SCHOOL OF ELECTRICAL ENGINEERING

AND TELECOMMUNICATIONS

Power Allocation for NOMA System with Statistical CSI

by

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Abstract

Non-orthogonal multiple access (NOMA) has been considered as a promising multiple access technology for the fifth-generation (5G) wireless communication systems since it enables energy and spectral efficient communication for growing different quality of service (QoS) requirements. In this report, we first introduce the background of this research and some basic conceptions of orthogonal multiple access (OMA) and NOMA. Then, we discuss a simple model of a single-carrier system to illustrate the fundamental principles of NOMA. After that, we discuss the power allocation for energy-efficient multicarrier NOMA (MC-NOMA) with statistical channel state information at the transmitter (CSIT) and QoS constraints. Subsequently, we propose a suboptimal computational efficient solution to solve the user scheduling problem. At last, we compare the performance of OMA and NOMA systems with different cell sizes and the number of users.

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Abbreviations

NOMA Non-orthogonal multiple access

QoS quality of service

OMA orthogonal multiple access

CSIT channel state information at the transmitter

ICT information and communication technology

IoT Internet-of-Things

MIMO multiple-input multiple-output

FDMA frequency division multiple access

TDMA time division multiple access

CDMA code division multiple access

OFDMA orthogonal frequency division multiple access

MAI multiple access interference

DoF degree of freedom

SIC serial interference cancellation

CP cycle prefix

ISI inter-symbol interference

BS base station

AWGN additive white Gaussian noise

CDF cumulative distribution function

Contents

Chapter 1

Introduction

We introduce some basic information about the project in this chapter, including research background, definition of NOMA, imperfect CSI, and the comparison between OMA and NOMA.

1.1 Background

The explosive traffic growth in the demand of wireless communication services has received significant interest in academia and industry which fuels the development of the next-generation wireless networks, which can significantly improve the coverage and user experience. The 5G cellular networks are expected to provide high spectral efficiency via advanced multiple access technologies, which plays a significant role in determining the performance of wireless communication systems.

With the popularity of intelligent terminals and the development of mobile network business, the capacity of the wireless network systems has to fulfill the stringent QoS requirements. Hence, the future of mobile communication systems is facing enormous challenges, mainly in the following two aspects. First, massive number of mobile terminals will be connected to mobile networks via limited spectrum resources. The increasing rate of the number of smartphones and intelligent terminals requiring mobile data services double every year. It is predicted that in 2020, the data load will be 500-1000 times more than it is now, and there will have about 50 billion terminal access to wireless networks in the world [1]. Second, the demand for green communications has become an emerging need in the design of communication system. As the current report, information and communication technology (ICT) industry requires a massive energy consumption, accounting for 10% of global energy consumption. In particular, 2% of global greenhouse gases are emitted as a by-product of the ICT sector, which equivalent to the overall emissions of the aviation industry [2]. Due the rapid development of wireless networks and the emergence of massive network nodes and terminals, communication industry will consume an enormous amount of energy in the future.

Thus, we need to develop the next generation wireless networks to solve these problems, which should support higher data rate, lower latency, larger capacity, and lower energy consumption [3].

The 5G communication systems aim to improve the quality of communication in different aspects. For instance, the 5G networks are expected to offer extreme capacity (10 Tbps per square kilometer) and data rate (multi-Gigabits per second), which is known as enhanced mobile broadband. 5G should also enable an ultra-high density (1 million nodes per square kilometer), ultra-low complexity (10s of bits per second) and energy consumption, which mainly supports the development of the Internet-of-Things (IoT) [4]. Specifically, IoT gives an opportunity to realize smart cities, smart homes, long-range object tracking, etc. Besides, 5G should provide ultra-low latency (as low as a millisecond), ultra-high reliability (less than 1 out of 100 million packets lost) and strong security [5], which helps to achieve mission-critical control such as autonomous vehicles, robotics, industrial automation, etc.

There are various disruptive technologies for realizing the 5G communication system, such as massive multiple-input-multiple-output (MIMO) [6], millimeter wave [7], visible light communication [8], and NOMA, etc. In this project, we will focus on NOMA systems. In a mobile communication system, all users share limited resources such as power, time, and bandwidth. Thus, we need technology to achieve that different users can communicate with each other at various locations and minimize the inter-user interference. This approach is called multiple access technology. Multiple access technology not only determines the basic capacity of the network and the system complexity but also have a high impact on deployment costs. Traditional mobile communication systems, e.g. 1G-4G, adopts OMA technology, which including frequency division multiple access (FDMA), time division multiple access (TDMA), code division multiple access (CDMA), and orthogonal frequency division multiple access (OFDMA) [9], [10] to avoid multiple interference between users.

In 4G and other existing communication systems, the reason of the general use of OMA is to reduce the computational complexity of the transmission and the multiple access interference (MAI) due to different users are allocated to orthogonal power region with in time, frequency or code domain in OMA technologies. From the viewpoint of multi-user information theory, OMA systems can reach the inner boundary of multi-user capacity region [11]. However, the OMA systems are not competent to support large-scale connections with different QoS requirements. Actually, because of the limited degrees of freedom (DoF), some users with better channel quality have higher priority and other users with poor channel quality must wait for access, which leads to more severe unfairness and longer delay. In addition, when the DoF is assigned to a user which having a poor channel quality, the efficiency for OMA systems is low [12]-[14]. That is why we focus on NOMA technologies which have promising to address the challenges and achieve the requirements of 5G.

1.2 NOMA

NOMA overcomes the near-far problems of the 3G systems and improve the fairness in resource allocation in the 4G systems. NOMA is a multi-user multiplexing scheme that exploits the frequency domain, time domain, and power domain similarly. Compared with the traditional orthogonal transmission, NOMA uses non-orthogonal transmission at the sending terminals, introducing interferenced information deliberately, and realizes the demodulation by the successive interference cancellation (SIC) technology at the receiving terminals [15]. NOMA technologies can still use the OFDM symbol as the smallest unit in the time domain, and insert the cycle prefix (CP) between the symbols to prevent inter-symbol interference (ISI). While, in the frequency domain, the smallest units can still be the sub-channels, and OFDM technologies are used in each subchannels to keep the sub-channels are orthogonal and non-interference with each other. However, the power of each sub-channel and the OFDM symbol is shared by multiple users instead of only for one user. In particular, the signal power of different users on the same subchannel and OFDM symbol is non-orthogonal, which led to MAI for shared channels [16]. In order to overcome the interference, NOMA at the receiver using a SIC technology for multi-user interference detection and deletion to ensure the normal communication of the systems [17]. Thus, the receiver complexity of NOMA has improved compared with orthogonal transmission, but it can get higher spectral efficiency.

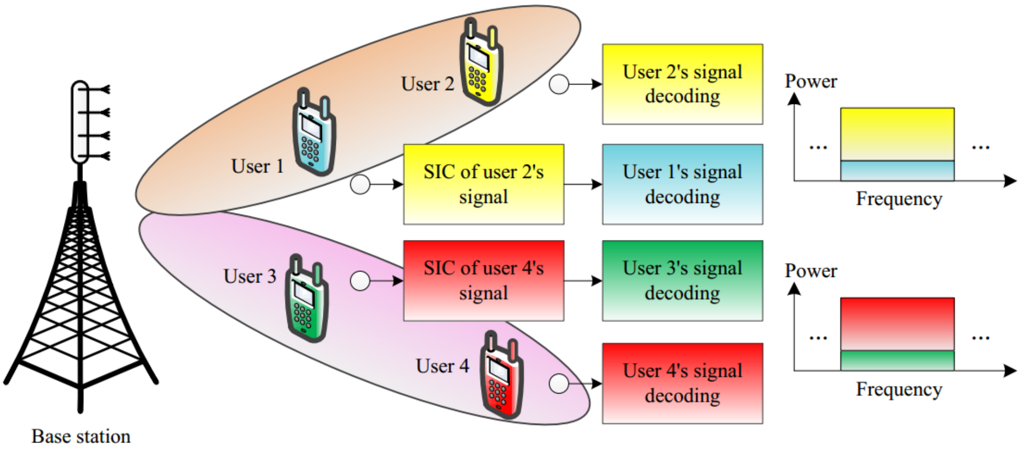

Figure 1 A downlink NOMA system model [1],

Figure 1 illustrates a multi-carrier downlink NOMA system with one BS and four users. In this NOMA system, each subcarrier multiplex two users. For user 1 who has a better channel quality, it should decode and remove the messages of user 2 via SIC before it decodes its own signal. The power allocation of user 2 is higher than user 1. User 3 and 4 are the similar with user 1 and 2.

1.2.1 Transition strategy for NOMA

NOMA technology has the characteristics of high spectrum utilization, high flexibility, and improved system capacity. According to the non-orthogonal transmission strategies' difference between users, NOMA technologies can be divided into two categories: signal domain segmentation technology and waveform design technology [56], [57]. Signal domain segmentation technology is based on the overall optimization of multiuser communication system. At the transmitting terminal, the user is differentiated based on the non-orthogonal features of multiple signal domains (e.g. power domain, generalized spatial domain, coding domain). At the receiving terminal, the multi-user detection receiver can be realized by using the SIC method or other sub-optimal detection algorithm based on the feature structure of the users' pattern. Signal domain segmentation multiple access representative technology mainly as power domain NOMA [18]-[21], bit division multiplexing (BDM) multiple access [22], superposition modulation (SM) [23], pattern division multiple access (PDMA) [24], space coupled multiple access (SCMA) [25]-[26], low density signature multiple access (LDSMA)[27]-[28] inter-leave division multiple access (IDMA)[29]-[31], etc.

Power domain NOMA technology assigns different powers to different users according to the users' channel quality [18]. In theory, each user can occupy all the time-frequency resources of the system. In order to realize the NOMA system, we can adopt user scheduling algorithm at the transmitter side and perform the SIC detection at the receiver side to separate the user signals from each other. For multi-user cellular communication systems, a proper power control can be performed at the transmitter, such that the interference to be effectively mitigated at the receiving terminal. The performance of the SIC detector highly depends on the received signal quality. In general, the performance of the SIC detector improves with the increasing disparities of the strength received signals.

