

Non-Orthogonal Multiple Access for 5G Communication Systems



By

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Approval

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Abstract

Non-orthogonal multiple access (NOMA) is a spectrally efficient multiple access technique which is anticipated to play an important role in improving the capacity of fifth generation (5G) networks. This thesis investigates a new cooperative NOMA strategy that employs distributed space time block coding (STBC) and is known as STBC-NOMA. In conventional NOMA, the strong users detect the messages of weak users through successive interference cancellation (SIC). In cooperative NOMA, these copies are then forwarded by strong users to weak users at the expense of extra time slots. However, the proposed scheme exploits this feature of cooperation using STBCs to enable cooperation among the users. The STBC-NOMA renders less complexity and less error propagation as compared to the conventional cooperative NOMA because of lesser number of SICs performed at each user. We derive the outage probability of the STBC-NOMA scheme which involves finding the distribution of signal-to-interference ratio (SIR) at the receiving terminals. The numerical results show that STBC-NOMA outperforms conventional NOMA and conventional cooperative NOMA in terms of outage and average sum rate. Moreover, an optimal power allocation scheme is proposed for STBC-NOMA based on game theory. To further elevate the system performance in

terms of achievable throughput a hybrid STBC-NOMA architecture, which incorporates the idea of successive bandwidth division (SBD) is also discussed. Performance analysis shows that our proposed scheme reduces the computational overhead at the user end while improving the system throughput and energy efficiency. Finally, potential applications and future research directions in this area are provided.

Dedication

I dedicate this thesis to my father **Dr. Mahmood Ul Hassan**, mother **Aliya Qadir** and my sisters **Aimen & Amna** for their endless prayers, love and encouragement.

Certificate of Originality

I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any degree or diploma at NUST SEECS or at any other educational institute, except where due acknowledgement has been made in the thesis. Any contribution made to the research by others, with whom I have worked at NUST SEECS or elsewhere, is explicitly acknowledged in the thesis.

I also declare that the intellectual content of this thesis is the product of my own work, except for the assistance from others in the project's design and conception or in style, presentation and linguistics which has been acknowledged.

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Chapter 1

Introduction

With the rapid development in fifth generation (5G) networks and Internet of Things (IoT), it is anticipated to have 1000-fold increase in data traffic and massive connectivity of devices by 2020 [1–3]. To handle the densification in future networks due to such explosive data traffic, spectral efficiency becomes one of the key challenges in 5G. In order to cope with the future network requirements and to overcome various challenges, advanced techniques are under rigorous investigation [4–21]. So far, some potential 5G enabling technologies have been proposed, such as massive multiple-input multiple-output (MIMO), millimeter wave (mmWave) communication, small cell and heterogeneous networks, device-to-device (D2D) communication, full duplex communication and others. A technology which has recently received considerable attention is the non-orthogonal multiple access (NOMA) [22, 23].

Generally, the multiple access (MA) techniques can be divided into two categories, i.e., orthogonal multiple access (OMA) and non-orthogonal multiple access (NOMA) schemes. OMA techniques, such as, orthogonal fre-

quency division multiple access (OFDMA), frequency division multiple access (FDMA), code division multiple access (CDMA), and time division multiple access (TDMA), allow multiple users to share the spectrum simultaneously, however each user is allocated orthogonal portion of the resources in either frequency, code, or time domain, such that there is no inter user interference. However, these OMA schemes cannot cope with the massive connectivity requirements of the IoT based future 5G networks, since the number of the users that can be served are limited by the number of available orthogonal resources.

On the other hand, in NOMA, multiple users are served simultaneously while using the same spectral resources. NOMA is recognized to be spectrally efficient, because the user multiplexing is done in the power domain, while sharing the same spectral resources. However, this improved spectral efficiency of NOMA comes at the cost of increased intra cell interference and a trade-off between system performance and receiver complexity. NOMA employs successive interference cancellation (SIC) at the receiver, thus bringing an additional cost and complexity.

With all the attractive features, such as, higher spectral efficiency, low latency and higher performance gains as compared to OMA, NOMA has been recognized as the potential 5G enabling technology. Different approaches have been proposed by researchers both in academia and industry to implement NOMA over the existing long term evolution (LTE) systems. For the Third Generation Partnership Project LTE-Advanced (3GPP-LTE-A) systems, a downlink NOMA scheme i.e., multiuser superposition transmission (MUST) has been proposed [24]. Similarly, NTT DoCoMo has proposed

NOMA to be a potential candidate for 5G, as part of the *Mobile and wireless communications Enablers for the 2020 Information Society (METIS)* project [25].

1.1 Basics of Downlink NOMA

To illustrate the NOMA concept, we consider the downlink communication scenario with two users as shown in Fig. 1.1. Without loss in generality, we assume User 1 to be the strong (i.e., having better channel conditions) user while User 2 is considered as the weak (i.e., having worse channel conditions) user. The base station (BS) can serve the two users at the same frequency, code, or time, but with different transmit power levels. In NOMA, more transmission power is given to the weak users while less power to the strong users, which is in contrast with the conventional power allocation schemes based on water filling strategies, where more transmission power is allocated to the strong users and vice versa. Therefore, the power allocation in NOMA, in addition to achieving greater performance than OMA, also ensures user fairness.

The BS transmits a superimposed signal, which is the mixture of the messages of the two users. User 2 being the weak user is allocated high transmission power, therefore, it can decode its message directly by treating the signal of User 1 as noise. However, User 1 being the strong user is allocated low transmission power, hence it cannot decode its message directly. User 1 first applies SIC to decode the message of User 2, it then subtracts it from the superimposed signal in order to get its own message with out any

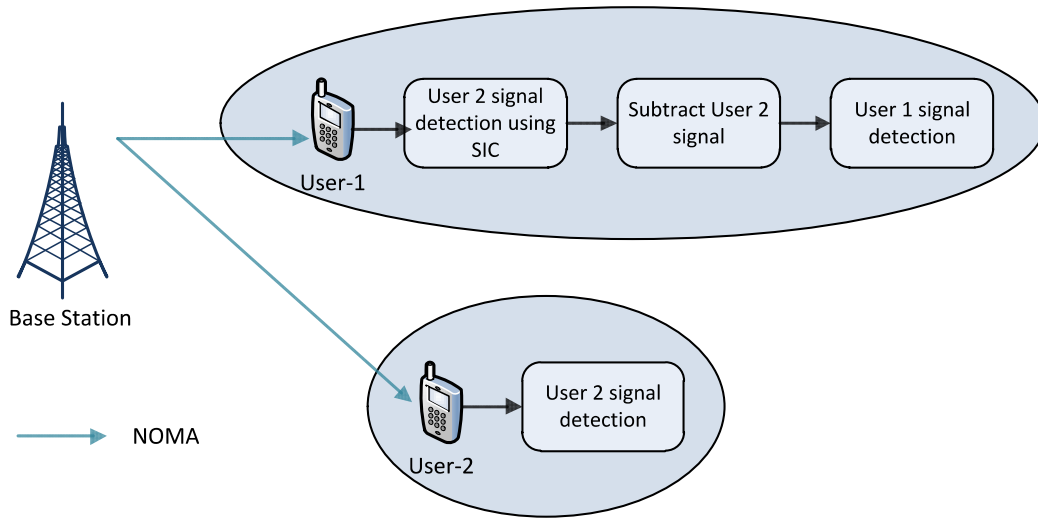


Figure 1.1: Illustration of downlink NOMA scenario for 2 users case.

interference ¹.

Unlike the conventional OMA schemes, where the bandwidth resources are split between the users, both users in NOMA use all the available bandwidth and, therefore, result in overall higher throughput as compared to OMA due to high signal-to-interference plus noise ratios (SINR) achieved by the individual users. In NOMA, there is a balanced trade-off between user fairness and system throughput. Consider again the scenario depicted in Fig. 1.1, if the only objective is to increase the system throughput, then all the power will be allocated to User 1 and it will result in the maximum possible throughput that the system could attain. However, doing so, User 2 will get no power at all and will remain in outage, which is not a fair power strategy. However, in case of NOMA, a completely opposite approach is followed, where the User 2 gets more transmission power than User 1 and thus achieves a balanced trade-off between user fairness and relatively high overall system

¹Note that the system assumes perfect SIC at the receiver.

