \operatorname{Pr}\left\{\max _{\left[A_{0} \times A_{1}\right]}\left\{\left|\mathbf{H}_{0}\right|^{2}\right\} \geq \frac{\gamma_{i}^{*}}{(1-\lambda) \beta_{i} \rho_{S}}\right\}}_{\text {where } i<N} \tag{7.127}
\end{equation*}
$$

From the PDF expressions [TTNam06, Eqs. (59), (60)], we obtain

$$
\begin{align*}
& L_{\mathcal{R}-x_{i}}^{\left(T_{1}^{(\theta)}\right)}=\prod_{a_{0}=1}^{A_{0}} \prod_{a_{1}=1}^{A_{1}} \int_{0}^{\frac{\gamma_{i}^{*}}{(1-\lambda) \beta_{i} \rho_{S}}} \frac{\exp \left(-x / \sigma_{\mathcal{R}}^{2}\right)}{\sigma_{\mathcal{R}}^{2}} d x \underbrace{\prod_{k=1}^{i+1} \prod_{a_{0}}^{A_{0}} \prod_{a_{1}}^{A_{1}} \int_{\frac{\gamma_{k}^{*}}{(1-\lambda) \beta_{k} \rho_{S}}}^{\infty} \frac{\exp \left(-y / \sigma_{R}^{2}\right)}{\sigma_{\mathcal{R}}^{2}} d y}_{k=N} \\
& =\prod_{a_{0}=1}^{A_{0}} \prod_{a_{1}=1}^{A_{1}}\left(1-\exp \left(-\frac{\gamma_{i}^{*}}{(1-\lambda) \beta_{i} \rho_{S} \sigma_{\mathcal{R}}^{2}}\right)\right) \underbrace{\prod_{k=N}^{i+1}\left(1-\prod_{a_{0}}^{A_{0}} \prod_{a_{1}}^{A_{1}}\left(1-\exp \left(-\frac{\gamma_{k}^{*}}{(1-\lambda) \beta_{k} \rho_{S} \sigma_{\mathcal{R}}^{2}}\right)\right)\right.}_{i<N} . \tag{7.128}
\end{align*}
$$

By substituting (7.128) into (7.115), we obtain the expression for OP at coupled relays $\mathcal{R}$ as shown (7.116).

From (7.118), we obtain

$$
\begin{equation*}
Q_{i}=\operatorname{Pr}\left\{\max _{\left[A_{0} \times A_{1}\right]}\left\{\mathbf{R}_{\mathcal{R}-x_{i}}^{\left(T_{1}^{(\theta)}\right)}\right\} \geq R_{i}^{*}\right\}=\operatorname{Pr}\left\{\max _{\left[A_{0} \times A_{1}\right]}\left\{\gamma_{\mathcal{R}-x_{i}}^{\left(T_{1}^{(\theta)}\right)}\right\} \geq \gamma_{i}^{*}\right\} \tag{7.129}
\end{equation*}
$$

From [TTNam06, Eq. (71)], we obtain the CDF expression as follows:

$$
\begin{align*}
& F \max _{\left[A_{0} \times A_{1}\right]\{ }\left\{\gamma_{\mathcal{R}-x_{i}}^{\left(T_{1}^{(\theta)}\right)}\right\}(\gamma)=\sum_{\psi=0}^{A_{0} A_{1}} \frac{(-1)^{\psi}\left(A_{0} A_{1}\right)!}{\psi!\left(A_{0} A_{1}-\psi\right)!} \exp \left(-\frac{\psi \gamma}{(1-\lambda)\left(\alpha_{i}-\gamma \sum_{j=1}^{i-1} \alpha_{j}\right) \rho_{S} \sigma_{\mathcal{R}}^{2}}\right),  \tag{7.130a}\\
& F \max _{\substack{ \\
\left[A_{0} \times A_{1}\right]}}\left\{\gamma_{\mathcal{R}-x_{i}}^{\left(T_{1}^{(\theta)}\right)}\right\}(\gamma)=\sum_{\psi=0}^{A_{0} A_{1}} \frac{(-1)^{\psi}\left(A_{0} A_{1}\right)!}{\psi!\left(A_{0} A_{1}-\psi\right)!} \exp \left(-\frac{\psi \gamma}{(1-\lambda) \alpha_{i} \rho_{S} \sigma_{\mathcal{R}}^{2}}\right) \text {, } \tag{7.130b}
\end{align*}
$$

where expression (7.130a) has $i>1$ and $\gamma<\alpha_{i} / \sum_{j=1}^{i-1} \alpha_{j}$. If $\gamma \geq \alpha_{i} / \sum_{j=1}^{i-1} \alpha_{j}$, the expression (7.130a) refers to one. Expression (7.130b) also has $i=1$.