On the other hand, waveform design techniques are primarily designed to optimize the multi-carrier modulation waveform and filter modes to achieve the non-orthogonal carriers. Waveform NOMA is mainly composed of faster-than-Nyquist (FTN) [32]-[33], generalized multi-carrier (GMC) [34], filter band multi-carrier (FBMC) [35], generalized frequency division multiplexing (GFDM) [36], universal filtered multi-carrier (UFMC) [36], biorthogonal frequency division multiplexing (BFDM) [36]-[38], and overlap time division multiplexing (OVTDM), etc.

1.2.2 Advantages for NOMA

In this part, we summarize some advantages about NOMA systems.

First, Non-Orthogonal Multiple Access can utilize the spectrum more efficiently, because it can admit closer users into the sub-carriers which engaged by farther users. It wouldn't influence a lot for their performance with appropriate power allocation and Successive Interference Cancellation techniques.

Second, Non-Orthogonal Multiple Access multiplexing strong users with weak users on purpose, it could utilize the heterogeneity of the condition of the channel. So, the performance effect of NOMA system is better than Orthogonal Multiple Access when channel gains of the multiplexed users turn to additionally different.

The third one is that it could enhance consumer fairness. By resting the orthogonal limitation of Orthogonal Multiple Access, Non-Orthogonal Multiple Access capacitate a more elastic regulation of the resources of radio, and it also supports an efficient method to increase consumer fairness through appropriate resource allocation.

At last, Non-Orthogonal Multiple Access can accept more terminals with different kinds of Quality of Service call for the same sub carrier. Thus, Non-Orthogonal Multiple Access is a good examinee to push Internet of Things which bands a lot of terminals and sensors. At the same time, there are several disadvantages about Non-Orthogonal Multiple Access system.

1.3 Resources Allocation on OMA and NOMA

In this part, we discuss the differences between OMA and NOMA technology in power allocation.

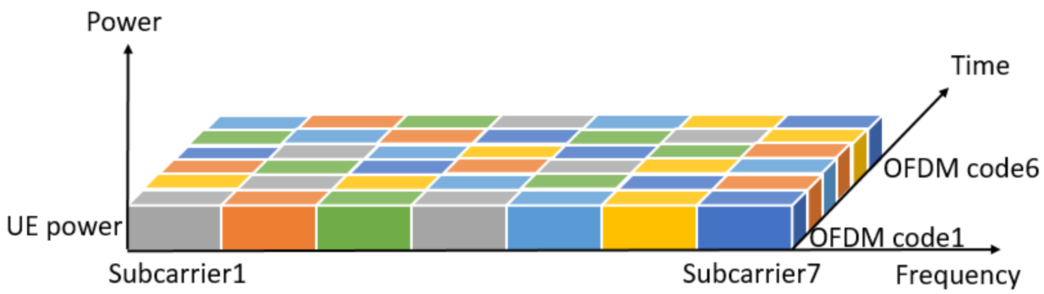

Figure 2 Resource allocation in an OFDM-based system.

Figure 2 shows the resource allocation for user information carried in frequency domain and time domain of the OFDM technology. For example, in LTE systems, the minimum unit in the frequency domain is the sub-carrier with a bandwidth of 15 kHz. The minimum unit of the time domain is an OFDM symbol with 1/14ms [39]-[41]. Each resource unit consists of one subcarrier and one OFDM symbol. LTE system adopt multi-antenna exploiting the degrees of freedom offered in spatial domain to carry user information. In particularly, each antenna utilizes the same frequency spectrum and time domain resources as other antennas.

In the power domain, since the frequency domain and the time domain carry the same users' information power, the OFDM technology in the LTE system does not adopt the power domain of the user information transmission [42]-[43]. It is the two-dimensional plane of resource carrying system, the transmission capability of the wireless channel relatively weak.

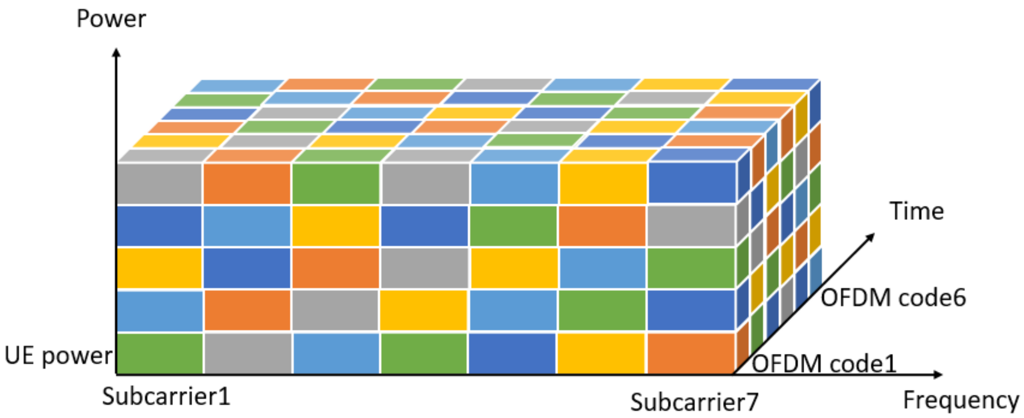

Figure 3 Resource allocation in NOMA-base system.

Figure 3 shows the resource allocation in the frequency domain, time domain, and power domain in a NOMA system. The frequency domain and time domain in the NOMA system are the same as the one in Figure 2. However, the difference between them is that each resource unit on the time domain and frequency domain plane can carry multiple users with different signal powers.

Obviously, NOMA technology is a system allowing a three-dimensional resource allocation. Hence, NOMA provides a higher flexibility in resource allocation compared to traditional OMA systems [44]. However, it is expected that there exist non-negligible multiuser interference and a more sophisticated interference management technology is needed.

Chapter 2

System Model

In cellular mobile communications, the system performance is usually limited by the low received signal-to-noise ratio (SNR) of the cell edge users. In the case of OMA transmission, if the objective of the system design is to maximize the system capacity, then those users located at the cell edge will rarely be scheduled. Therefore, it results in an unfair resource allocation and user starving. This section improves this situation by NOMA. In particular, we examine the detection algorithm of the SIC receiver using the power domain in the channel and the power allocation strategy taking into account user rate fairness requirement in the system. The closed form solution of the power allocation of NOMA system and the corresponding detection algorithm of the user power allocation and the corresponding detection algorithm are deduced, and the relationship between the system and the rate gain and the power distribution factor is explained.

2.1 Single carrier NOMA System

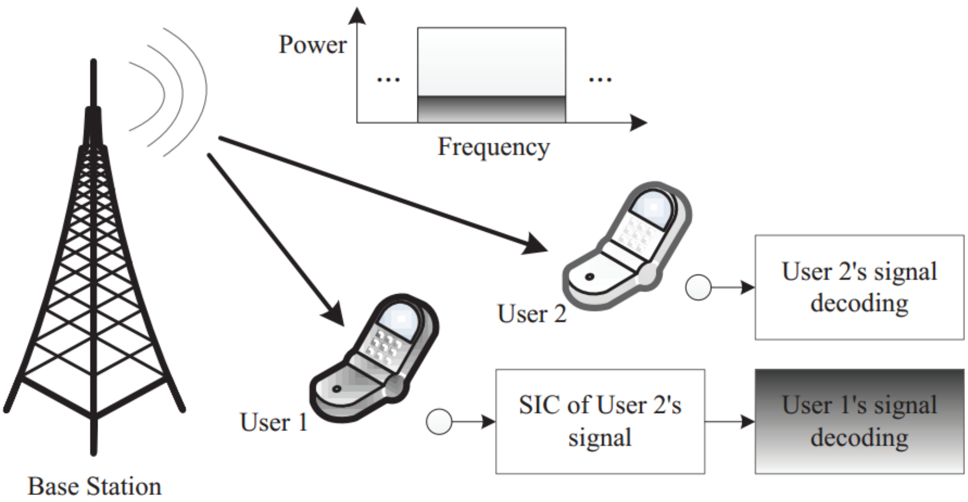

Figure 4 Downlink NOMA Model [45].

As shown in Figure 4, these two users: user 1 and user 2 (s_1 and s_2) transmitted on the same subcarrier with different transmit power (p_1 and p_2) respectively by a BS. The corresponding transmitted signal x is given by

$$x = \sqrt{p_1}s_1 + \sqrt{p_2}s_2, \tag{2.1}$$

where the transmit power p_1 and p_2 for signal s_1 and s_2 is restricted by $p_1 + p_2 = 1$. The received signal at user i is represented follow:

$$y_i = h_i x + v_i, \tag{2.2}$$

where h_i represents the channel coefficient capturing the joint effect of small-scale fading and large-scale fading. v_i is additive white Gaussian noise (AWGN), i.e., $v_i \sim CN(0, \sigma_i^2)$, which means that it follows the Gaussian distribution with zero mean and σ_i^2 variance. Assume that the user 1 is a weak user who is farther with the BS (with a worse channel on average) and the user 2 is a strong user who is closer with the BS (with a better channel on average). Thus, the BS will allocate more power to user 1 (weak user), which means $p_1 \geq p_2$ due to the NOMA protocol [46].

In this report, we assume that the users' channels between the BS and users are followed the Rayleigh fading channel gain, which are h_1 and h_2 respectively.

Without loss of generality, we denote the power allocation for user 1 and user 2 as a_1^2 and a_2^2 respectively, where $a_1^2 + a_2^2 = 1$. Note that $a_1 \geq a_2$ holds since $|h_1|^2 \leq |h_2|^2$ due to the principle of NOMA, Thus, the rates achieved by these two users are given by:

$$R_1 = \log\left(1 + \frac{|h_1|^2 a_1^2}{|h_1|^2 a_2^2 + \frac{1}{\rho}}\right), \tag{2.3}$$

and

$$R_2 = \log(1 + \rho |h_2|^2 a_2^2), \tag{2.4}$$

where ρ represents the transmit SNR.