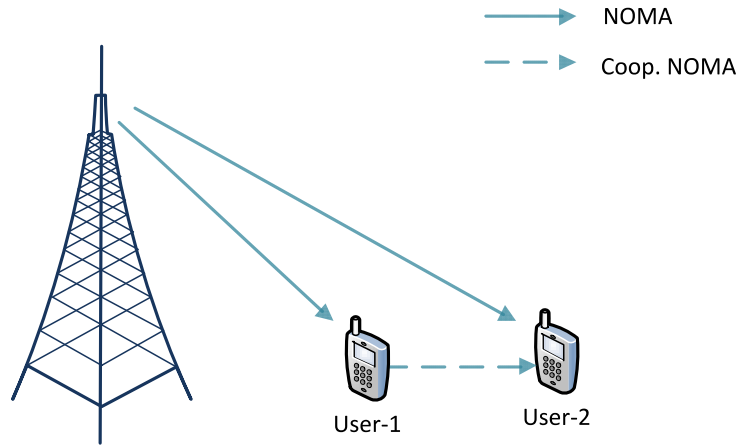


Figure 1.2: Illustration of Cooperative NOMA for 2 users case.

throughput as compared to OMA.

1.2 Cooperative NOMA

In cooperative NOMA (C-NOMA) scheme, the user with strong channel conditions cooperate with users having weaker channel conditions in a device-to-device manner [26]. C-NOMA takes advantage of the fact that the strong users have already decoded the messages of the weak users as a result of employing SIC. Hence the strong users can act as relays to help the weak users by sending them a copy of their (weak users') messages at the expense of extra time slots, resulting in increased diversity gain and thus low outage events.

C-NOMA consists of two phases; a direct transmission phase and a cooperative phase. Consider a downlink NOMA scenario with K users, such that $k \in \mathbb{K}$, where $\mathbb{K} = \{1, 2, \dots, K\}$ is the set of all users. Without loss in generality we assume that the first user is the strongest while K -th user

is the weakest. In the direct transmission phase, i.e., the first time slot, the BS broadcasts a NOMA-based superimposed signal with transmit power, P , where all the users decode their signals either applying SIC (in case of strong users) or by directly decoding their signal while treating other signals as noise (in case of weak users). The cooperation phase consists of $K - 1$ time slots. The first strongest user applies SIC to decode its own signal, and in order to do so, it decodes the messages of the $K - 1$ users and subtracts them from the superimposed signal one by one. Since the first user has already decoded the signals of $K - 1$ users, therefore, in the first time slot of the cooperative phase, User 1 broadcasts a new NOMA-based superimposed signal consisting of $K - 1$ messages to the remaining $K - 1$ users which repeat the same process, i.e., extract their messages by SIC or by direct decoding. After K time slots, every k -th user receives k different NOMA signals, applies SIC on each superimposed signal and combines multiple decoded copies of the message using maximum ratio combining (MRC). A two users case is depicted in Fig. 1.2. The C-NOMA scheme improves the outage performance of the weak users and also increases the overall system throughput.

1.3 Motivation

Apart from all the performance gains of conventional C-NOMA, the main disadvantage of this scheme is the higher number of SICs performed overall in the system. Since the SIC in downlink is performed at the user equipment (UE), the entire process is resource constrained due to the limited computational power and battery. Therefore, increasing the number of SICs

performed at a UE increases the computational overhead at UEs, thereby, resulting in increased complexity. Keeping in view, we present a new system model for C-NOMA, which takes advantage of space time block coding and we call it STBC-NOMA. The proposed scheme greatly reduces the number of SICs performed overall in the system, thus reducing the system complexity.

1.4 Thesis Contribution

The main contributions of this thesis are the following

- We propose to use distributed STBC in cooperative NOMA and evaluate its performance in terms of outage probability and sum rates.
- To find the outage probability, we derive the expression of the probability distribution function (PDF) of SIR, where SIR turns out to be the sum of the ratio of exponential and hypoexponential random variables (RVs) with a gamma RV.
- We propose an optimal power allocation scheme for STBC-NOMA based on game theory.
- To further elevate the system performance in terms of achievable throughput a hybrid STBC-NOMA architecture, which incorporates the idea of successive bandwidth division (SBD) is also discussed.

1.5 Thesis Organization

The rest of the thesis is organized as follows: Chapter 2 presents the background and existing literature on NOMA and cooperative NOMA schemes. In Chapter 3, we formulate a framework for cooperative NOMA which uses distributed STBC. Closed form expressions for the SIR outage and rate outage probability are derived in Chapter 4. Chapter 5 presents a fair power allocation scheme for STBC-NOMA based on game-theoretic approach. Furthermore in Chapter 6, we propose a hybrid framework which incorporates SBD into STBC-NOMA. Finally, Chapter 7 provides the conclusion and future works.

Chapter 2

Literature Review

This chapter presents the background and literature review on NOMA and C-NOMA. With the evolution of fifth generation (5G) networks and increasing demand of high data rates and higher connectivity, new solutions are being investigated in both academia and industry. Recently the technology that has received considerable attention is non orthogonal multiple access (NOMA), which is considered to be one of the key 5G enabling technologies [22, 23].

The authors in [27] studied NOMA with random user deployment in the downlink scenario. Their analysis demonstrated that NOMA shows better performance as compared to OMA if the individual user data rates and power allocation coefficients are carefully selected. But the analysis also showed that there is lesser gain of NOMA at low signal-to-noise ratio (SNR) values, and the use of SIC adds more complexity to the system.

In [28], the authors studied the effects of user pairing on the overall performance of NOMA and showed that the user pairing has a great effect on the overall gain. NOMA can achieve greater performance gains by selecting

the users with certain channel conditions for pairing, i.e., the strong user should be paired with the weak user to fully achieve the NOMA gain.

The idea of dividing the bandwidth of NOMA into orthogonal sub-bands known as the successive bandwidth division (SBD) has been proposed in [29] and [30]. In SBD the users are divided into smaller sub-groups and the bandwidth is divided into orthogonal sub-bands. This is a hybrid scheme which combines OMA and NOMA, where each sub-group gets a separate orthogonal sub-band, thereby, reducing the interference and increasing the overall system performance.

In [31], a simultaneous wireless information and power transfer (SWIPT) NOMA protocol is introduced, where the strong users of NOMA act as energy harvesting relays in order to help the weak users of NOMA. In [26], the authors proposed a cooperative NOMA scheme, in which the strong users cooperate with weak users by sending a new NOMA-based superimposed signal composed of the decoded signals of other users. The analysis showed that the cooperative NOMA has a better outage performance than the conventional NOMA. However the drawback of this scheme is the increased complexity of the system because of higher number of SICs performed on multiple received NOMA signals.

In [32] the power allocation problem in NOMA is formulated which maximizes the sum rate of the system and the optimal transmission power of each user is obtained based on the instantaneous channel state information (CSI). Some other work on power allocation has been discussed in [33–37]. In [33] a different power allocation schemes for NOMA have been presented considering fixed power allocation (FPA) and full search power allocation (FSPA).

The FSPA shows better performance but at the cost of higher complexity while the FPA has worse performance in terms of sum rates.

A game theory based power allocation scheme for MTC NOMA systems has been discussed in [34]. The users play a non-cooperative game in order to solve the power control problem of the NOMA systems. In [37] a refereed power control game is proposed where the players play a non-cooperative game in order to maximize their utility function. In the proposed game the BS acts as a referee to ensure user fairness among the players. In non-cooperative game, a player can select a power level above the maximum allowed threshold, in this scenario the role of BS is to punish any user whose received power is higher than the maximum allowed power threshold.