By applying the CDF expressions given by (7.130a) and (7.130b), we obtain

$$
\begin{equation*}
Q_{i}=1-F \max _{\left[A_{0} \times A_{1}\right]}\left\{\gamma_{R-x_{i}}^{\left(T_{1}^{(\theta)}\right)}\right\} \gamma_{i}^{\left(\gamma_{i}^{*}\right)=1-\sum_{\psi=0}^{A_{0} A_{1}} \frac{(-1)^{\psi}\left(A_{0} A_{1}\right)!}{\psi!\left(A_{0} A_{1}-\psi\right)!} \exp \left(-\frac{\psi \gamma_{i}^{*}}{(1-\lambda) \beta_{i} \rho_{S} \sigma_{\mathcal{R}}^{2}}\right) . ~} \tag{7.131}
\end{equation*}
$$

By substituting (7.131) into (7.118), we obtain the OP at coupled relays as shown (7.119).

### 7.11.2 Appendix B

From (7.120), we obtain

$$
\begin{align*}
& O P_{n}^{(\theta)}=\sum_{i=N}^{n}\left(\prod_{a_{0}}^{A_{0}} \prod_{a_{1}}^{A_{1}} \int_{0}^{\frac{\gamma_{i}^{*}}{(1-\lambda) \beta_{i} \rho_{S}}} \frac{\exp \left(-x / \sigma_{R}^{2}\right)}{\sigma_{\mathcal{R}}^{2}} d x \prod_{k=N}^{i+1} \prod_{a_{0}}^{A_{0}} \prod_{a_{1}}^{A_{1}} \int_{\frac{\gamma_{k}^{*}}{(1-\lambda) \beta_{k} \rho_{S}}}^{\infty} \frac{\exp \left(-x / \sigma_{\mathcal{R}}^{2}\right)}{\sigma_{\mathcal{R}}^{2}} d x\right) \\
&+\sum_{i=N}^{n}\left(\prod_{a_{1}}^{A_{1}} \prod_{a_{2}}^{A_{2}} \int_{0}^{\frac{\gamma_{i}^{*}}{\beta_{i} \rho_{\mathcal{R}}}} \frac{\exp \left(-x / \sigma_{n}^{2}\right)}{\sigma_{n}^{2}} d x \prod_{k=N}^{i+1} \prod_{a_{1}}^{A_{1}} \prod_{a_{2}}^{A_{2}} \int_{\gamma_{k}^{*}}^{\infty} \frac{\exp \left(-x / \sigma_{n}^{2}\right)}{\sigma_{n}^{2}} d x\right. \\
& \beta_{k} \rho_{\mathcal{R}}  \tag{7.132}\\
& \times \prod_{t=N}^{n} \prod_{a_{0}}^{A_{0}} \prod_{a_{1}}^{A_{1}} \int_{\left.\frac{\gamma_{t}^{*}}{\infty} \frac{\exp \left(-x / \sigma_{\mathcal{R}}^{2}\right)}{\sigma_{\mathcal{R}}^{2}} d x\right) .}^{(1-\lambda) \beta_{t} \rho_{S}}
\end{align*}
$$

Expression (7.132) can be solved and obtained in closed form as shown (7.121).
From (7.122), we obtain

$$
\left.O P_{n}^{(\theta)}=1-\prod_{i=N}^{n}\left(1-F \max _{\left.\left[A_{0} \times A_{1}\right]\right\}}\left\{\gamma_{\mathcal{R}-x_{i}}^{\left(T_{1}^{(\theta)}\right)}\right\}^{\left(\gamma_{i}^{*}\right)}\right)\left(\begin{array}{l}
1-F  \tag{7.133}\\
\max _{\left[A_{1} \times A_{2}\right]}\left\{\gamma_{n-x_{i}} \tau^{(\theta)}\right)
\end{array}\right\}_{i}^{\left(\gamma_{i}^{*}\right)}\right),
$$

where $F \max _{\left[A_{0} \times A_{1}\right]}\left\{\gamma_{\mathcal{R}-x_{i}}^{\left(T_{1}^{(\theta)}\right)}\right\}^{(\gamma) \text { is given by (7.130a) or (7.130b) and } F} \max _{\left[A_{1} \times A_{2}\right]}\left\{\gamma_{n-x_{i}}^{\left(T_{2}^{(\theta)}\right)}\right\}^{(\gamma) \text { is given }}$ by

$$
\begin{align*}
& F \underset{\substack{\left.A_{1} \times A_{2}\right]}}{ }\left\{\gamma_{n-x_{i}}^{\left(T_{2}^{(\theta)}\right)}\right\}^{(\gamma)=} \sum_{\mu=0}^{A_{1} A_{2}} \frac{(-1)^{\mu}\left(A_{0} A_{1}\right)!}{\mu!\left(A_{0} A_{1}-\mu\right)!} \exp \left(-\frac{\mu \gamma}{\left(\alpha_{i}-\gamma \sum_{j=1}^{i-1} \alpha_{j}\right) \rho_{\mathcal{R}} \sigma_{n}^{2}}\right),  \tag{7.134a}\\
& F \max _{\left[A_{1} \times A_{2}\right]}\left\{\gamma_{n-x_{i}}^{\left(T_{2}^{(\theta)}\right)}\right\}(\gamma)=\sum_{\mu=0}^{A_{1} A_{2}} \frac{(-1)^{\mu}\left(A_{1} A_{2}\right)!}{\mu!\left(A_{1} A_{2}-\mu\right)!} \exp \left(-\frac{\mu \gamma}{\alpha_{i} \rho_{\mathcal{R}} \sigma_{n}^{2}}\right) \text {, } \tag{7.134b}
\end{align*}
$$

where expression (7.134a) has $i>1$ and $0 \leq \gamma<\alpha_{i} / \sum_{j=1}^{i-1} \alpha_{j}$, and expression (7.134b) has $i=1$ and $\gamma \geq 0$.