2.2 Multicarrier NOMA System

We consider a multi-carrier downlink NOMA system which has one BS and K users, as shown in Figure 4. There are M subcarriers serving K users simultaneity. In this report, we assume that there are L subcarriers assigned for only one user, in order to support the fairness of resource allocation. Besides, we assume that the maximum number of users allocated to each subcarrier of M orthogonal subcarriers is two, reducing the computational complexity caused by SIC decoding and the delay caused by the receiver side (KL ≤ 2M). Based on the NOMA protocol [46], on subcarrier $m \in \{1, \dots, M\}$, the transmission signals form BS to user i and j are s_i^m and s_j^m respectively, and the transmit power for them are p_i^m and p_j^m , $i, j \in \{1, \dots, K\}$, respectively. The corresponding transmitted signal is provided by

$$x^m = \sqrt{p_i^m} s_i^m + \sqrt{p_j^m} s_j^m. \tag{2.5}$$

The received signal at user $i \in \{1, \dots, K\}$ on subcarrier m is represented by

$$y_i^m = h_i^m x^m + z_i^m, \tag{2.6}$$

where $z_i^m \sim \mathcal{CN}(0, \sigma^2)$ represents the additive white Gaussian noise (AWGN) for user i on subcarrier m. The variable $h_i^m \in \mathbb{C}$ denotes the channel coefficient covering the conjunction effect of small-scale fading and large-scale fading, i.e., $h_i^m = \frac{g_i^m}{\sqrt{1+d_i^m}}$ and $g_i^m \sim \mathcal{CN}(0,1)$, where d_i represents the distance from the BS to user i, and α representing the path loss exponent. In addition, we assume that the channel gain is Rayleigh distributed for small scale fading, and the path loss information at the BS is foregone because of the long-term measurement. The cumulative distribution function (CDF) of user i on subcarrier m of the channel gain is provided by

$$F_{|h_i^m|^2}(x) = 1 - e^{-(1+d_i^\alpha)x}, x \geq 0, \tag{2.7}$$

2.3 Successive Interference Cancellation

NOMA performs multiple access using the power domain [47]-[48]. The BS realizes power allocation and user scheduling, according to the availability of CSIT. In addition, some downlink users will exploit SIC to alleviate multi-user interference. In the literature [49]-[51], including perfect CSIT and ignoring QoS requirements, before strong user, who has better channel quality, decoding itself, they will decode and eliminate signal of weak user, i.e., worse channel quality, first. However, the weak user will treat the signal of the strong user as noise and directly decode its own signal. Besides, in order to achieve fairness and to facilitate the SIC process, the weak user will be allocated more power by the BS.

Unfortunately, based on the ordered channel gain information, the BS cannot decide the SIC decoding order without perfect CSIT. Similar to the case of NOMA with perfect CSIT, the distances between the BS and the users can be adopted as a metric to determine the average channel conditions. However, this metric does not take the QoS requirements into account, which also impact of the SIC decoding order, and then change the performance of power allocation [52]. For instance, if a user near a BS, the user requires a lower outage probability than the other one, choosing this user to perform SIC requires more transmission power than choosing another user, which is as opposed to the conventional NOMA regardless of the QoS requirements.

Furthermore, it can be seen that for the situation of NOMA systems with QoS requirements and perfect CSIT, only choosing the strong user to exploit the SIC will require less transmission power than executing the SIC for these two users [53]. Intuitively, the allocated power for two users will be raised to handle the interference of decoding messages to other users. Therefore, we assume that there should be only one user to exploit SIC on each subcarrier. In particular, if the SIC is performed based on the selected power consumption which lower than the selection user j, the BS executes the SIC on the subcarrier m by selecting the user i. At the end of this report, based on this imagine, we can process the precise SIC decoding order from the QoS requirements.

Moreover, the total required target rate for a given user j is R_j, which can be divide into L allocated subcarriers, because that only statistical CSIT is achievable at the BS. Thus, the target rate of the user j on its assigned subcarrier m is represent by

$$\tilde{R}_j^m = \frac{R_j}{L}, \tag{2.8}$$

and the corresponding target SINR is represented by

$$\tilde{\gamma}_j^m = 2^{\tilde{R}_j^m} - 1, \tag{2.9}$$

Assuming on subcarrier m, SIC at user i is successful when the decoding rate of the signal for user j is not less than the target rate of user j, i.e.,

$$R_{i\to j}^m \geq \tilde{R}_j^m, \tag{2.10}$$

where $R_{i\to j}^m$ represents the achievable rate for user i which decodes the signal of user j on subcarrier m, and it is represent by

$$R_{i\to j}^m = log_2\left(1 + \frac{p_j^m |h_i^m|^2}{p_i^m |h_i^m|^2 + \sigma^2}\right). \tag{2.11}$$

Chapter 3

Problem Formulation

In this section, we formulate the power allocation and define the QoS requirements for NOMA system.

3.1 Quality of Service

Normally, QoS is defined by the required outage probability and a target rate. Considering the target rate $\widetilde{R_i^m}$ for each user allocated on each subcarrier, the QoS required by user i on subcarrier m is given by the following outage probability constraint:

$$Pr\{R_i^m \geq \widetilde{R_i^m}\} \geq 1 - \delta_i^m, \forall i, \tag{3.1}$$

with

$$R_i^m = \begin{cases} R_{i,i}^m & if\ R_{i \to j}^m \geq \tilde{R}_j^m, \\ R_{i,j}^m & otherwise, \end{cases} \tag{3.2}$$

where δ_i^m and R_i^m represent the required outage probability and the achievable rate of user i on subcarrier m, separately. It should be noted that each subcarrier defines their own outage probability, which is normally adopte in the literature for the simplification of the resource allocation design [42], [54]. Variables $R_{i,i}^m$ and $R_{i,j}^m$ show the achievable rates for user i on subcarrier m with and without SIC, separately, and they are represented by

$$R_{i,i}^m = log_2\left(1 + \frac{p_i^m |h_i^m|^2}{\sigma^2}\right) \text{ and} \tag{3.3}$$

$$R_{i,j}^m = log_2\left(1 + \frac{p_i^m |h_i^m|^2}{p_j^m |h_i^m|^2 + \sigma^2}\right). \tag{3.4}$$

3.2 Optimization Problem Formulation

The scheduling and joint power allocation design for the considered NOMA system as an optimization problem:

$$\underset{\vec{p},\vec{c}}{\text{mininize}} \sum_{m=1}^{M} \sum_{i=1}^{M} \sum_{j=1}^{K} c_{i,j}^{m} (p_i^m + p_i^m) \quad (3.5a)$$

$$\text{s.t. } \Pr\{R_i^m \geq \widetilde{R_i^m}\} \geq c_{i,j}^m (1 - \delta_i^m), \forall i, m, \quad (3.5b)$$

$$p_i^m \geq 0, \forall i, m, \quad (3.5c)$$

$$\sum_{i=1}^{K} \sum_{j=1}^{K} c_{i,j}^m \leq 2, \forall m, \quad (3.5d)$$

$$\sum_{m=1}^{K} \sum_{j=1}^{K} c_{i,j}^m = L, \forall i, \quad (3.5e)$$

$$c_{i,j}^m \in \{0,1\}, \forall i, j, m, \quad (3.5f)$$

where $c_{i,j}^m$ is the binary subcarrier allocation variable. It will be one if both user i and user j are multiplexed on the same subcarrier m, and it will be zero if they are not. The vectors $\vec{c} \in \mathbb{Z}^{MK^2\times 1}$, i.e., all the $MK^2\times 1$ vectors are integer entries, and $\vec{p} \in \mathbb{R}^{MK\times 1}$,i.e., all the $MK\times 1$ vectors are real entries, represent the set of user scheduling variables and power allocation variables. Equation (3.5b) is used to guarantee the QoS of all the users on their allocated subcarriers and it is inactive when subcarrier m is not allocated for user i, i.e., $c_{i,j}^m = 0$. Equation (3.5c) is non-negative constraint for power allocation variables. Equations (3.5d) and (3.5f) are applied to ensure that the maximum number of users multiplexed on one subcarrier is two, and all the subcarriers are allocated to decrease the total power consumption. Equation (3.5e) is applied for resource allocation fairness so that all the users have the same quantity of frequency resources [45].

We take notice that the subcarrier m is specifically allocated to user i for the condition of $c_{i,j}^m = 1$, $i = j$, and the user scheduling strategy for subcarrier m is simplified to routine orthogonal allocation. In other words, the optimization framework proposed in (3.5) summarizes the resource allocation for routine OMA as a subcase. We notice that the problem in (3.5) is a mixture of nonconvex problem. In general, there doesn't exist a computational efficient and systematic method to solve it optimally. The user scheduling is jointly influenced by target rate $\widetilde{R_i^m}$, distance d_i, and the required outage probability δ_i, According to (3.5), while the counterpart of traditional NOMA system with perfect CSIT only based on channel gain order [55]. Besides, the user scheduling and power allocation variables are jointed base on (3.5a) and (3.5b). Therefore, we propose a suboptimal solution in the following two sections. In particular, we aim to solve the user scheduling and power allocation independently.

Chapter 4

Optimization Solution

Without loss of generality, for a given user scheduling policy c that satisfies constraints (3.5d), (3.5e), and (3.5f), we can perform the power allocation on each subcarrier independently. Thus, the original problem (3.5) can be simplified to a power allocation problem for two-user on each subcarrier. For the sake of simplicity, we discard the subcarrier index m. The optimization problem per subcarrier given by

$$\underset{p_1,p_2}{\text{mininize}} \sum_{i=1}^{2} p_i, \tag{4.1a}$$

$$\text{s.t. } Pr\{R_i \geq \widetilde{R_i}\} \geq (1-\delta_i^m), i \in \{1,2\}, \tag{4.1b}$$

$$p_i \geq 0, i \in \{1,2\}, \tag{4.1c}$$

where R_i is given by (3.2).

In the following, we assume that there is only one user executeing the SIC to solve the problem in (4.1), and then based on the power allocation solution and compare its expression with OMA derived the SIC decoding order.