Chapter 3

Space Time Block Coding Based Cooperative NOMA System

In this thesis, a distributed STBC-based downlink cooperative NOMA scheme is introduced. In the proposed STBC-NOMA scheme, the strong users cooperate with the weak users, however, unlike conventional cooperation, the strong users do not send a new superimposed signal to the weak users. Instead the strong users employ distributed Alamouti STBC scheme to cooperate with the weak users. The advantages of using STBC-NOMA against the conventional cooperative NOMA scheme are lesser number of SICs performed overall in the system, implying less complexity and error.

3.1 System Model

We consider the downlink of a communication system with a single base station (BS) and M users, where each user is equipped with a single antenna. Let the set of all users be denoted by $\mathcal{M} = \{1, 2, \dots, M\}$ where without the loss in generality, we assume that the first user is the strongest whereas M -th user is the weakest user. The conventional cooperative NOMA has two phases; in the first phase, i.e., first time slot, the BS sends a superimposed signal to all the M users. Each user decodes its signal either by treating other users' signal as noise (in case of a weak user) or by using SIC (in case of a strong user). The second phase is the cooperation phase and consists of $M - 1$ time slots. In each time slot, the n -th user, where $n \in \mathcal{M}$ and $n \neq M$, broadcasts a new superimposed signal which is composed of the $M - n$ decoded messages. For instance, for $n = 1$, the first user transmits a superimposed signal to the rest of $M - 1$ users and so on. After M time slots, each n -th user receives n superimposed signals, where SIC is applied on each superimposed signal and different observations of the same message are combined using maximum ratio combining (MRC). A two user scenario is depicted in Fig. 3.1a.

In the proposed STBC-NOMA scheme, the strong users instead of sending superimposed signal, perform distributed Alamouti coding to cooperate with weak users. Just like the conventional cooperative NOMA, there are two phases in the STBC-based cooperative NOMA, as described below.

The first phase is the conventional NOMA phase, where the BS sends a

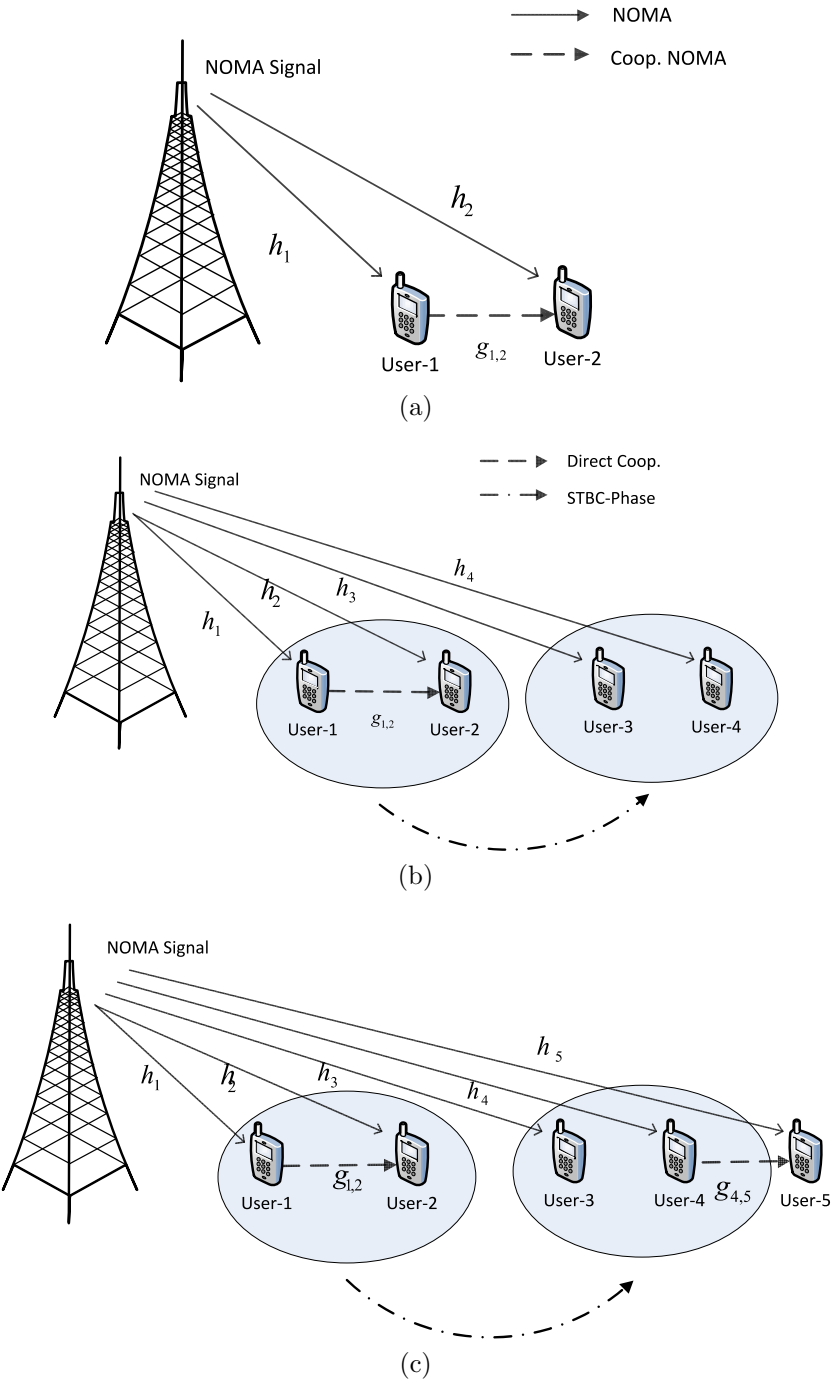


Figure 3.1: Illustration of the system model of STBC-NOMA: (a) $M=2$; (b) $M=4$; (c) $M=5$.

superimposed signal, X_S to all the M users, such that

$$X_S = \sum_{i=0}^M \sqrt{u_i P} x_i, \quad (3.1)$$

where u_i is the power allocation coefficient of the i -th user while x_i is the message for the i -th user in (3.1), P is the total transmission power of BS and $\sqrt{u_i P} \triangleq \sqrt{P_i}$ represents the portion of the power given to the i -th user from the total transmission power P . The signal received by the k -th user is given by

$$y_k = h_k \sum_{i=0}^M \sqrt{P_i} x_i + n_k, \quad (3.2)$$

where h_k represents the Rayleigh fading channel coefficient from BS to the k -th user and n_k represents the Gaussian noise. As mentioned previously, the channel coefficients of M users are assumed in descending order as, $|h_1|^2 \geq |h_2|^2 \cdots \geq |h_M|^2$, thereby assuming user 1 as the strongest while M -th user as the weakest. The power coefficients are allocated based on the principle of NOMA, i.e., the user with the lowest channel gain gets the highest power allocation coefficient, such that, $u_1 \leq u_2 \cdots \leq u_M$, where $\sum_{i=0}^M u_i = 1$.

The k -th user, such that $k \neq M$, detects j -th user's message signal, where $j < k$, and then performs SIC and subtracts it from the superimposed signal in (3.1). The SINR at the k -th user after the conventional NOMA phase is given by

$$SINR_k = \frac{|h_k|^2 P_k}{\sum_{i=1}^I |h_k|^2 P_i + \sigma^2}, \quad (3.3)$$

where I is the number of interfering signals, such that, $1 \leq I \leq (k-1)$ and σ^2 is the noise variance assumed identical for all users.

The second phase of the proposed architecture is further divided into two sub phases, i.e., *direct cooperation phase* and the *STBC cooperation phase*. Note that there are $M - 1$ time slots in the second phase, which are used by the strong users to cooperate with the weak users using a combination of direct cooperation and STBC cooperation. In the first time slot of the cooperation phase, user 1 cooperates directly with user 2 by sending a copy of user's 2 signal as shown in Fig. 3.1b. Notice that user 2 has now two copies of its intended signal; one from first NOMA phase and second from this cooperative phase, which are combined using MRC. In the case where M is even, users 1 and 2 cooperate with users 3 and 4 using a 2×2 distributed Alamouti scheme. This happens in the second and third time slots of the cooperation phase. In the next two time slots, users 3 and 4 cooperate with the next two users again using STBC and this process continues till the data is received by $(M - 1)$ -th and M -th user. In case where M is odd, the process is similar until the $(M - 1)$ -th time slot in which $(M - 1)$ -th user cooperates with the M -th user directly, as shown in Fig. 3.1c. Note that for a fair comparison, the protocol is devised so that the time slots for conventional cooperative NOMA and STBC-NOMA remain equal.