By substituting expression (7.130a), (7.130b), (7.134a) and (7.134b) into expression (7.133), we obtain the OP at devices $D_{n}$ in closed form as shown (7.123).

## Chapter 8:

## Summary

THE IoT networks in this dissertation were designed to serve a large number of devices simultaneously to reach low latency. The dissertation also solved the aims for obtaining improved system performance in IoT networks inspired by emerging techniques such as NOMA, massive MIMO, TAS, SWIPT, HD/FD cooperative relays, etc.

To achieve the first aim, I designed a novel cooperating IoT-NOMA network model with $N-1$ relay nodes, described in Chapter 5. The initial signals are transmitted from the BS to the farthest $\mathrm{UE}_{N}$ via the $N-1$ relay nodes. Each relay node decodes the data symbol from the received signal and forwards the signal after selecting the best next relay node. The analyzed results show that my MPCR models can extend networking coverage and also better serve far devices [TTNam03].

As an extension of the first aim, the second aim was to optimize system performance by selecting a suitable forwarding protocol. Chapter 6 (Part I) describes an IoT-NOMA network which deploys various pairing protocols according to six scenarios: HD-DF relaying, FD-DF relaying, HD-AF with fixed gain relaying, HD-AF with variable gain relaying, FD-AF with fixed gain relaying, and FD-AF with variable gain relaying. The analysis and simulations results confirmed that the system performance of an IoT network can be improved by adopting my proposed PSS mechanism [TTNam04]. The work in Chapter 6 (Part II) extends this task by also adopting DF and AF with FG/VG protocols at the relay. However, the BS, relays and devices examined in Chapter 6 (part II) were equipped multiple antennae at all networking nodes instead of a single antenna, as in Chapter 6 (Part I). In particular, I exploited instantaneous AF factor maximization to aid in optimizing the system performance of an IoT-NOMA network [TTNam05].

With regard to the third aim, I investigated the system performance of an IoT-NOMA network based on OP and SOP performance [TTNam06]. Chapter 7 (Part I) describes my design for a low power IoT-NOMA network. To assist the far device, I deployed the near device as a relay. However, the near device was a low energy device. Therefore, I adopted the SWIPT technique and designed a novel HD/FD PS framework which could reach ultra-low latency and enhance the OP/SOP performance of an IoT network. The analyzed results were verified with simulation results. The analysis and simulation results confirmed that my PS frameworks provide fairness in QoS for devices and combat eavesdroppers [TTNam09]. I also designed a novel PS framework for massive MIMO-IoT networks which adopted the SWIPT protocol,described in Chapter 7 (Part II). By adopting switchable coupled relays and equipping multiple antennae on coupled relays, I deployed the RS and TAS protocols to select the best channel for maximizing system performance in a massive MIMO-IoT network. Through these solutions, system performance may be significantly improved [TTNam07].

As a final step in the research for my dissertation, I obtained novel closed form expressions of the investigated results, proved and verified with Monte Carlo simulations. In summary, I conclude that my dissertation contributes to the wireless communication research community and future IoT networks which may require low energy for G-WNs, low latency for massive users and high reality for PLS. In future research, I will extend the work in Chapter 7 (Parts I and II) by using the EH to transmit friendly jammers to assist in combating eavesdroppers in IoT networks.