4.1 Power Allocation Solution

To derive the optimal power allocation solution for the problem in (4.1), we divide the situation into the following two cases. For the first case, we only allow user 1 to execute SIC and acquire the corresponding power allocation solution. It is also possible to obtain a power allocation solution for the second case, which only allows user 2 to perform SIC. Then, the optimal solution for the problem in (4.1) is given by the solutions for both cases with the lower power consumption.

According to (2.10), if user 1 is allowed to exploit SIC and prevent user 2 to do that, the following condition precedent should be satisfied:

$$p_2 - p_1\tilde{\gamma}_2 > 0, \tag{4.2}$$

$$p_1 - p_2\tilde{\gamma}_1 \leq 0, \tag{4.3}$$

We notice that, the condition precedent in (4.2) cannot guarantee the success of SIC due to the channel uncertainty, and the success of SIC also cannot guarantee outage free transmission. Hence, the resource allocation for MC-NOMA system in this report is completely different from the case of perfect CSIT, e.g. [58], [59]. In these two prerequisite conditions, (4.2) and (4.3), the outage probability for these two users are represent by

$$P_1^{out} = Pr\{R_{1\to 2}^m \geq \tilde{R}_2^m, R_{1,1} < \widetilde{R_1}\} + Pr\{R_{1\to 2}^m < \tilde{R}_2^m, R_{1,2} < \widetilde{R_1}\}, \tag{4.4}$$

$$P_2^{out} = Pr\{\, R_{2,1} < \widetilde{R_2}\}, \tag{4.5}$$

where P_1^{out} and P_2^{out} express the outage probability of user 1 and user 2, respectively. Constraint (13b) needs that $P_i^{out} \leq \delta_i$. We notice that P_1^{out} includies two terms which show the outage probability with a successful SIC and an unsuccessful SIC at user 1, respectively.

Substituting (2.11), (3.3), and (3.4) into (4.4) and (4.5), and then yields

$$P_1^{out} = Pr\left\{log_2\left(1 + \frac{p_2|h_1|^2}{p_1|h_1|^2+\sigma^2}\right) \geq log_2(\tilde{\gamma}_2 + 1), log_2\left(1 + \frac{p_2|h_1|^2}{\sigma^2}\right) < log_2(\tilde{\gamma}_2 + 1)\right\}$$

$$+Pr\left\{log_2\left(1 + \frac{p_2|h_1|^2}{p_1|h_1|^2+\sigma^2}\right) < log_2(\tilde{\gamma}_2 + 1), log_2\left(1 + \frac{p_2|h_1|^2}{\sigma^2}\right) < log_2(\tilde{\gamma}_2 + 1)\right\}, \tag{4.6}$$

$$P_2^{out} = Pr\left\{\, log_2\left(1 + \frac{p_2|h_2|^2}{p_1|h_2|^2+\sigma^2}\right) < log_2\left(\tilde{\gamma}_2 + 1\right)\right\}. \tag{4.7}$$

Performing mathematical incompletion of (4.6) and (4.7) yields

$$P_1^{out} = Pr\left\{\frac{p_2|h_1|^2}{p_1|h_1|^2+\sigma^2} \geq \tilde{\gamma}_2, \frac{p_2|h_1|^2}{\sigma^2} < \tilde{\gamma}_2\right\} + Pr\left\{\frac{p_2|h_1|^2}{p_1|h_1|^2+\sigma^2} < \tilde{\gamma}_2, \frac{p_2|h_1|^2}{\sigma^2} < \tilde{\gamma}_2\right\}, \tag{4.8}$$

$$P_2^{out} = Pr\left\{\, \frac{p_2|h_2|^2}{p_1|h_2|^2+\sigma^2} < \tilde{\gamma}_2\right\}. \tag{4.9}$$

Then, we here:

$$P_1^{out} = Pr\left\{|h_1|^2 \geq \frac{\tilde{\gamma}_2\sigma^2}{p_2 - p_1\tilde{\gamma}_2}, |h_1|^2 < \frac{\tilde{\gamma}_1\sigma^2}{p_1}\right\} + Pr\left\{|h_1|^2 < \frac{\tilde{\gamma}_2\sigma^2}{p_2 - p_1\tilde{\gamma}_2}, |h_1|^2 < \frac{\tilde{\gamma}_1\sigma^2}{p_1 - p_2\tilde{\gamma}_1}\right\}$$

$$= \Pr\left\{|h_1|^2 < \max\left(\frac{\widetilde{\gamma_1}\sigma^2}{p_1}, \frac{\widetilde{\gamma_2}\sigma^2}{p_2 - p_1\widetilde{\gamma_2}}\right)\right\}, \quad (4.10)$$

$$P_2^{out} = Pr\left\{ |h_2|^2 < \frac{\widetilde{\gamma_2}\sigma^2}{p_2 - p_1\widetilde{\gamma_2}}\right\}. \quad (4.11)$$

Substituting (3.1) and (4.1b) into (4.10) and (4.11) yields

$$P_1^{out} = \Pr\left\{|h_1|^2 < \max\left(\frac{\widetilde{\gamma_1}\sigma^2}{p_1}, \frac{\widetilde{\gamma_2}\sigma^2}{p_2 - p_1\widetilde{\gamma_2}}\right)\right\} \le \delta_1, \quad (4.12)$$

$$P_2^{out} = \Pr\left\{|h_2|^2 < \frac{\widetilde{\gamma_2}\sigma^2}{p_2 - p_1\widetilde{\gamma_2}}\right\} \le \delta_1. \quad (4.13)$$

Exploiting the CDF of channel gain (2.7) in (4.12) and assuming $\frac{\tilde{\gamma}_2\sigma^2}{p_2 - p_1\tilde{\gamma}_2} > \frac{\tilde{\gamma}_1\sigma^2}{p_1}$ obtains

$$P_1^{out}\left(\frac{\tilde{\gamma}_2\sigma^2}{p_2 - p_1\tilde{\gamma}_2} > \frac{\tilde{\gamma}_1\sigma^2}{p_1}\right) = Pr\left\{|h_1|^2 < \frac{\tilde{\gamma}_1\sigma^2}{p_1}\right\} \quad (4.7)$$

$$= F_{|h_1|^2}\left(\frac{\tilde{\gamma}_1\sigma^2}{p_1}\right)$$

$$= 1 - e^{-(1+d_1^{\alpha})\left(\frac{\tilde{\gamma}_1\sigma^2}{p_1}\right)} \le \delta_1.$$

Exponent operating (4.7) gets

$$\ln(1 - \delta_1) \le -(1 + d_1^{\alpha})\left(\frac{\tilde{\gamma}_1\sigma^2}{p_1}\right), \quad (4.8)$$

$$\frac{\tilde{\gamma}_1}{p_1} \le -\frac{\ln(1-\delta_1)}{(1+d_1^{\alpha})\sigma^2}, \quad (4.9)$$

where $\beta_1 = -\frac{\ln(1-\delta_1)}{(1+d_1^{\alpha})\sigma^2}$, then we get

$$\frac{\tilde{\gamma}_1}{\beta_1} \le p_1. \quad (4.10)$$

Assuming $\frac{\tilde{\gamma}_1\sigma^2}{p_1} \ge \frac{\tilde{\gamma}_2\sigma^2}{p_2 - p_1\tilde{\gamma}_2}$, we obtain

$$P_1^{out}\left(\frac{\tilde{\gamma}_1\sigma^2}{p_1} \ge \frac{\tilde{\gamma}_2\sigma^2}{p_2 - p_1\tilde{\gamma}_2}\right) = Pr\left\{|h_1|^2 < \frac{\tilde{\gamma}_2\sigma^2}{p_2 - p_1\tilde{\gamma}_2}\right\} \quad (4.11)$$

$$= F_{|h_1|^2}\left(\frac{\tilde{\gamma}_2\sigma^2}{p_2 - p_1\tilde{\gamma}_2}\right)$$

$$= 1 - e^{-(1+d_1^\alpha)\left(\frac{\tilde{\gamma}_2\sigma^2}{p_2 - p_1\tilde{\gamma}_2}\right)} \leq \delta_1.$$

Performing mathematical operating of (4.11), we get

$$\ln(1 - \delta_1) \leq -(1 + d_1^\alpha)\left(\frac{\tilde{\gamma}_2\sigma^2}{p_2 - p_1\tilde{\gamma}_2}\right), \tag{4.12}$$

$$\frac{\tilde{\gamma}_2}{p_2 - p_1\tilde{\gamma}_2} \leq -\frac{\ln(1-\delta_1)}{(1+d_1^\alpha)\sigma^2}, \tag{4.13}$$

then we get

$$\frac{\tilde{\gamma}_2}{\beta_1} \leq p_2 - p_1\tilde{\gamma}_2. \tag{4.14}$$

Exploiting the CDF of channel gain (2.7) in (4.13) obtains

$$P_2^{out} = \Pr\left\{|h_2|^2 < \frac{\widetilde{\gamma_2}\sigma^2}{p_2 - p_1\widetilde{\gamma_2}}\right\} \tag{4.15}$$

$$= F_{|h_2|^2}\left(\frac{\tilde{\gamma}_2\sigma^2}{p_2 - p_1\tilde{\gamma}_2}\right)$$

$$= 1 - e^{-(1+d_2^\alpha)\left(\frac{\tilde{\gamma}_2\sigma^2}{p_2 - p_1\tilde{\gamma}_2}\right)} \leq \delta_1$$

Performing mathematical operating of (4.15), we get

$$\ln(1 - \delta_2) \leq -(1 + d_2^\alpha)\left(\frac{\tilde{\gamma}_2\sigma^2}{p_2 - p_1\tilde{\gamma}_2}\right), \tag{4.16}$$

$$\frac{\tilde{\gamma}_2}{p_2 - p_1\tilde{\gamma}_2} \leq -\frac{\ln(1-\delta_2)}{(1+d_2^\alpha)\sigma^2}, \tag{4.17}$$

where $\beta_2 = -\frac{\ln(1-\delta_2)}{(1+d_2^\alpha)\sigma^2}$, then we get

$$\frac{\tilde{\gamma}_2}{\beta_2} \leq p_2 - p_1\tilde{\gamma}_2. \tag{4.18}$$

Calculating (4.10), (4.14) and (4.18) yields

$$\text{when } \beta_1 > \beta_2 \begin{cases} p_1 \geq \frac{\tilde{\gamma}_1}{\beta_1} \\ p_2 \geq \frac{\tilde{\gamma}_2}{\beta_2} + \frac{\tilde{\gamma}_1\tilde{\gamma}_2}{\beta_1}, \end{cases} \tag{4.19}$$

$$\text{when } \beta_2 \geq \beta_1 \begin{cases} p_1 \geq \frac{\tilde{\gamma}_1}{\beta_1} \\ p_2 \geq \frac{\tilde{\gamma}_2}{\beta_1} + \frac{\tilde{\gamma}_1\tilde{\gamma}_2}{\beta_2}. \end{cases} \tag{4.20}$$