The total transmission power, P_t , of both the phases is given by $P_t = P + P_c$, where P is the power transmitted in the conventional NOMA phase by the BS and P_c is the total power transmitted in the cooperation phase. The power transmitted in the cooperation phase is the sum of the power transmitted in the direct cooperation phase represented by $P_c^{(1)}$ and the STBC cooperation phase represented by $P_c^{(2)}$, such that $\sum_{i=1}^2 P_c^{(i)} = P_c$.

In case of conventional cooperative NOMA, the total number of SICs

Table 3.1: Percentage Reduction in the Total Number of SICs for STBC-NOMA Compared to C-NOMA

Number of users, M	4	6	8	10
%age reduction in SIC	40%	57%	66.7%	72.7%

performed for M users is given by $\sum_{j=0}^{M-2} \sum_{i=1}^{M-1-j} (M - (i + j))$, while for STBC-NOMA it is given by $\sum_{i=1}^{M-1} (M - i)$. For instance, for $M = 4$, the total number of SICs performed in case of conventional cooperative NOMA is 10, while it is 6 for STBC-NOMA. The percentage reduction in the number of SICs performed overall in the system for STBC-NOMA as compared to conventional cooperative NOMA is given in Table I. It should however, be noticed that STBC-NOMA requires strict timing synchronization between user pairs to perform distributed STBC [38, 39].

We now focus our attention on the SNR and SINR of the users. For $k = 1$, the SNR of user 1, SNR_1 , is given as¹

$$SNR_1 = \frac{|h_1|^2 P_1}{\sigma^2}. \quad (3.4)$$

Whereas for $k = 2$,

$$SINR_2 = \frac{|h_2|^2 P_2}{|h_2|^2 P_1 + \sigma^2} + \frac{|g_{1,2}|^2 \hat{P}}{\sigma^2}, \quad (3.5)$$

where \hat{P} represents the portion of the power allocated to a single direct transmission from the total transmission power of direct cooperation phase, $P_c^{(1)}$. In (3.5), $|g_{1,2}|^2$ is the channel gain between user 1 and 2. For $2 < k \leq M$,

¹Note that the first user detects data for all $(M - 1)$ users using $(M - 1)$ SIC operations.

the SINR is given by

$$\begin{aligned} SINR_k = & \frac{|h_k|^2 P_k}{\sum_{i=1}^I |h_k|^2 P_i + \sigma^2} \\ & + \frac{(|g_{k-n-1,k}|^2 + |g_{k-n-2,k}|^2) \tilde{P}}{\sigma^2}, \end{aligned} \quad (3.6)$$

where \tilde{P} represents the portion of the power allocated to a single STBC transmission from the total transmission power of STBC cooperation phase, $P_c^{(2)}$, while $n = \{0, 1\}$ represents the first and second receiver in the STBC receiver pair. The second term in (3.6) represents the gain due to the Alamouti scheme. For the case when M is odd, the SINR for $k = M$ is given by

$$SINR_k = \frac{|h_k|^2 P_k}{\sum_{i=1}^I |h_k|^2 P_i + \sigma^2} + \frac{|g_{k-1,k}|^2 \hat{P}}{\sigma^2}. \quad (3.7)$$

3.2 Simulation Results

In this chapter, the performance of the proposed scheme is investigated via numerical simulations. For analysis, the downlink of a communication system is considered with a single BS and M users, where the channel coefficients between BS and users are Rayleigh flat faded. The maximum transmit power of a user in cooperation phase is taken to be $1W$. A user takes part in cooperation only if its rate is greater than the rate threshold, ζ . For a fair comparison, the total transmission power of the three schemes is kept equal, i.e., $P_t^{NOMA} = P_t^{C-NOMA} = P_t^{STBC-NOMA}$.

Fig. 3.2 compares the average sum rates of non-cooperative NOMA, cooperative NOMA and STBC-NOMA for $M = 8$ and $\zeta = 1.5$. The simulation

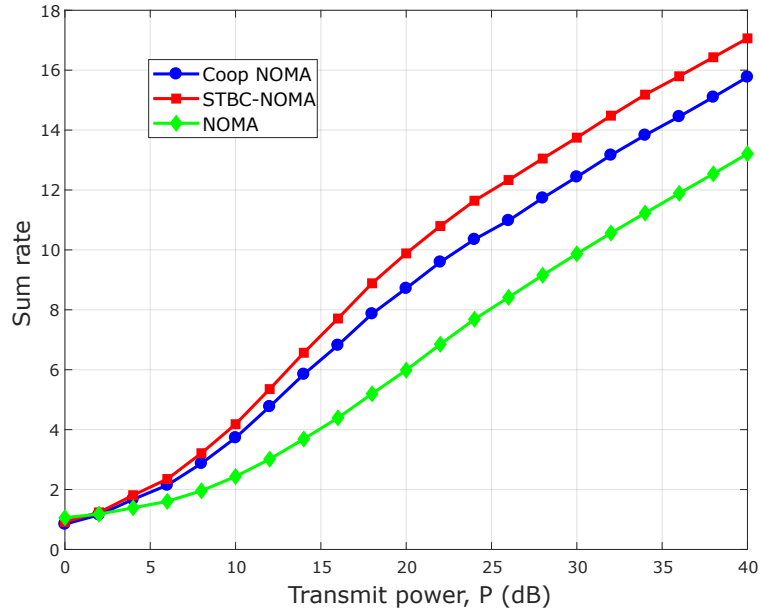


Figure 3.2: Comparison of sum rates of NOMA, cooperative NOMA and STBC-NOMA, for $M=8$ and $\zeta=1.5$.

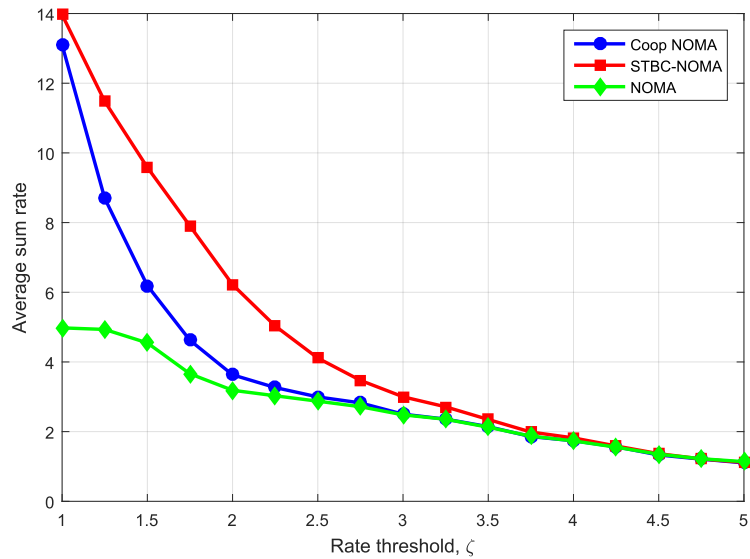


Figure 3.3: Comparison of sum rates as a function of rate threshold, ζ of NOMA, cooperative NOMA and STBC-NOMA, for $M = 8$.