## References

1. Ding, Z. et al. Application of non-orthogonal multiple access in LTE and 5G networks. IEEE Communications Magazine 55, 185-191 (2017).
2. Dai, L. et al. Non-orthogonal multiple access for 5G: solutions, challenges, opportunities, and future research trends. IEEE Communications Magazine 53, 74-81 (2015).
3. Saito, Y., Benjebbour, A., Kishiyama, Y. \& Nakamura, T. System-level performance of downlink non-orthogonal multiple access (NOMA) under various environments in 2015 IEEE 81st Vehicular Technology Conference (VTC Spring) (2015), 1-5.
4. Ding, Z., Fan, P. \& Poor, H. V. Impact of user pairing on 5G nonorthogonal multiple-access downlink transmissions. IEEE Transactions on Vehicular Technology 65, 6010-6023 (2015).
5. Liu, Y., Pan, G., Zhang, H. \& Song, M. On the capacity comparison between MIMO-NOMA and MIMO-OMA. IEEE Access 4, 2123-2129 (2016).
6. Ding, Z., Yang, Z., Fan, P. \& Poor, H. V. On the performance of non-orthogonal multiple access in 5G systems with randomly deployed users. IEEE Signal Processing Letters 21, 1501-1505 (2014).
7. Timotheou, S. \& Krikidis, I. Fairness for non-orthogonal multiple access in 5G systems. IEEE Signal Processing Letters 22, 1647-1651 (2015).
8. Cui, J., Ding, Z. \& Fan, P. A novel power allocation scheme under outage constraints in NOMA systems. IEEE Signal Processing Letters 23, 1226-1230 (2016).
9. Yang, Z., Ding, Z., Fan, P. \& Al-Dhahir, N. A general power allocation scheme to guarantee quality of service in downlink and uplink NOMA systems. IEEE Transactions on Wireless Communications 15, 7244-7257 (2016).
10. Islam, S. R., Avazov, N., Dobre, O. A. \& Kwak, K.-S. Power-domain non-orthogonal multiple access (NOMA) in 5G systems: Potentials and challenges. IEEE Communications Surveys $\mathcal{E}$ Tutorials 19, 721-742 (2016).
11. Saito, Y. et al. Non-orthogonal multiple access (NOMA) for cellular future radio access in 2013 IEEE 77th Vehicular Technology Conference (VTC Spring) (2013), 1-5.
12. Higuchi, K. \& Kishiyama, Y. Non-orthogonal multiple access using intra-beam superposition coding and successive interference cancellation for cellular MIMO downlink. IEICE Transactions on Communications 98, 1888-1895 (2015).
13. Zhang, Z., Ma, Z., Xiao, M., Ding, Z. \& Fan, P. Full-duplex device-to-device-aided cooperative nonorthogonal multiple access. IEEE Transactions on Vehicular Technology 66, 4467-4471 (2016).
14. Liu, Y., Ding, Z., Elkashlan, M. \& Poor, H. V. Cooperative non-orthogonal multiple access with simultaneous wireless information and power transfer. IEEE Journal on Selected Areas in Communications 34, 938-953 (2016).
15. Men, J., Ge, J. \& Zhang, C. Performance analysis of nonorthogonal multiple access for relaying networks over Nakagami- $m$ fading channels. IEEE Transactions on Vehicular Technology 66, 1200-1208 (2016).
16. Zhong, C. \& Zhang, Z. Non-orthogonal multiple access with cooperative full-duplex relaying. IEEE Communications Letters 20, 2478-2481 (2016).
17. Liu, Y., Ding, Z., Elkashlan, M. \& Yuan, J. Nonorthogonal multiple access in large-scale underlay cognitive radio networks. IEEE Transactions on Vehicular Technology 65, 1015210157 (2016).
18. Lu, F. et al. Non-orthogonal multiple access with successive interference cancellation in millimeter-wave radio-over-fiber systems. Journal of Lightwave Technology 34, 4179-4186 (2016).
19. Marshoud, H., Kapinas, V. M., Karagiannidis, G. K. \& Muhaidat, S. Non-orthogonal multiple access for visible light communications. IEEE Photonics Technology Letters 28, 51-54 (2015).
20. Liu, Y., Elkashlan, M., Ding, Z. \& Karagiannidis, G. K. Fairness of user clustering in MIMO non-orthogonal multiple access systems. IEEE Communications Letters 20, 14651468 (2016).
21. Ding, Z., Adachi, F. \& Poor, H. V. The application of MIMO to non-orthogonal multiple access. IEEE Transactions on Wireless Communications 15, 537-552 (2015).
22. Yu, Y. et al. Antenna selection for MIMO nonorthogonal multiple access systems. IEEE Transactions on Vehicular Technology 67, 3158-3171 (2017).
23. Men, J. \& Ge, J. Non-orthogonal multiple access for multiple-antenna relaying networks. IEEE Communications Letters 19, 1686-1689 (2015).
24. Han, W., Ge, J. \& Men, J. Performance analysis for NOMA energy harvesting relaying networks with transmit antenna selection and maximal-ratio combining over Nakagami- $m$ fading. IET Communications 10, 2687-2693 (2016).
25. Liu, X. \& Wang, X. Efficient antenna selection and user scheduling in 5G massive MIMONOMA system in 2016 IEEE 83rd Vehicular Technology Conference (VTC Spring) (2016), 1-5.