According to (4.2) and (4.3), we get

$$p_2 \geq \frac{1}{\beta_1}. \tag{4.21}$$

Therefore, we acquire the solution of (4.1) where the minimized total transmit power as:

$$p_1^{(1)} = \frac{\tilde{\gamma}_1}{\beta_1} \text{ and} \tag{4.22}$$

$$p_2^{(1)} = \max\left(\frac{\tilde{\gamma}_1\tilde{\gamma}_2}{\beta_1} + \frac{\tilde{\gamma}_2}{\beta_1}, \frac{\tilde{\gamma}_1\tilde{\gamma}_2}{\beta_1} + \frac{\tilde{\gamma}_2}{\beta_2}, \frac{1}{\beta_1}\right). \tag{4.23}$$

where $\beta_i = -\frac{\ln(1-\delta_i)}{(1+d_i^{\alpha})\sigma^2}$, $p_i^{(1)}$, $i \in \{1,2\}$, is the allocated power for user i for the first case, and the superscript (1) express that it allow user 1 to exploit SIC. Note that $\frac{1}{\beta_i}$ can be treated as the level of QoS requirements for user i, where a large $\frac{1}{\beta_i}$ means user i is far away from the BS or has a lower required outage probability, such that a higher transmit power is necessary to satisfy its stringent QoS requirement. Similar to the case of NOMA with perfect CSIT, we can define a user with larger β_i as a QoS non-demanding user and define the other user as a QoS demanding user.

For the second case, it allows user 2 to exploit SIC and forbids user 1 to do that, the prerequisite conditions are denoted by

$$p_1 - p_2\tilde{\gamma}_1 > 0 \text{ and} \tag{4.24}$$

$$p_2 - p_1\tilde{\gamma}_2 \leq 0. \tag{4.25}$$

Similarly, with the previous case, the solution of power allocation for (4.1) can be deduced and denoted as

$$p_1^{(2)} = \max\left(\frac{\tilde{\gamma}_1\tilde{\gamma}_2}{\beta_2} + \frac{\tilde{\gamma}_1}{\beta_2}, \frac{\tilde{\gamma}_1\tilde{\gamma}_2}{\beta_2} + \frac{\tilde{\gamma}_1}{\beta_1}, \frac{1}{\beta_2}\right) \text{ and} \tag{4.26}$$

$$p_2^{(2)} = \frac{\tilde{\gamma}_2}{\beta_2}, \tag{4.27}$$

where the superscript (2) express that it allows user 2 to exploit SIC.

In summary, the optimal solution for the problem in (4.1) can be selected by

$$(p_1, p_2) = \begin{cases} \left(p_1^{(1)}, p_2^{(1)}\right) & \text{if } p_1^{(1)} + p_2^{(1)} \leq p_1^{(2)} + p_2^{(2)}, \\ \left(p_1^{(2)}, p_2^{(2)}\right) & \text{otherwise,} \end{cases} \tag{4.28}$$

and the BS will message user i to exploit SIC and prevent the other user to do that if $\left(p_1^{(i)}, p_2^{(i)}\right)$ is selected.

4.2 A Simple SIC Decoding Order

In order to achieve minimum power consumption, optimization of power allocation options in (4.28) includes the SIC decoding strategy. However, we can acquire a clear rule to decide a normal case for $\tilde{\gamma}_1 \geq 1$ and $\tilde{\gamma}_2 \geq 1$ of the SIC decoding order, which means the target rates of two users are not less than 1 bit/s/Hz. In this case, $\frac{1}{\beta_1}$ and $\frac{1}{\beta_2}$ will not be selected in (4.23) and (4.26), separately. Therefore, we have a simple solution for the joint optimization of power allocation and SIC decoding order:

$$(p_1, p_2) = \begin{cases} \left(p_1^{(1)}, p_2^{(1)}\right) & \text{if } \beta_1 \geq \beta_1, \\ \left(p_1^{(2)}, p_2^{(2)}\right) & \text{otherwise,} \end{cases} \tag{4.29}$$

which denotes that in order to minimize the power consumption, we always select the QoS non-demanding user to exploit SIC.

Therefore, for a normal case of $\tilde{\gamma}_1 \geq 1$ and $\tilde{\gamma}_2 \geq 1$, β_1 defines the optimal SIC decoding policy in terms of power efficiency, where we only allow the QoS non-demanding user to exploit SIC to decrease the total power consumption. In addition, for $\tilde{\gamma}_1 < 1$, in order to find the SIC decoding order we have to evaluate both solutions and compare them in (4.28).

4.3 Comparison between NOMA and OMA

For a NOMA system with perfect CSIT, it is well known that when the channel gains differences between the multiplexed users increased, the performance gain of NOMA over OMA will increases [49], [51]. In this report, we can use our solution to obtain a similar conclusion to reduction in power consumption in the case of imperfect CSIT. For a fair comparison, we apply the same spectral efficiency for NOMA and OMA, where the individual subcarriers are further divided into two subcarriers with equal bandwidth for the OMA system. Thus, the power allocation for two OMA users with statistical CSIT on one subcarrier is given by

$$(p_1^{OMA}, p_2^{NOMA}) = \left(\frac{2^{2\tilde{R}_1 - 1}}{2\beta_1}, \frac{2^{2\tilde{R}_2 - 1}}{2\beta_2}\right), \tag{4.30}$$

where the superscript "OMA" expresses the case of OMA.

Now, we provide a sufficient condition that the power consumption of NOMA is no larger than that of OMA. Suppose $\tilde{R}_1 \geq 1$ bit/s/Hz and $\tilde{R}_2 \geq 1$ bit/s/Hz, we can obtain the performance gain of NOMA over OMA in terms of power reduction as follows:

$$p_{total}^{OMA} - p_{total}^{NOMA} = \begin{cases} \frac{\tilde{\gamma}_1\tilde{\gamma}_2}{\sqrt{\beta_1}}\left(\frac{1}{\sqrt{\beta_2}} - \frac{1}{\sqrt{\beta_1}}\right) + \frac{1}{2}\left(\frac{\tilde{\gamma}_2}{\sqrt{\beta_2}} - \frac{\tilde{\gamma}_1}{\sqrt{\beta_1}}\right)^2 \geq 0 & if\ \beta_1 \geq \beta_2, \\ \frac{\tilde{\gamma}_1\tilde{\gamma}_2}{\sqrt{\beta_2}}\left(\frac{1}{\sqrt{\beta_1}} - \frac{1}{\sqrt{\beta_2}}\right) + \frac{1}{2}\left(\frac{\tilde{\gamma}_1}{\sqrt{\beta_1}} - \frac{\tilde{\gamma}_2}{\sqrt{\beta_2}}\right)^2 > 0 & otherwise, \end{cases} \tag{4.31}$$

on a single subcarrier, the total power consumption for OMA and NOMA is expressed by p_{total}^{OMA} and p_{total}^{NOMA}, separately. It can be noticed that, the power reduction of NOMA over OMA is non-negative under the sufficient conditions. More importantly, with $\tilde{R}_1 \geq 1$ bit/s/Hz and $\tilde{R}_2 \geq 1$ bit/s/Hz, when the difference in the level of QoS requirements or the target rate between the QoS demanding user and QoS nondemanding user become larger, e.g. $\beta_1 \gg \beta_2$ or $\tilde{\gamma}_1 \gg \tilde{\gamma}_2$, the performance gain of NOMA over OMA also increases. Note that when the multiplexed users have same distances and QoS requirements, i.e., $\beta_1 = \beta_2$ and $\tilde{\gamma}_1 = \tilde{\gamma}_2$, for the case of statistical CSIT, the difference of total power consumption between NOMA and OMA is zero.

In general, from (26) and (28), we deduce that the level of QoS requirements $\frac{1}{\beta_i}$ plays a significant role in SIC decoding order and power allocation design.

Chapter 5

User Scheduling Algorithm

According to (3.5), the K users can be considered as KL independent users because their QoS equations (3.5b) are used independently on each subcarrier. Besides, in high system load situation, NOMA provides significant system performance gain. Therefore, we focus on an actual overload case, i.e., $KL > M$. Now, to serve K users via M subcarriers, we intend to generate a combination of $KL - M$ users pairs and $2M - KL$ individual users, corresponding to NOMA and OMA, separately. In all candidate user combinations, user scheduling needs to select one combination that consumes the minimal power.

In the absence of generality, in this part we assume $L = 1$. For $L > 1$, we simply exclude the situation that one user who is paired with itself to satisfy the equation (3.5e). As mentioned above, only these two multiplexed users can affected the power consumption of each subcarrier. In order to allocated K user on M subcarriers, there are $\binom{K}{2}$ possible candidate pairs for these users, and we can get all the power consumption from (4.28), i.e., $p_{i,j}$, $i \in \{1, \ldots, \mathrm{K}\}$ and $i \neq j$. Besides, for orthogonal subcarrier assignment, the power consumption for user i is denoted by $p_{i,j} = \frac{\gamma_i}{\beta_i}$.

The number of all candidate combinations is denoted by

$$\mathrm{N} = \binom{K}{2M-K} \prod_{m=1}^{K-M} (2m-1). \tag{5.1}$$

Algorithm 1 User Scheduling Algorithm

1: Compute $p_{i,j}$, $i \neq j$, $i, j \in \{1, \ldots, \mathrm{K}\}$, through (4.28).

2: Generate the dendrogram based on $p_{i,j}$ via agglomerative hierarchical clustering.