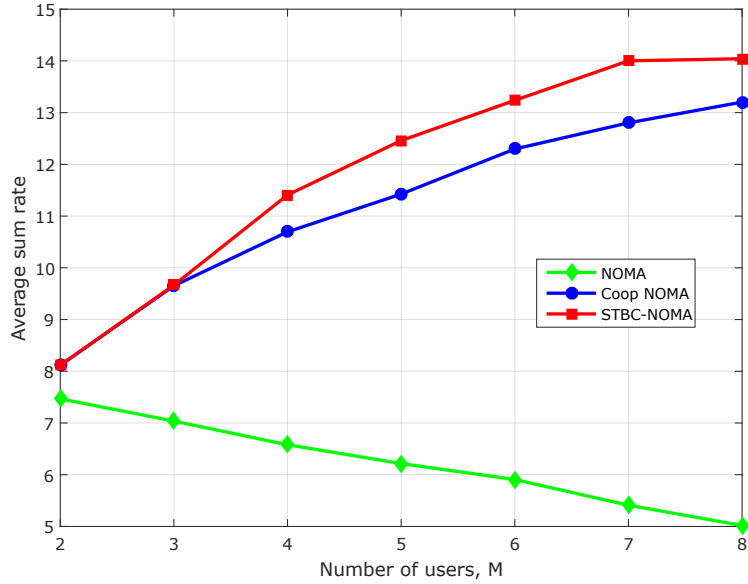


Figure 3.4: Sum rates comparison of NOMA, cooperative NOMA and STBC-NOMA, for $M=8$.

results show that STBC-NOMA has better performance in terms of average sum rate. It can be seen that for low BS transmit power, P , there is no visible performance gain of cooperative NOMA and STBC-NOMA as compared to NOMA. But as the total transmit power, P , increases, a large performance gain is observed.

The plot of sum rates against ζ for the three schemes, for $M = 8$ and $P = 20$ dB, is shown in Fig. 3.3. The simulation results show that STBC-NOMA outperforms the conventional cooperative NOMA. It can also be observed from the graphs that with increasing ζ , the performance of both the cooperative NOMA and STBC-NOMA becomes similar to that of NOMA. This is due to the fact that for every user to cooperate, its rate should be greater than the rate threshold, ζ . By increasing the value of ζ , the

number of users fulfilling this condition for cooperation becomes smaller and thus the performance of three schemes becomes the same. Fig. 3.4 shows the comparison of average sum rates with number of users, M for $\zeta = 1.5$ and $P = 20$ dB. It can be observed that STBC-NOMA exhibits better performance. The performance of NOMA degrades with increasing M , which is due to the fact that with large number of users, the allocated power to each user in NOMA becomes small and the gain becomes insignificant.

Chapter 4

Performance Analysis

In this chapter, the outage probability and outage rate analysis is provided. We assume an interference-limited scenario and hence noise can be ignored.

4.1 Outage Probability Analysis

The SIR in (3.6) can be written as

$$A = K + Z , \quad (4.1)$$

where $K = X/Y$ denotes the SIR at the k -th user after the conventional NOMA phase, while Z denotes the STBC gain after the cooperative phase. In the definition of K , X denotes the power of the desired signal, which is exponentially distributed, and its probability density function is given as

$$f_X(x) = \frac{1}{\lambda} \exp \left(-\frac{x}{\lambda} \right) , \quad (4.2)$$

where λ is the mean power of the desired signal X . On the other hand, Y is the sum of $(k - 1)$ exponentially distributed RVs with distinct parameters. Hence the distribution of Y is hypoexponential and is given by

$$f_Y(y) = \sum_{i=1}^I C_i \frac{1}{\Omega_i} \exp\left(-\frac{y}{\Omega_i}\right), \quad (4.3)$$

$$C_i = \prod_{j \neq i} \frac{1/\Omega_j}{1/\Omega_j - 1/\Omega_i}, \quad (4.4)$$

where I is the total number of interferers such that, $1 < I < (k - 1)$ and Ω_i is the mean power of the i -th interferer.

The distribution of Z in (4.1) is given by

$$f_Z(z) = \frac{z}{\eta^2} \exp\left(-\frac{z}{\eta}\right), \quad (4.5)$$

where η is the mean power of the signal received from a user transmitting in cooperation mode. The outage probability of a user in STBC-NOMA can be expressed as

$$\mathbb{P}\{SIR < \tau\} = 1 - \int_{\tau}^{\infty} f_A(a) da, \quad (4.6)$$

where τ is the SIR threshold. To find the outage probability, we require the PDF of A in (4.6), which is the sum of two RVs, namely K and Z . Since X and Y are mutually independent, the cumulative distribution function (CDF) of K is obtained as

$$\mathbb{P}\{K > k\} = \int_{x=0}^{\infty} \left(\int_{y=0}^{x/k} f_Y(y) dy \right) f_X(x) dx , \quad (4.7)$$

where,

$$\int_{y=0}^{x/k} f_Y(y) dy = \sum_{i=1}^I C_i \left[1 - \exp \left(- \frac{x}{k\Omega_i} \right) \right] . \quad (4.8)$$

The expression in (4.8) is the CDF of the hypoexponential RV [40]. Using (4.2) and (4.8), (4.7) can be written as

$$\begin{aligned} \mathbb{P}\{K > k\} = \int_{x=0}^{\infty} \sum_{i=1}^I C_i \left[1 - \exp \left(- \frac{x}{k\Omega_i} \right) \right] \\ \times \frac{1}{\lambda} \exp \left(- \frac{x}{\lambda} \right) dx , \end{aligned} \quad (4.9)$$

which after mathematical manipulations becomes

$$\mathbb{P}\{K > k\} = \sum_{i=1}^I C_i \left(\frac{\lambda}{\lambda + k\Omega_i} \right) . \quad (4.10)$$

The PDF of K is thus given as

$$f_K(k) = \sum_{i=1}^I C_i \Omega_i \left(\frac{\lambda}{(\lambda + k\Omega_i)^2} \right) . \quad (4.11)$$

Using the properties of random variables, the PDF of A in (4.1) can be obtained by convolving the PDF of K in (4.11) with the PDF of Z in (4.5) and is given as

$$\begin{aligned}
f_A(a) = & \sum_{i=1}^I \frac{C_i}{\Omega_i^2 \eta^3} \exp\left(-\frac{\lambda + \Omega_i a}{\eta \Omega_i}\right) \left[\exp\left(\frac{\lambda}{\eta \Omega_i}\right) \right. \\
& \times \eta \Omega_i (\lambda - e^{\frac{a}{\eta}} \lambda - a \Omega_i) + \lambda (\lambda + \Omega_i (a - \eta)) \\
& \left. \times \left(Ei\left[\frac{\lambda + a \Omega_i}{\eta \Omega_i}\right] - Ei\left[\frac{\lambda}{\eta \Omega_i}\right] \right) \right], \tag{4.12}
\end{aligned}$$

where Ei represents the exponential integral function, i.e., $Ei(x) = \int_{-\infty}^x \frac{e^t}{t} dt$. The outage probability of a user in the STBC cooperative NOMA scheme is thus given as

$$\begin{aligned}
P_{out}(\tau) = & \sum_{i=1}^I \frac{C_i}{\Omega_i^2 \eta^2} \exp\left(-\frac{\lambda + \Omega_i \tau}{\eta \Omega_i}\right) \left[\exp\left(\frac{\lambda}{\eta \Omega_i}\right) \right. \\
& \times \eta \Omega_i (e^{\frac{\tau}{\eta}} (\lambda + \eta \Omega_i) - \Omega_i (\tau + \eta) - \lambda) + \lambda (\lambda + \tau \Omega_i) \\
& \left. \times \left(Ei\left[\frac{\lambda}{\eta \Omega_i}\right] - Ei\left[\frac{\lambda + \tau \Omega_i}{\eta \Omega_i}\right] \right) \right]. \tag{4.13}
\end{aligned}$$