26. Bloch, M., Barros, J., Rodrigues, M. R. \& McLaughlin, S. W. Wireless informationtheoretic security. IEEE Transactions on Information Theory 54, 2515-2534 (2008).
27. Zhang, Y., Wang, H.-M., Yang, Q. \& Ding, Z. Secrecy sum rate maximization in nonorthogonal multiple access. IEEE Communications Letters 20, 930-933 (2016).
28. Qin, Z., Liu, Y., Ding, Z., Gao, Y. \& Elkashlan, M. Physical layer security for $5 G$ nonorthogonal multiple access in large-scale networks in 2016 IEEE International Conference on Communications (ICC) (2016), 1-6.
29. Liu, Y., Qin, Z., Elkashlan, M., Gao, Y. \& Hanzo, L. Enhancing the physical layer security of non-orthogonal multiple access in large-scale networks. IEEE Transactions on Wireless Communications 16, 1656-1672 (2017).
30. Zhu, J., Zou, Y., Wang, G., Yao, Y.-D. \& Karagiannidis, G. K. On secrecy performance of antenna-selection-aided MIMO systems against eavesdropping. IEEE Transactions on Vehicular Technology 65, 214-225 (2015).
31. Lei, H. et al. Secrecy outage performance of transmit antenna selection for MIMO underlay cognitive radio systems over Nakagami- $m$ channels. IEEE Transactions on Vehicular Technology 66, 2237-2250 (2016).
32. Lei, H. et al. On secure NOMA systems with transmit antenna selection schemes. IEEE Access 5, 17450-17464 (2017).
33. Wei, Z., Yuan, J., Ng, D. W. K., Elkashlan, M. \& Ding, Z. A survey of downlink nonorthogonal multiple access for 5G wireless communication networks. ZTE Communications (2016).
34. Lu, X., Wang, P., Niyato, D., Kim, D. I. \& Han, Z. Wireless Networks With RF Energy Harvesting: A Contemporary Survey. IEEE Communications Surveys \& Tutorials 17, 757789 (2015).
35. Chen, X., Yuen, C. \& Zhang, Z. Wireless energy and information transfer tradeoff for limited-feedback multiantenna systems with energy beamforming. IEEE Transactions on Vehicular Technology 63, 407-412 (2013).
36. Xiao, Y. et al. Forwarding strategy selection in dual-hop NOMA relaying systems. IEEE Communications Letters 22, 1644-1647 (2018).
37. Emadi, M. J., Davoodi, A. G. \& Aref, M. R. Analytical power allocation for a full-duplex decode-and-forward relay channel. IET Communications 7, 1338-1347 (2013).
38. Ding, Z., Dai, H. \& Poor, H. V. Relay selection for cooperative NOMA. IEEE Wireless Communications Letters 5, 416-419 (2016).
39. Gao, H., Ejaz, W. \& Jo, M. Cooperative wireless energy harvesting and spectrum sharing in 5G networks. IEEE Access 4, 3647-3658 (2016).
40. Tonello, A. M., Versolatto, F. \& D'Alessandro, S. Opportunistic relaying in in-home PLC networks in 2010 IEEE Global Telecommunications Conference GLOBECOM 2010 (2010), 1-5.
41. Lampe, L. \& Vinck, A. H. Cooperative multihop power line communications in 2012 IEEE International Symposium on Power Line Communications and Its Applications (2012), 16.
42. Cheng, X., Cao, R. \& Yang, L. Relay-aided amplify-and-forward powerline communications. IEEE Transactions on Smart Grid 4, 265-272 (2013).
43. Rabie, K. M., Adebisi, B., Gacanin, H., Nauryzbayev, G. \& Ikpehai, A. Performance evaluation of multi-hop relaying over non-Gaussian PLC channels. Journal of Communications and Networks 19, 531-538 (2017).
44. Dubey, A., Mallik, R. K. \& Schober, R. Performance analysis of a multi-hop power line communication system over log-normal fading in presence of impulsive noise. IET communications 9, 1-9 (2014).
45. Dubey, A. \& Mallik, R. K. PLC system performance with AF relaying. IEEE Transactions on Communications 63, 2337-2345 (2015).
46. Ding, Z., Peng, M. \& Poor, H. V. Cooperative non-orthogonal multiple access in 5G systems. IEEE Communications Letters 19, 1462-1465 (2015).
47. Choi, J. Non-orthogonal multiple access in downlink coordinated two-point systems. IEEE Communications Letters 18, 313-316 (2014).
48. Kim, J.-B. \& Lee, I.-H. Non-orthogonal multiple access in coordinated direct and relay transmission. IEEE Communications Letters 19, 2037-2040 (2015).
49. Choi, J. On the spectral efficient nonorthogonal multiple access schemes in 2016 European Conference on Networks and Communications (EuCNC) (2016), 277-281.
50. Laneman, J. N., Tse, D. N. \& Wornell, G. W. Cooperative diversity in wireless networks: Efficient protocols and outage behavior. IEEE Transactions on Information theory 50, 3062-3080 (2004).
51. Ju, H., Oh, E. \& Hong, D. Improving efficiency of resource usage in two-hop full duplex relay systems based on resource sharing and interference cancellation. IEEE Transactions on Wireless Communications 8, 3933-3938 (2009).
52. Zhang, Z., Chai, X., Long, K., Vasilakos, A. V. \& Hanzo, L. Full duplex techniques for 5G networks: self-interference cancellation, protocol design, and relay selection. IEEE Communications Magazine 53, 128-137 (2015).