3: Allocate the right $2M - K$ users on $2M - K$ subcarriers exclusively.

4: Partition the left $2K - 2M$ users into two groups and pair them in successive order on $K - M$ subcarriers [45].

Chapter 6

Results

6.1 The simulation for the difference between OMA and NOMA

In this part, we assume there are two users in one subcarrier, the distance between users and BS is 1000 meters and 20 meters respectively. And the path loss exponent n = 3.6. For noise power, Boltzmann's constant $K = 1.38 \times 10^{-23}$, temperature in Kelvin T = 300K, noise bandwidth B = 2.1 GHz.

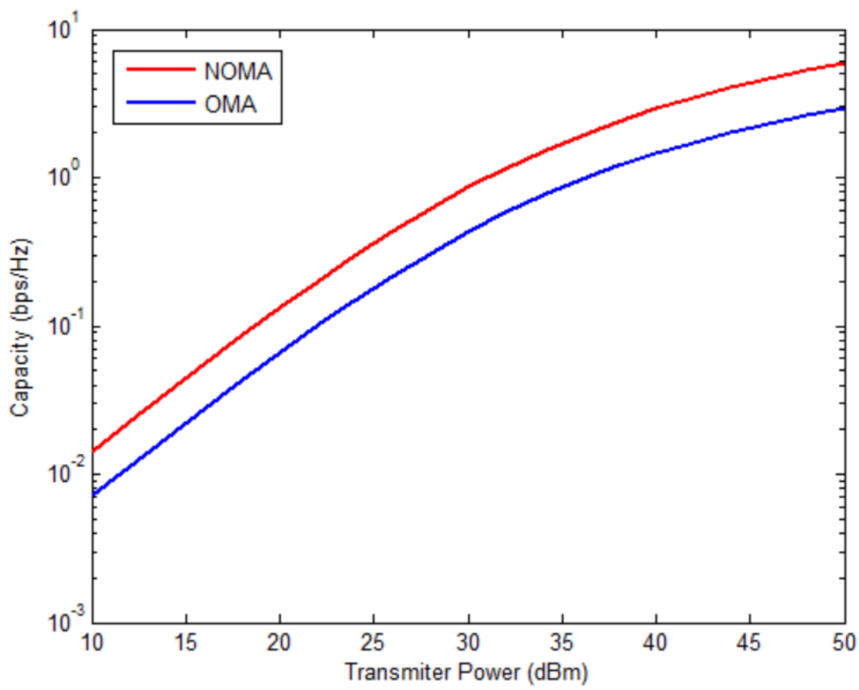

Figure 5 System capacity versus transmitter power for OMA and NOMA.

This part is a prepare step which could help us understand the function of OMA and NOMA system of perceptual intuition. Assume these two users are located at same distance with the BS, and does not consider the interference between these two users temporarily. We simulate the capacity difference between OMA and NOMA during the increase of transmit power, which eliminate the influence of channel, noise, path loss, and interference. As the figure 5 illustrate, the capacity of OMA system is less than NOMA system for all the transmitter power.

6.2 The simulation for the Power allocation for 2-user NOMA

In this part, we simulate the different power allocation for 2-user at NOMA system. Assume these two users does not consider the interference between these two users temporarily.

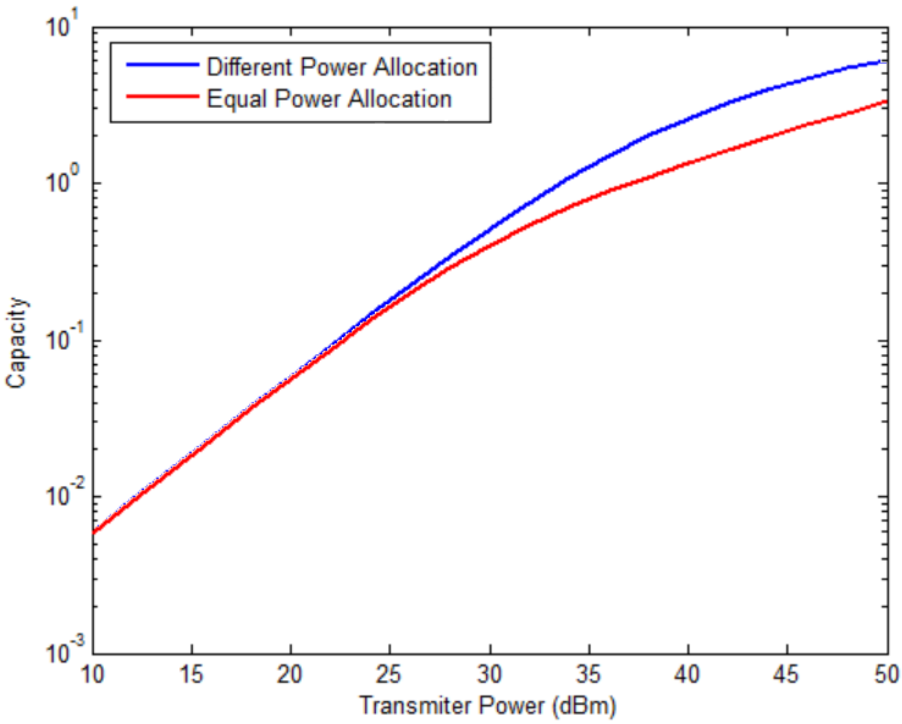

Figure 6 NOMA system capacity versus transmitter power.

As the figure 6 shows, the "blue" curve is the sum capacity of two users which have a huge distinction of power allocation, also known as large distance between them. And the "red" curve is for two users who have equal power allocation, which means that they are allocate at same distance with the BS.

6.3 Power Consumption versus Cell Size

In this part, we assume the BS located at the centre of the cell with size D, and there are K users allocated between 30 m and D m randomly, i.e., $d_i \sim U[30, D]$ m. Besides, the target rates for all users are created by $\tilde{R}_i \sim U[0.1, 10]$ bit/s/Hz. There are two kinds of outage probability evaluated to compare the performance gain by introducing the QoS constraints in the following simulations: Case I with equal outage probability $\delta_i = 10^{-2}$ and Case II with random outage probability $\delta_i \sim U[10^{-5}, 0.1]$. The user noise power on each subcarrier is $\sigma^2 = -128$ dBm. The 3GPP path loss model with path loss exponent $\alpha = 3.6$ is adopted in our simulations.

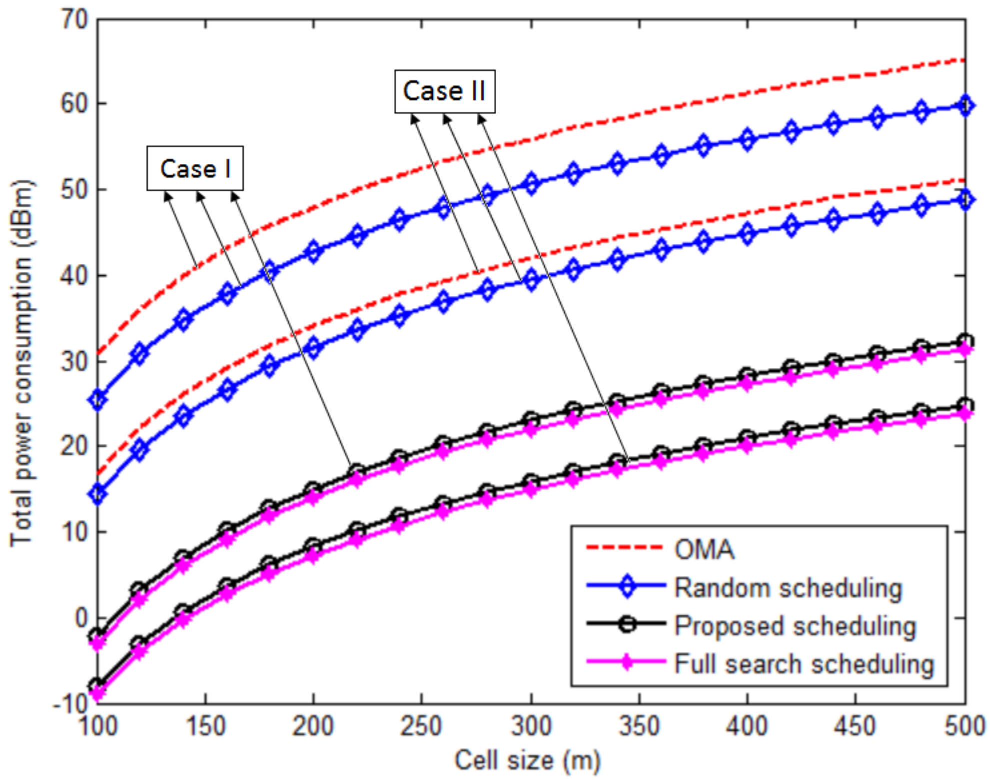

Figure 7 Power consumption (dBm) verses cell size.

In Figure 7, we investigate the power consumption versus cell size D for the considered MC-NOMA system with $M = 5$, $K = 4$, and $L = 2$. For comparison, we also show the performance of OMA, random scheduling and, full search scheduling. Note that power consumption for OMA is given with (4.30) by replacing $2\tilde{R}_i$ with $K/M\tilde{R}_i$ since the available frequency bandwidth is split equally for K users. In addition, we note that the random scheduling and the full search scheduling are performed together with the proposed power allocation solution (4.28). It can be seen that our proposed user scheduling method provides a significant power saving compared to the random scheduling, and achieves a performance close to the full search scheduling in both cases. The reason for this improvement is that our proposed user scheduling method considers the joint effect of $1/\beta_l$ and $\tilde{\gamma}_i$, and exploits the heterogeneity of QoS requirements, which achieves a better utilization of power domain. More importantly, the performance gain of our proposed scheme over OMA in Case II is larger than Case I. This result demonstrates the effectiveness of our proposed scheme in exploiting the QoS heterogeneity to reduce power consumption.