4.2 Outage Rate Analysis

The analytical expression of the outage probability has been derived in the above section, for users with SIR less than the threshold, τ . Here the expression for rate outage probability is provided, which is the probability that the rate of a certain user is less than some threshold, ζ . Given the SIR outage probability of a user is less than a threshold τ , $P_{out}(\tau)$, the outage rate probability is given by

$$P(\zeta) = P_{out} (2^{\zeta/B} - 1), \tag{4.14}$$

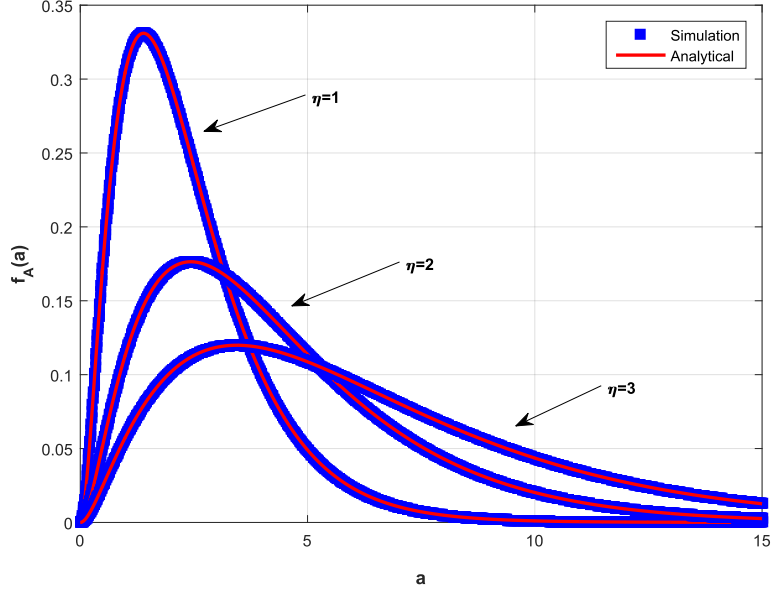


Figure 4.1: Comparison of the simulated and analytical PDFs for $I = 3$, $\lambda = 3$, $\Omega_i = [2, 4, 6]$ and varying η .

where ζ is the rate threshold and B is the bandwidth [41].

4.3 Simulation Results

Fig. 4.1 compares the PDF of SIR derived in Section 4.1 with the simulation results for $M = 4$ and different values of η . It can be seen that the simulation results closely match the analytical results. Figs. 4.2 and 4.3 show the SIR outage probability and rate outage probability as a function of τ and ζ , respectively, for $P = 20$ dB. It can be observed from both the graphs that the outage performance of the system degrades with increasing the number of users. Furthermore, the analytical results obtained from the derived equations agree with the simulation results.

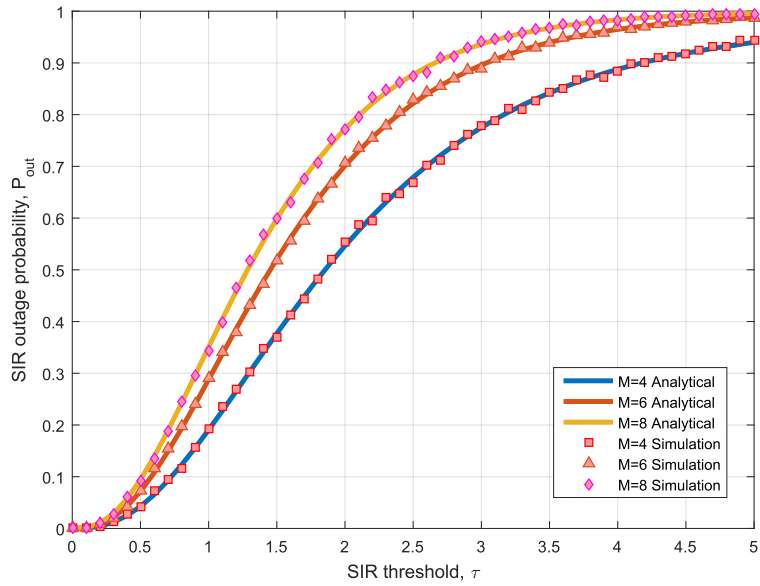


Figure 4.2: SIR outage performance of STBC-NOMA for varying number of users.

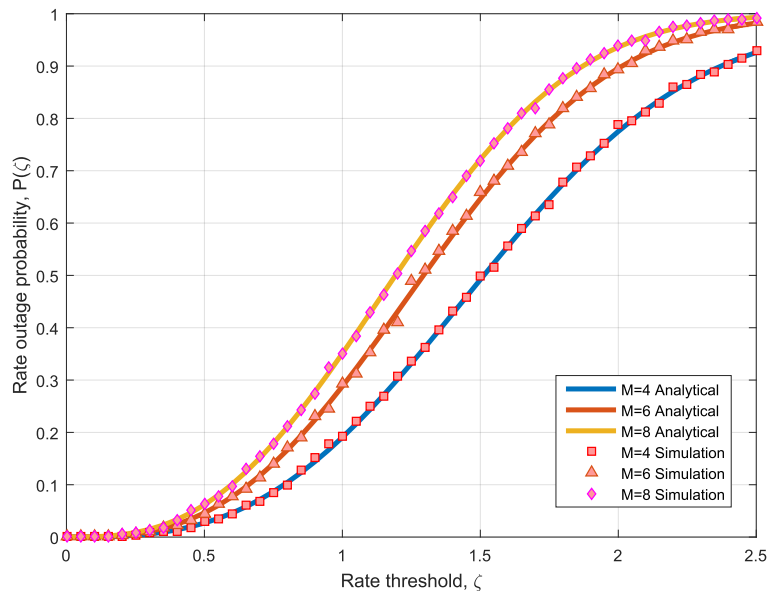


Figure 4.3: Rate outage performance of STBC-NOMA for varying number of users.

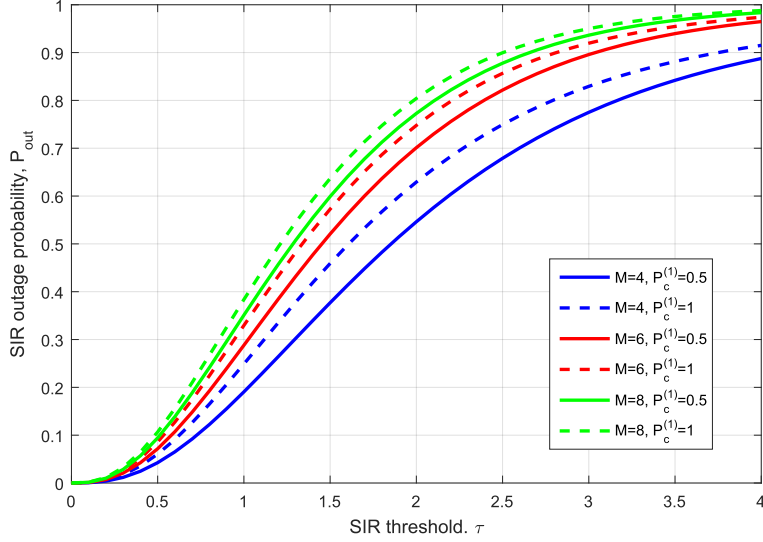


Figure 4.4: Effect of power allocation on the outage probability of STBC-NOMA.

Fig. 4.4 shows the effect of the power allocation for the cooperation phase on the outage probability of STBC-NOMA. We compare the outage probabilities of two power allocation schemes. Consider $M = 4$, since $P_t^{NOMA} = P_t^{C-NOMA} = P_t^{STBC-NOMA}$ and the maximum transmit power of the user in cooperation phase is taken to be $1W$, hence the total transmission power for the cooperation phase is, $P_c = 3W$. In the first scheme, we assume $P_c^{(1)} = 0.5W$ and the remaining power is equally divided for the four transmissions in the STBC cooperation phase. While in the second scheme, we take $P_c^{(1)} = 1W$ and the rest is used in the STBC cooperation phase. It can be seen from the graph that by reducing $P_c^{(2)}$, i.e., the power consumed in STBC phase, the outage performance of the STBC-NOMA degrades. Another observation is that for large M , the performance difference between the two schemes by using different power allocations becomes smaller. This is

because the overall power consumed in STBC becomes small which doesn't significantly increase the performance. This implies that optimal power allocation in STBC-NOMA significantly impacts the system performance.

Chapter 5

Power Allocation

In the previous chapter, fixed power allocation is considered such that less transmit power (i.e., fixed amount of power) is allocated to the strong users while more transmit power is allocated to the weak users. This fixed power allocation scheme does not take into account the instantaneous channel conditions of different users and can sometimes be very unfair. However, in this chapter we devise a more sophisticated power allocation scheme which allocates power to different users based on their instantaneous channel conditions. Generally speaking, our aim is to devise a fair power allocation scheme for STBC-NOMA which maximizes the overall sum rate of the system by maximizing individual data rates of the users under a fixed total power constraint.