53. Osorio, D. M., Olivo, E. B., Alves, H., Santos Filho, J. C. S. \& Latva-aho, M. Exploiting the direct link in full-duplex amplify-and-forward relaying networks. IEEE Signal Processing Letters 22, 1766-1770 (2015).
54. Kwon, T., Lim, S., Choi, S. \& Hong, D. Optimal duplex mode for DF relay in terms of the outage probability. IEEE Transactions on Vehicular Technology 59, 3628-3634 (2010).
55. Riihonen, T., Werner, S. \& Wichman, R. Hybrid full-duplex/half-duplex relaying with transmit power adaptation. IEEE Transactions on Wireless Communications 10, 30743085 (2011).
56. Yue, X., Liu, Y., Kang, S., Nallanathan, A. \& Ding, Z. Exploiting full/half-duplex user relaying in NOMA systems. IEEE Transactions on Communications 66, 560-575 (2017).
57. Yue, X., Liu, Y., Kang, S. \& Nallanathan, A. Performance analysis of NOMA with fixed gain relaying over Nakagami- $m$ fading channels. IEEE Access 5, 5445-5454 (2017).
58. Li, B. et al. Security-reliability tradeoff analysis for cooperative NOMA in cognitive radio networks. IEEE Transactions on Communications 67, 83-96 (2018).
59. Zhou, F., Chu, Z., Sun, H., Hu, R. Q. \& Hanzo, L. Artificial noise aided secure cognitive beamforming for cooperative MISO-NOMA using SWIPT. IEEE Journal on Selected Areas in Communications 36, 918-931 (2018).
60. Zhou, F., Chu, Z., Wu, Y., Al-Dhahir, N. \& Xiao, P. Enhancing PHY security of MISO NOMA SWIPT systems with a practical non-linear EH model in 2018 IEEE International Conference on Communications Workshops (ICC Workshops) (2018), 1-6.
61. Jameel, F., Wyne, S., Kaddoum, G. \& Duong, T. Q. A comprehensive survey on cooperative relaying and jamming strategies for physical layer security. IEEE Communications Surveys § Tutorials 21, 2734-2771 (2018).
62. Kong, L., Vuppala, S. \& Kaddoum, G. Secrecy Analysis of Random MIMO Wireless Networks Over $\alpha-\mu$ Fading Channels. IEEE Transactions on Vehicular Technology 67, 1165411666 (2018).
63. Tran, D.-D., Tran, H.-V., Ha, D.-B. \& Kaddoum, G. Secure transmit antenna selection protocol for MIMO NOMA networks over Nakagami-m channels. IEEE Systems Journal 14, 253-264 (2019).
64. Feng, Y., Yan, S. \& Yang, Z. Secure transmission to the strong user in non-orthogonal multiple access. IEEE Communications Letters 22, 2623-2626 (2018).
65. Feng, Y., Yan, S., Liu, C., Yang, Z. \& Yang, N. Two-stage relay selection for enhancing physical layer security in non-orthogonal multiple access. IEEE Transactions on Information Forensics and Security 14, 1670-1683 (2018).
66. Liu, Y., Wang, L., Duy, T. T., Elkashlan, M. \& Duong, T. Q. Relay selection for security enhancement in cognitive relay networks. IEEE Wireless Communications Letters 4, 46-49 (2014).
67. Nguyen, N.-P., Duong, T. Q., Ngo, H. Q., Hadzi-Velkov, Z. \& Shu, L. Secure 5G wireless communications: A joint relay selection and wireless power transfer approach. IEEE Access 4, 3349-3359 (2016).
68. Rodriguez, L. J. et al. Physical layer security in wireless cooperative relay networks: State of the art and beyond. IEEE Communications Magazine 53, 32-39 (2015).
69. Zhu, Z., Chu, Z., Wang, Z. \& Lee, I. Outage constrained robust beamforming for secure broadcasting systems with energy harvesting. IEEE Transactions on Wireless Communications 15, 7610-7620 (2016).
70. Pan, G. et al. On secrecy performance of MISO SWIPT systems with TAS and imperfect CSI. IEEE Transactions on Communications 64, 3831-3843 (2016).
71. Salem, A., Hamdi, K. A. \& Rabie, K. M. Physical layer security with RF energy harvesting in AF multi-antenna relaying networks. IEEE Transactions on Communications 64, 30253038 (2016).
72. Zhao, R., Yuan, Y., Fan, L. \& He, Y.-C. Secrecy performance analysis of cognitive decode-and-forward relay networks in Nakagami-m fading channels. IEEE Transactions on Communications 65, 549-563 (2016).
73. Wang, L., Elkashlan, M., Huang, J., Tran, N. H. \& Duong, T. Q. Secure transmission with optimal power allocation in untrusted relay networks. IEEE Wireless Communications Letters 3, 289-292 (2014).
74. Pan, G., Tang, C., Li, T. \& Chen, Y. Secrecy performance analysis for SIMO simultaneous wireless information and power transfer systems. IEEE Transactions on Communications 63, 3423-3433 (2015).
75. Nasir, A. A., Tuan, H. D., Duong, T. Q. \& Poor, H. V. Secrecy rate beamforming for multicell networks with information and energy harvesting. IEEE Transactions on Signal Processing 65, 677-689 (2016).
76. Rabie, K. M., Salem, A., Alsusa, E. \& Alouini, M. Energy-harvesting in cooperative AF relaying networks over log-normal fading channels in 2016 IEEE International Conference on Communications (ICC) (2016), 1-7.