6.4 Total Power Consumption versus Number of Users

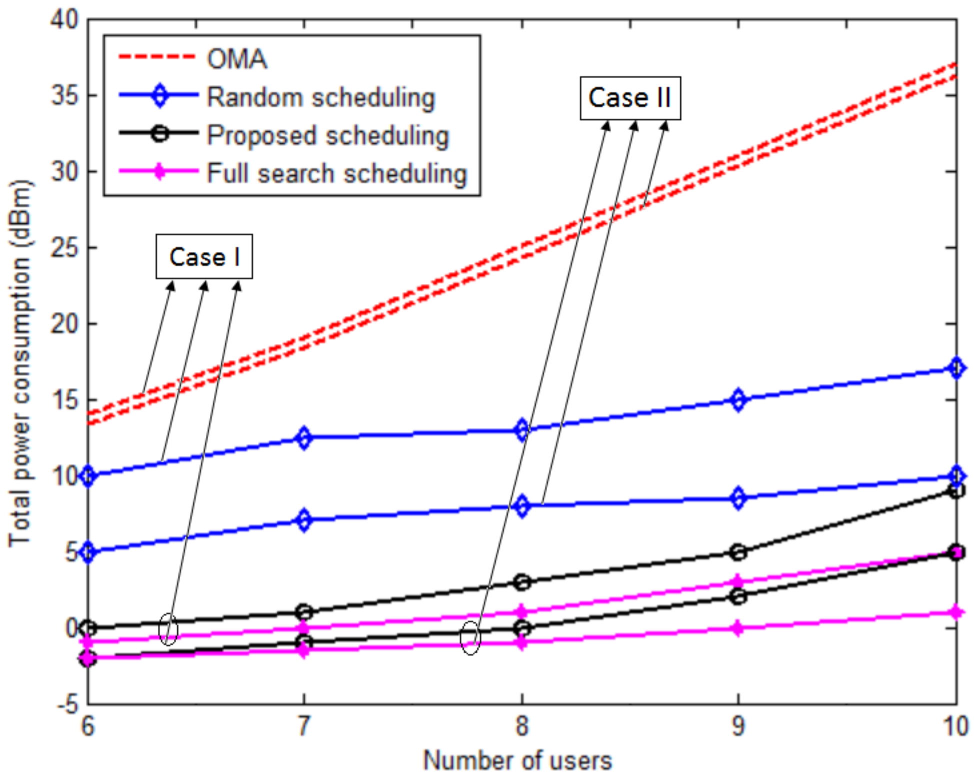

Figure 8 Power consumption (dBm) versus number of users.

In Figure 8, we investigate the performance of our proposed scheme versus the number of users. A MC-NOMA system with $M = 5$ subcarriers and cell size D =200 m is considered. We assume $L = 1$ in this case, and the number of user K varies from 6 to 10. It can be observed that our proposed resource allocation scheme reduces the power consumption substantially compared to the random scheduling, and performs closely to the full search scheduling in both cases. Besides, it can be observed that the performance gain of our proposed scheme over OMA in Case II is also larger than that in Case I owing to a better resource utilization via considering the diversification of

QoS requirements. More importantly, it can be seen that the performance gain over OMA increases with number of users in both cases, which is consistent with the case of NOMA with perfect CSIT. In fact, the QoS requirements and average user channel gain become more heterogeneous for an increasing number of users. Thus, the conventional OMA scheme fails to accommodate the diverse needs, and our proposed scheme will obtain more performance gain.

Chapter 7

Conclusion

In this report, we consider the resource allocation of NOMA systems with statistical CSIT and efficient power based on the difference of QoS requirements. We propose a suboptimal solution with low computational complexity to solve the problem of user scheduling and power allocation. We obtain the power allocation solution and the SIC decoding order which depends on the level of QoS requirements. In addition, the power reduction obtained by NOMA increases with the difference in QoS levels between multiplexed users, which under the sufficient conditions. We propose a computational efficient algorithm for the user scheduling via agglomerative hierarchical clustering. The simulation results show that the scheme achieves almost the optimal performance, which is effective in reducing power consumption by exploiting different QoS requirements.

References

[1] Z. Wei, J. Yuan, D. W. K. Ng, M. Elkashlan, and Z. Ding, “A Survey of Downlink Non-orthogonal Multiple Access for 5G Wireless Communication Networks,” accepted by ZTE Communications, Sep. 2016.

[2] L. Dai, B. Wang, Y. Yuan, S. Han, C. I. I, Z. Wang, "Non-orthogonal multiple access for 5g: solutions challenges opportunities and future research trends," IEEE Communications Magazine, vol. 53, no. 9, pp. 74-81, Sep. 2015.

[3] J. Choi, "Non-orthogonal multiple access in downlink coordinated two-point systems," IEEE Communications Letters, vol. 18, pp. 313-316, Feb. 2014.

[4] Q. Wu, G. Y. Li, W. Chen, D. W. K. Ng, R. Schober, “An Overview of Sustainable Green 5G Networks,” IEEE Communications Society, vol. 24, no. 4, pp. 72-80, Aug. 2017.

[5] V. W.S. Wong, R. Schober, D. W. K. Ng, and L.-C. Wang, "Key Technologies for 5G Wireless Systems," The Institution of Engineering and Technology, Cambridge University Press, Apr. 2017, ISBN-10: 1107172411.

[6] J. Chen, X. Chen, W. Gerstacker, and D. W. K. Ng, "Resource Allocation for a Massive MIMO Relay Aided Secure Communication," IEEE Trans. on Inf. Forensics & Security, vol. 11, pp. 1700-1711, Aug. 2016.

[7] L. Zhao, D. W. K. Ng, and J. Yuan, "Multi-user Precoding and Channel Estimation for Hybrid Millimeter Wave Systems," IEEE Journal of Selected Areas in Communications (IEEE JSAC) Special Issue on Millimeter Wave Communications for Future Mobile Networks, vol. 35, no. 7, pp. 1576-1590, Jul. 2017.

[8] J. Liu, P. W. C. Chan, D. W. K. Ng, E. S. Lo, and S. Shimamoto, "Hybrid Visible Light Communications in Intelligent Transportation Systems with Position Based Services," in Proceedings of the IEEE Global Communications Conference (Globecom) 2012 Workshop on Optical Wireless Communications (OWC), Anaheim, USA, Dec. 2012.

[9] D. W. K. Ng, E. S. Lo, and R. Schober, "Wireless Information and Power Transfer: Energy Efficiency Optimization in OFDMA Systems," IEEE Trans. Wireless Commun., vol. 12, pp. 6352 - 6370, Dec. 2013.

[10] D. W. K. Ng, E. S. Lo, and R. Schober, "Energy-Efficient Resource Allocation in OFDMA Systems with Hybrid Energy Harvesting Base Station," IEEE Trans. Wireless Commun., vol. 12, pp. 3412 - 3427, Jul. 2013.

[11] P. Cao, E. Jorswieck, S. Shi, "Pareto boundary of the rate region for single-stream MIMO interference channels: linear transceiver design," IEEE Trans. on Signal Processing, vol. 60, no. 20, pp. 4907-4922, Oct. 2013.

[12] D. W. K. Ng, E. S. Lo, and R. Schober, "Energy-Efficient Resource Allocation in Multi-Cell OFDMA Systems with Limited Backhaul Capacity," IEEE Trans. Wireless Commun., vol. 11. pp. 3618 - 3631, Oct. 2012.

[13] D. W. K. Ng, E. S. Lo, and R. Schober, "Energy-Efficient Resource Allocation in OFDMA Systems with Large Numbers of Base Station Antennas," IEEE Trans. Wireless Commun., vol. 11. pp. 3292 - 3304, Sep. 2012.

[14] D. W. K. Ng, E. S. Lo, and R. Schober, "Energy-Efficient Resource Allocation for Secure OFDMA Systems," IEEE Trans. on Veh. Technol, vol. 61, pp. 2572 - 2585, Jul. 2012.

[15] Y. Sun, D. W. K. Ng, Z. Ding, and R. Schober, "Optimal Joint Power and Subcarrier Allocation for Full-Duplex Multicarrier Non-Orthogonal Multiple Access Systems," IEEE Trans. Commun., vol. 65, no. 3, pp. 1077-1091, Mar. 2017.

[16] X. Chen, Z. Zhang, C. Zhong, and D. W. K. Ng, "NOMA in Downlink SDMA with Limited Feedback: Performance Analysis and Optimization," IEEE JSAC SI in Non-Orthogonal Multiple Access for 5G Systems, vol. 35, no. 10, pp. 2281-2294, Oct. 2017.

[17] B. Wang, L. Dai, Z. Wang, N. Ge, S. Zhou, "Spectrum and energy efficient beamspace MIMO-NOMA for millimeter-wave communications using lens antenna array," IEEE J. Sel. Areas Commun., vol. 35, no. 10, pp. 2370-2382, Oct. 2017.

[18] J. Schaepperle, A. Rüegg, "Enhancement of Throughput and Fairness in 4G Wireless Access Systems by Non-Orthogonal Signaling," Bell Labs Technical Journal, vol. 13, No. 4, 2009, pp. 59-77.

[19] T. Takeda and K. Higuchi, "Enhanced User Fairness Using Nonorthogonal Access with SIC in Cellular Uplink," IEEE 74th Vehicular Technology Conference, Sept. 2011.

[20] N. Otao, Y. Kishiyama, K. Higuchi, "Performance of non-orthogonal access with sic in cellular downlink using proportional fair-based resource allocation," Wireless Communication Systems (ISWCS) 2012 International Symposium on, pp. 476-480, 2012.

[21] B. Kimy et al., "Non-orthogonal multiple access in a downlink multiuser beamforming system," Proc. IEEE Military Commun. Conf. (MILCOM), pp. 1278-1283, Nov. 2013.

[22] H. Jin, K. Peng, and J. Song, "Bit division multiplexing for broadcast-ing," IEEE Trans. Broadcast., vol. 59, no. 3, pp. 539-547, Sept. 2013.

[23] S. Zhao, X. Ma, and B. Bai, "Decoding algorithms of LDPC coded superposition modulation," IEEE Communications Letters, vol. 18, no. 3, pp. 487-490, Mar. 2014.