5.1 Game-Theoretic Proposed Power Allocation Scheme

The power allocation problem for the proposed system model is two-fold; first the power allocation is performed for the NOMA phase, whereas the second step of the power allocation is performed for the cooperative phase. Mathematically, the first step of power allocation problem can be formulated as

$$\begin{aligned}
 & \underset{P_k}{\text{maximize}} R_k \\
 \text{subject to} & \sum_{k=1}^M P_k \leq P, \forall k \\
 & P_k \geq 0, \forall k \\
 & R_k \geq r_{min}, \forall k
 \end{aligned} \tag{5.1}$$

where the first and second constraints represent the total fixed power constraint for BS transmission, while the last constraint in (1) ensures user fairness among the users by ensuring that the users achieve data rates at least as high as r_{min} . In order to solve the problem in (5.1), we use a game theoretic approach [42, 43]. In our proposed scheme, two games are played in a hierarchical order. The first game deals with the power allocation of the NOMA phase in which the NOMA users are considered as the players of the game that play a non-cooperative game to maximize their utility function. The strategy of each player is the transmission power, P_k , such that, $P_k \in \mathcal{P}_k$, where \mathcal{P}_k is the strategy space of k -th player, which is the set of all the

possible values of the transmission power for the k -th user. The strategy space of the k -th user is in the interval $\mathcal{P}_k = [0, P_k^{max}]$, i.e., the power level of each player has a finite ceiling. The joint strategy space is the Cartesian product of all the individual strategy spaces, such that $\mathcal{P} = \mathcal{P}_1 \times \mathcal{P}_2 \times \dots \times \mathcal{P}_M$.

The utility function of k -th user is denoted by $U_k(P_k, \mathbf{P}_{-k})$, where \mathbf{P}_{-k} is the power vector of all the users except the k -th user. The utility function of the k -th user is given as

$$U_k(P_k, \mathbf{P}_{-k}) = B \log(1 + SINR_k) \quad \forall k = 1, 2, \dots, M. \quad (5.2)$$

The optimization problem in (5.1) can be expressed as

$$\max_{P_k \in \mathcal{P}_k} U_k(P_k, \mathbf{P}_{-k}) \quad \forall k = 1, 2, \dots, M. \quad (5.3)$$

In the considered non-cooperative game, each user chooses an appropriate power level to maximize its utility. This non-cooperative game achieves convergence using the solution to the pure strategy Nash equilibrium. A player achieves Nash equilibrium if for every user k

$$U_k(P_k^*, \mathbf{P}_{-k}^*) \geq U_k(P_k, \mathbf{P}_{-k}^*) \quad \forall P_k \in \mathcal{P}_k, \quad (5.4)$$

where P_k^* denotes the equilibrium solution for the k -th player. In case of NOMA, by playing a non-cooperative game, the strong users gain more than the weak users which leads to unfair power allocations. In order to ensure the user fairness in the system, we consider a refereed game as in [44], in which the BS acts as a referee which enforces user fairness in the game. In

order to fulfill the fairness criterion, every user must have a rate greater the minimum rate threshold such that

$$R_k \geq r_{min}, \quad (5.5)$$

where R_k is the data rate of the $k - th$ user while r_{min} is the minimum rate threshold. For rate to be greater than a threshold, the SINR, γ of a user should be greater than the minimum SINR threshold for that user such that

$$\gamma_k \geq \gamma_k^{th}. \quad (5.6)$$

The SINR of $k - th$ user can be expressed as

$$\gamma_k = \Psi_k P_k, \quad (5.7)$$

where P_k is the transmission power of the $k - th$ user and $\Psi_k = \frac{|h_k|^2}{\sum_{j=1}^I |h_k|^2 P_j + \sigma^2}$, is the gain of the $k - th$ user. The minimum transmission power threshold for the $k - th$ user to achieve the minimum SINR threshold can be obtained as

$$P_k^{th} = \frac{\gamma_k}{\Psi_k}. \quad (5.8)$$

In the non-cooperative game, every user tries to increase its own utility. In order for a user to be in coverage, P_k should be greater the threshold, i.e., $P_k \geq P_k^{th}$. As the BS has the channel state information (CSI), it can calculate the P_k^{th} for all the users. If a user selects a power level such that $P_k > P_k^{th}$, resulting in the outage of another user. In this case the role of

the BS is to enforce the fairness in the power control by reducing the power level of that user to the minimum required threshold, P_k^{th} . This way the BS ensures user fairness in the non-cooperative game.

The next game deals with the D2D power allocation in the cooperation phase to maximize the sum-rate and energy efficiency (EE), η_{EE} , of the system, where η_{EE} is the amount of energy required by the system to transmit data, expressed in bits/sec/Watt and is given by

$$\eta_{EE} = \frac{\sum_{k=1}^M R_k}{P + P_c}. \quad (5.9)$$

The players play a second a non-cooperative game with the goal of maximizing sum-rate without affecting the system performance by selecting optimum values of D2D transmission power, \tilde{P}_k . Mathematically this power allocation problem can be formulated as

$$\begin{aligned} & \underset{\tilde{P}_k}{\text{maximize}} \quad \eta_{EE} \\ & \text{subject to} \quad \tilde{P}_k \leq \tilde{P}_k^{max}, \quad \forall k \\ & \quad \quad \quad \tilde{P}_k \geq 0, \quad \forall k \\ & \quad \quad \quad R_k \geq r_{min}, \quad \forall k \end{aligned} \quad (5.10)$$

where the first and second constraints ensure the upper bound on the maximum transmission powers of the users in order to maximize the EE, while the third constraint ensures that the rate achieved by the users is at least as high as r_{min} . Let a non-cooperative game is denoted by $\mathcal{G} = [\mathcal{M}, \{\mathcal{A}_k\}, \{u_k\}]$ where $\mathcal{M} = \{1, \dots, M\}$, and $\mathcal{A}_k = [0, \tilde{P}_{max}]$ is the strategy set for the k-th

player. Here, \tilde{P}_{max} is the maximum allowed D2D transmission power. The users maximize the system energy efficiency by maximizing their individual energy efficiency, η_{EE}^k . Hence the utility function of k -th user is given by

$$u_k = \eta_{EE}^k, \quad (5.11)$$

where η_{EE}^k is the energy efficiency in bits/sec/Watt of the k -th user and is given by

$$\eta_{EE}^k = \frac{R_k}{P_k + \tilde{P}_k}. \quad (5.12)$$

Therefore the best response strategy for the k -th user is to maximize its utility:

$$\max u_k = \max \eta_{EE}^k, \quad (5.13)$$

and the optimization problem in (5.10) can be expressed as

$$\max_{\tilde{P}_k \in \mathcal{A}_k} u_k(\tilde{P}_k, \tilde{\mathbf{P}}_{-k}) \quad \forall k = 1, 2, \dots, M. \quad (5.14)$$

A player achieves Nash equilibrium if for every user k

$$u_k(\tilde{P}_k^*, \tilde{\mathbf{P}}_{-k}^*) \geq u_k(\tilde{P}_k, \tilde{\mathbf{P}}_{-k}^*) \quad \forall \tilde{P}_k \in \mathcal{A}_k. \quad (5.15)$$

The optimal solution to the above game is: $\tilde{P}_1^* = \tilde{P}_{min}$, while $\tilde{P}_k^* = \tilde{P}_{max}$ where $k = \{2, \dots, M\}$, i.e., the optimal power allocation in the cooperation phase which maximizes the EE of the system is to use minimum transmission power, \tilde{P}_{min} in the first direct transmission from User 1 to User 2, while using maximum allowed transmission power, \tilde{P}_{max} for all the other transmissions