77. Perera, T. D. P. \& Jayakody, D. N. K. Analysis of time-switching and power-splitting protocols in wireless-powered cooperative communication system. Physical Communication 31, 141-151 (2018).
78. Islam, S. R., Zeng, M., Dobre, O. A. \& Kwak, K.-S. Resource allocation for downlink NOMA systems: Key techniques and open issues. IEEE Wireless Communications 25, 4047 (2018).
79. Wan, D., Wen, M., Ji, F., Liu, Y. \& Huang, Y. Cooperative NOMA systems with partial channel state information over Nakagami-m fading channels. IEEE Transactions on Communications 66, 947-958 (2017).
80. Saito, Y. et al. Non-Orthogonal Multiple Access (NOMA) for Cellular Future Radio Access in 2013 IEEE 77th Vehicular Technology Conference (VTC Spring) (2013), 1-5.
81. Liu, H., Ding, Z., Kim, K. J., Kwak, K. S. \& Poor, H. V. Decode-and-Forward Relaying for Cooperative NOMA Systems With Direct Links. IEEE Transactions on Wireless Communications 17, 8077-8093 (2018).
82. Sreng, V., Yanikomeroglu, H. \& Falconer, D. D. Relayer selection strategies in cellular networks with peer-to-peer relaying in 2003 IEEE 58th Vehicular Technology Conference. VTC 2003-Fall (IEEE Cat. No. 03CH37484) 3 (2003), 1949-1953.
83. Sadek, A. K., Han, Z. \& Ray Liu, K. J. A Distributed Relay-Assignment Algorithm for Cooperative Communications in Wireless Networks in 2006 IEEE International Conference on Communications 4 (2006), 1592-1597.
84. Jing, Y. \& Jafarkhani, H. Single and multiple relay selection schemes and their achievable diversity orders. IEEE Transactions on Wireless Communications 8, 1414-1423 (2009).
85. Kim, J.-B. \& Lee, I.-H. Capacity analysis of cooperative relaying systems using nonorthogonal multiple access. IEEE Communications Letters 19, 1949-1952 (2015).
86. Fang, F., Zhang, H., Cheng, J. \& Leung, V. C. Energy-efficient resource allocation for downlink non-orthogonal multiple access network. IEEE Transactions on Communications 64, 3722-3732 (2016).
87. Zhang, Z., Qu, H., Zhao, J. \& Wang, W. Energy Efficient Transmission Design of Cooperative NOMA with SWIPT Network in 2019 IEEE 4th International Conference on Signal and Image Processing (ICSIP) (2019), 566-572.
88. Zhang, Z., Qu, H., Zhao, J., Wang, W. \& Wang, S. Fairness based power allocation optimization of cooperative NOMA with SWIPT network in 2019 IEEE 4th International Conference on Signal and Image Processing (ICSIP) (2019), 555-560.
89. Xu, Y. et al. Joint beamforming and power-splitting control in downlink cooperative SWIPT NOMA systems. IEEE Transactions on Signal Processing 65, 4874-4886 (2017).
90. Do, T. N., da Costa, D. B., Duong, T. Q. \& An, B. Improving the performance of cell-edge users in MISO-NOMA systems using TAS and SWIPT-based cooperative transmissions. IEEE Transactions on Green Communications and Networking 2, 49-62 (2017).
91. Gonzalez, D. C., da Costa, D. B. \& Santos Filho, J. C. S. Distributed TAS/MRC and TAS/SC schemes for fixed-gain AF systems with multiantenna relay: Outage performance. IEEE Transactions on Wireless Communications 15, 4380-4392 (2016).
92. Yang, Z., Ding, Z., Fan, P. \& Al-Dhahir, N. The impact of power allocation on cooperative non-orthogonal multiple access networks with SWIPT. IEEE Transactions on Wireless Communications 16, 4332-4343 (2017).
93. Tam, H. H. M., Tuan, H. D., Nasir, A. A., Duong, T. Q. \& Poor, H. V. MIMO energy harvesting in full-duplex multi-user networks. IEEE Transactions on Wireless Communications 16, 3282-3297 (2017).
94. Lv, L., Ni, Q., Ding, Z. \& Chen, J. Application of non-orthogonal multiple access in cooperative spectrum-sharing networks over Nakagami- $m$ fading channels. IEEE Transactions on Vehicular Technology 66, 5506-5511 (2016).
95. Ye, Y., Li, Y., Wang, D. \& Lu, G. Power splitting protocol design for the cooperative NOMA with SWIPT in 2017 IEEE International Conference on Communications (ICC) (2017), 1-5.
96. Liu, Y., Ding, Z., Eikashlan, M. \& Poor, H. V. Cooperative non-orthogonal multiple access in $5 G$ systems with SWIPT in 2015 23rd European Signal Processing Conference (EUSIPCO) (2015), 1999-2003.
97. Altunbas, I., Yilmaz, A., Kucur, S. S. \& Kucur, O. Performance analysis of dual-hop fixed-gain AF relaying systems with OSTBC over Nakagami- $m$ fading channels. $A E U$ International Journal of Electronics and Communications 66, 841-846 (2012).
98. Jing, Y. \& Jafarkhani, H. Single and multiple relay selection schemes and their achievable diversity orders. IEEE Transactions on Wireless Communications 8, 1414-1423 (2009).
99. Lee, S., Da Costa, D. B., Vien, Q.-T., Duong, T. Q. \& de Sousa Jr, R. T. Non-orthogonal multiple access schemes with partial relay selection. IET Communications 11, 846-854 (2016).