[24] X. Dai, S. ShaoHui, W. Yingming and R. Zou, "Successive interference cancellation amiable space-time codes with good multiplexing-diversity tradeoff," 2009 15th Asia-Pacific Conference on Communications, Shanghai, 2009, pp. 237-240, Jan, 2010.

[25] D. Truhachev, "Universal Multiple Access via Spatially Coupling Data Transmission," in IEEE Int. Symp. on Inf. Theory, Istanbul, Jul. 2013.

[26] C. Schlegel and D. Truhachev, "Multiple Access Demodulation in the Lifted Signal Graph with Spatial Coupling," IEEE Transactions on Information Theory, vol. 59, no. 4, pp. 2459-2470, April. 2013.

[27] J. van de Beek, B. M. Popovic, "Multiple access with low-density signatures," Global Telecommunications Conference 2009. GLOBE-COM 2009. IEEE, Nov. 2009.

[28] R. Razavi, R. Hoshyar, M. A. Imran, Y. Wang, "Information theoretic analysis of LDS scheme," IEEE Commun. Lett., vol. 15, no. 8, pp. 798-800, Aug. 2011.

[29] P. Li, L. Liu, K. Wu and W. Leung, "Interleave division multiple-access," IEEE Transactions on Wireless Communications, vol. 5, no. 4, pp. 938-947, 2006.

[30] F. Begum, "Implementation of Interleave Division Multiple Access (IDMA) with Multiple Users in Wireless Communication System," International Journal of Computer Applications, vol. 134, no. 15, pp. 6-10, 2016.

[31] Q. Wu, M. Tao, and W. Chen, "Joint Tx/Rx Energy-Efficient Scheduling in Multi-Radio Wireless Networks: A Divide-and-Conquer Approach," IEEE Transactions on Wireless Communications, vol. 15, no. 4, pp. 2727 - 2740, Apr. 2016.

[32] A. Liveris, C. N. Georghiades, "Exploiting faster-than-Nyquist signaling," IEEE Trans. Commun., vol. 47, pp. 1502-1511, Sep. 2003.

[33] M. McGuire and M. Sima, "Discrete Time Faster-Than-Nyquist Signalling," 2010 IEEE Global Telecommunications Conference GLOBECOM 2010, Miami, FL, 2010, pp. 1-5, Jan. 2011.

[34] X. Zhang, M. Li, H. Hu, H. Wang, B. Zhou, X. You, "DFT spread generalized multi-carrier scheme for broadband mobile communications," 17th IEEE International Symposium on Personal Indoor and Mobile Radio Communications, pp. 1-5, Sept. 2006.

[35] C. Y. Liu et al., "A MMSE Joint Feedback Feed-forward Equalizer for FBMC-OQAM Baseband Receiver in the 60 GHz Band," in IEEE Journal on Emerging and Selected Topics in Circuits and Systems, vol. PP, no. 99, pp. 1-1, Sept. 2017.

[36] Deliverable 3.1, 5G Waveform Candidate Selection, 5GNOW, Nov. 2013.

[37] D. Schafhuber, G. Matz, F. Hlawatsch, "Pulse-shaping OFDM/BFDM systems for time-varying channels: ISI/ICI analysis optimal pulse design and efficient implementation," Proc. IEEE PIMRC-02, pp. 1012-1016, Sept. 2002.

[38] Q. Wu, G. Y. Li, W. Chen, and D. W. K. Ng, "Energy-efficient Small Cell with

Spectrum Power trading," IEEE Journal on Selected Areas in Communications, vol. 34, no. 12, pp. 3394 - 3408, Dec. 2016.

[39] D. W. K. Ng, E. S. Lo, and R. Schober, "Dynamic Resource Allocation in MIMO-OFDMA System with Full-Duplex and Hybrid Relaying," IEEE Trans. Commun, vol. 60, pp. 1291 - 1304, May 2012.

[40] D. W. K. Ng, E. S. Lo, and R. Schober, "Secure Resource Allocation and Scheduling for OFDMA Decode-and-Forward Relay Networks," IEEE Trans. Wireless Commun., vol. 10, pp. 3528 - 3540, Oct. 2011.

[41] D. W. K. Ng and R. Schober, "Resource Allocation and Scheduling in Multi-Cell OFDMA Systems with Decode-and-Forward Relaying Networks," IEEE Trans. Wireless Commun., vol. 10, pp. 2246 - 2258, Jul. 2011.

[42] D. W. K. Ng and R. Schober, "Cross-Layer Scheduling for OFDMA Amplify-and-Forward Relay Networks," IEEE Trans. on Veh. Technol., vol. 59, pp. 1443 - 1458, Mar. 2010.

[43] V. Lau, D. W. K. Ng, and D. S. W. Hui, "Asymptotic Tradeoff between Cross-Layer Goodput Gain and Outage Diversity in OFDMA Systems with Slow Fading and Delayed CSIT," IEEE Trans. Wireless Commun., vol. 7, pp. 2732 - 2739, Jul. 2008.

[44] Q. Wu, W. Chen, D. W. K. Ng, and R. Schober, "Spectral and Energy Efficient Wireless Powered IoT Networks: NOMA or TDMA? ," IEEE Transactions on Vehicular Technology, submitted, 2017.

[45] Z. Wei, D. W. K. Ng, J. Yuan, and H-M. Wang, "Optimal Resource Allocation for Power-Efficient MC-NOMA with Imperfect Channel State Information," IEEE Trans. Commun., vol. 65, no. 9, pp. 3944-3961, Sept. 2017.

[46] A. Benjebbour, A. Li, Y. Saito, Y. Kishiyama, A. Harada, and T. Nakamura, "System-level performance of downlink NOMA for future LTE enhancements," in Proc. IEEE Global Commun. Conf., pp. 66–70, Dec. 2013.

[47] Y. Liu, Z. Ding, M. Elkashlan, and J. Yuan, "Non-orthogonal multiple access in large-scale underlay cognitive radio networks," IEEE Trans. Veh. Technol., vol. PP, no.

99, pp. 1–1, Feb. 2016.

[48] Z. Ding, Z. Yang, P. Fan, and H. Poor, "On the performance of nonorthogonal multiple access in 5G systems with randomly deployed users", IEEE Signal Process. Lett., vol. 21, no. 12, pp. 1501–1505, Dec. 2014.

[49] Y. Saito, A. Benjebbour, Y. Kishiyama, T. Nakamura, "System-level performance evaluation of downlink non-orthogonal multiple access (NOMA)", Proc. IEEE Annu. Symp. Pers. Indoor Mobile Radio Commun. (PIMRC), pp. 611-615, Sep. 2013.

[50] Y. Sun, D. W. K. Ng, and R. Schober, "Resource Allocation for MCNOMA Systems with Cognitive Relaying," accepted for presentation, IEEE Globecom 2017 workshop, Singapore.

[51] A. Benjebbour, Y. Saito, Y. Kishiyama, A. Li, A. Harada, T. Nakamura, "Concept and practical considerations of non-orthogonal multiple access (NOMA) for future radio access", 2013 International Symposium on Intelligent Signal Processing and Communication Systems, pp. 770-774, Nov. 2013.

[52] Y. Sun, D. W. K. Ng, and R. Schober, "Optimal Resource Allocation for Multicarrier MISO-NOMA Systems," in Proceedings of the IEEE ICC 2017.

[53] Z. Wei, D. W. K. Ng, and J. Yuan, "Joint Power and Subcarrier Allocation for Cooperative NOMA Systems," invited paper, in Proceedings of the IEEE VTC 2017.

[54] H. Zhu and J. Wang, “Chunk-based resource allocation in OFDMA systems - part I: chunk allocation,” IEEE Trans. Commun., vol. 57, no. 9, pp. 2734–2744, Sep. 2009.

[55] Z. Wei, D. W. K. Ng, and J. Yuan, "Power-Efficient Resource Allocation for MC-NOMA with Statistical Channel State Information," in Proceedings of the IEEE Globecom. 2016, Washington, DC, USA, Dec. 2016.

[56] X. Wang, J. Wang, L. He, Z. Tang and J. Song, "On the Achievable Spectral Efficiency of Spatial Modulation Aided Downlink Non-Orthogonal Multiple Access", IEEE Communications Letters, vol. 21, no. 9, pp. 1937-1940, Sept. 2017.

[57] M. S. Ali, H. Tabassum, E. Hossain, "Dynamic user clustering and power

allocation for uplink and downlink non-orthogonal multiple access (NOMA) systems", IEEE Access, vol. 4, pp. 6325-6343, Aug. 2016.

[58] D. W. K. Ng, E. S. Lo and R. Schober, "Resource Allocation for Secure OFDMA Networks with Imperfect CSIT," 2011 IEEE Global Telecommunications Conference - GLOBECOM 2011, Houston, TX, USA, Dec. 2011.

[59] P. Xu and K. Cumanan, "Optimal Power Allocation Scheme for Non-Orthogonal Multiple Access With $\alpha $ -Fairness," in IEEE Journal on Selected Areas in Communications, vol. 35, no. 10, pp. 2357-2369, Oct. 2017.

[60] J. Zhang, X. Xue, E. Björnson, B. Ai and S. Jin, "Spectral Efficiency of Multipair Massive MIMO Two-Way Relaying with Hardware Impairments," in *IEEE Wireless Communications Letters*, vol. PP, no. 99, pp. 1-1.

[61] R. Jiao, L. Dai, J. Zhang, R. MacKenzie and M. Hao, "On the Performance of NOMA-Based Cooperative Relaying Systems over Rician Fading Channels," in *IEEE Transactions on Vehicular Technology*, vol. PP, no. 99, pp. 1-1.

[62] M. You, H. Sun, J. Jiang and J. Zhang, "Unified Framework for the Effective Rate Analysis of Wireless Communication Systems Over MISO Fading Channels," in *IEEE Transactions on Communications*, vol. 65, no. 4, pp. 1775-1785, April 2017.

[63] X. Li, J. Li, L. Li, J. Jin, J. Zhang and D. Zhang, "Effective Rate of MISO Systems Over $\kappa $ - $\mu $ Shadowed Fading Channels," in *IEEE Access*, vol. 5, pp. 10605-10611, 2017.