## Candidate's Results Cited in the Dissertation

The list of results indexed in SCI/SCIE/ESCI journals during my Ph.D. studies, where individual ideas of the dissertation are published.
[TTNam01] Thanh-Nam Tran, Dinh-Thuan Do, and Miroslav Voznak, On outage probability and throughput performance of cognitive radio inspired by the NOMA relay system", (VŠB-TUO) Advances in Electrical and Electronic Engineering, 16 (4), pp. 501-512 (2018). DOI: 10.15598/aeee.v16i4.2801.
[TTNam02] Thanh-Nam Tran, Dinh-Thuan Do, and Miroslav Voznak, "Full-duplex Cognitive Radio NOMA Networks: Outage and throughput performance analysis", (Polish Academy of Sciences) International Journal of Electronics and Telecommunications, 65 (1), pp. 103-109 (2019). DOI: 10.24425/ijet.2019.126289
[TTNam03] Thanh-Nam Tran, and Miroslav Voznak, "Multi-points cooperative relay in NOMA system with N-1 DF relaying nodes in HD/FD mode for N user equipment with energy harvesting", (MDPI) Electronics, 8 (2), art. no. 167 (2019). DOI: 10.3390/electronics8020167. IF 1.764
[TTNam04] Thanh-Nam Tran, and Miroslav Voznak, "HD/FD and DF/AF with a fixedgain or variable-gain protocol switching mechanism over cooperative NOMA for green-wireless networks", (MDPI) Sensors, 19 (8), art. no. 1845 (2019). DOI: 10.3390/s19081845. IF 3.031
[TTNam05] Thanh-Nam Tran, Peppino Fazio, Miroslav Voznak, and Van-Cuu Ho, "Emerging Cooperative MIMO-NOMA Networks Combining TAS and SWIPT Protocols Assisted by an AF-VG Relaying Protocol with Instantaneous Amplifying Factor Maximization", (Elsevier) AEU - International Journal of Electronics and Communications, vol. 135, art. ID 153695 (2021). DOI: $10.1016 / \mathrm{j}$.aeue.2021.153695. IF 2.924
[TTNam06] Thanh-Nam Tran, and Miroslav Voznak, "On secure system performance over SISO, MISO and MIMO-NOMA wireless networks equipped a multiple antenna based on a TAS protocol", (Springer) EURASIP Journal on Wireless Communications and Networking, vol. 2020, art. no. 11 (2020). DOI: 10.1186/s13638-019-1586-y. IF 1.408
[TTNam07] Thanh-Nam Tran, and Miroslav Voznak, "Switchable Coupled Relays Aid Massive Non-Orthogonal Multiple Access Networks with Transmit Antenna Selection and Energy Harvesting", (MDPI) Sensors, 21 (4), art. no. 1101 (2021). DOI: 10.3390/s21041101. IF 3.031
[TTNam08] Thanh-Nam Tran, and Miroslav Voznak, "Adaptive Multiple Access Assists Multiple Users over MIMO-NOMA Wireless Networks", (Wiley) International Journal of Communication Systems, vol. 2021, article ID e4803 (2021). DOI: 10.1002/dac.4803. IF 1.319
[TTNam09] Thanh-Nam Tran, Thoai Phu Vo, Peppino Fazio and Miroslav Voznak, "SWIPT Model Adopting a PS Framework to Aid IoT Networks Inspired by the Emerging Cooperative NOMA Technique", (IEEE) IEEE Access, Vol. 9, pp. 61489-61512 (2021). DOI: 10.1109/access.2021.3074351. IF 3.745

## About the Candidate

## Research Activities

I provide the following list of indexed results in relevant scientific databases as documentary evidence of my research activities during the period of my doctoral studies:

ORCID: 0000-0002-7065-7951
Scopus Author ID: 57207308811
Web of Science ResearcherID: V-1518-2019
Records in WoS/Scopus: 9 articles in journals
$\boldsymbol{h}$-index according to WoS/Scopus: 4 (34 citations)

## Participation in Research Projects

The research leading to the results shown in the dissertation received funding from :

- The Czech Ministry of Education, Youth and Sports, institutional grants reg. No. SP2019/41, SP 2020/65 and SP2021/25 "Networks and Communication Technologies for Smart Cities I - III" conducted at VSB-Technical University of Ostrava in period 2019-2021.
- The Czech Ministry of Education, Youth and Sports within "Large Infrastructures for Research, Experimental Development and Innovations" project reg. No. LM2018140 conducted at VSB-Technical University of Ostrava in period 2020-2021.


[^0]:    ${ }^{1}$ This dissertation used Matlab software version R2017b, made by MathWorks, Inc., 3 Apple Hill Drive Natick, MA 01760 USA 508-647-7000 (Free classroom licence)