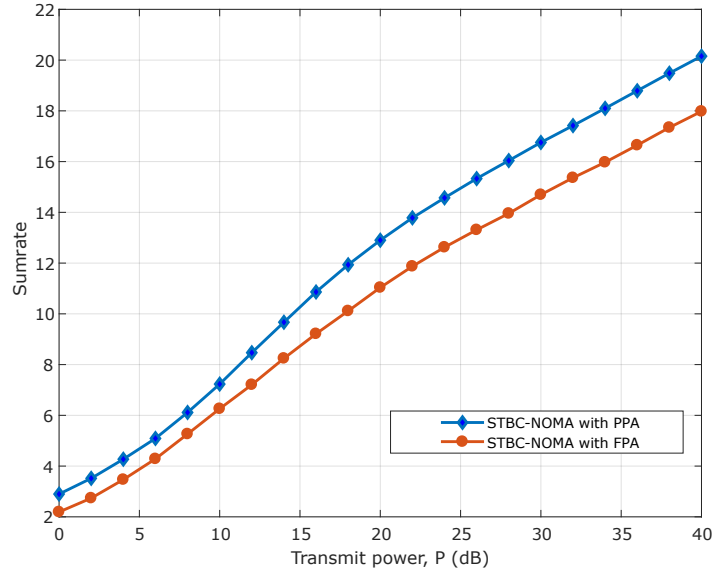


Figure 5.1: Throughput comparison between STBC-NOMA with proposed power allocation and with fixed power allocation for $M=4$, $B=1\text{Hz}$ and $\zeta=1.5$.

in the cooperation phase.

5.2 Simulation Results

Fig. 5.1 shows the sum rate comparison between STBC-NOMA with fixed power and with proposed power allocation (i.e., applying both games) for 4 users case. It can be observed that there is a notable increase in the overall throughput as compared to the fixed power allocation. While an outage capacity comparison between both the schemes is illustrated in Fig. 5.2. Where outage capacity is the success probability of the users multiplied by the maximum rate maintained by each user. It is evident from the graph that the average outage capacity and user fairness is better in the case of the

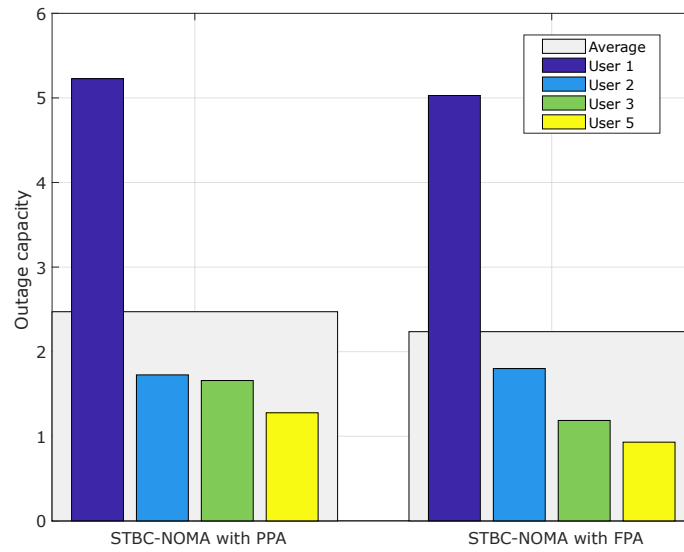


Figure 5.2: Outage Capacity comparison between STBC-NOMA with PPA and with FPA for $M=4$ and $\zeta=1.5$.

proposed power allocation as compared to fixed power allocation.

Chapter 6

STBC-NOMA with Successive Bandwidth Division

In STBC-NOMA scheme discussed in Chapter 3, there is no limit on the number of users that share the same bandwidth resources (e.g. a subcarrier). As the number of users that are simultaneously sharing the same spectrum increases, the system becomes more complex and the performance starts to degrade. This is because with the increasing number of users, the practical implementation of STBC-NOMA system faces many challenges:

- Excessive (extra) time slots are required for the user cooperation phase, which increases the latency and degrades the overall throughput of the system.
- The number of interfering signals becomes large which makes the application of SIC complex and more prone to residual errors.
- The total number of SICs performed at a single user equipment also be-

comes prohibitively large, thereby, increasing the computational complexity at the user end.

- The coordination including precise timing synchronization among a large number of users greatly increases the system overhead.

Keeping in view all the aforementioned challenges, it becomes more practical to divide the users sharing a spectrum resource into smaller groups and divide the spectrum into orthogonal bands. Successive Bandwidth Division (SBD), proposed in [29] and [30], is the idea of dividing the bandwidth of NOMA into orthogonal sub-bands.

6.1 System Model

In this chapter, we propose a scheme which incorporates the idea of SBD into the STBC-NOMA, where the bandwidth, B , is divided into orthogonal sub-bands and the users are divided into smaller groups. The BS sends a separate NOMA signal for each band and STBC-NOMA is implemented within each group. This hybrid scheme, which is the combination of SBD-NOMA and STBC-NOMA is known as Hybrid STBC-NOMA (HS-NOMA). The concept of HS-NOMA is illustrated in Fig. 6.1. In HS-NOMA, the M users are divided into S sub-groups, therefore, each sub-band gets an orthogonal bandwidth, $B_{sub} = B/S$ and the BS transmits S different NOMA signals separately for each sub-band with transmit power, $P_{sub} = P/S$. There are two variants of HS-NOMA which are discussed below.

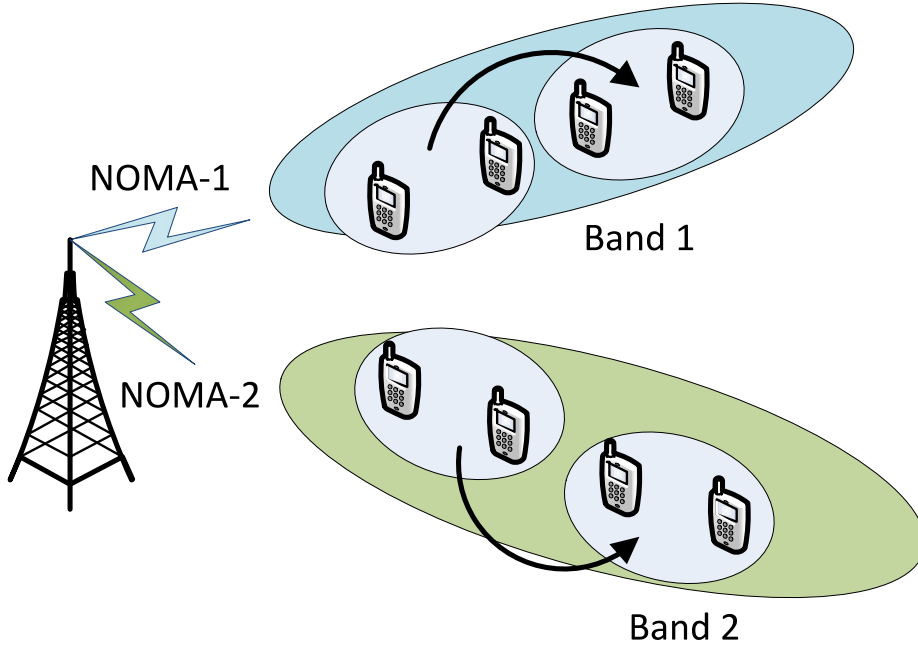


Figure 6.1: Illustration of Hybrid STBC-NOMA scheme for $M=8$. Each band employs STBC-NOMA for $M=4$.

6.1.1 HS-NOMA Variant I

In HS-NOMA scheme, the total available bandwidth, B which is shared by M users is further divided into S orthogonal sub-bands, where each sub-band has a bandwidth of $B_{sub} = B/(S)$. However, the base case of STBC-NOMA is when $M = 4$, therefore the minimum value of S can be 4. For the case when $S = M$, the HS-NOMA scheme converts to the basic STBC-NOMA scheme.

To understand the idea more clearly, consider the case of $M = 8$ as depicted in Fig. 6.1. Here the 8 users are grouped into 2 sub-groups, each consisting of 4 users. The bandwidth for each sub-group is, $B_{sub} = B/2$. In the first time slot, the BS transmits 2 NOMA signals, each for the 2 sub-bands. Then in the next three time slots separate STBC-NOMA is im-

plemented within each of the sub-groups simultaneously. It can be seen that in the HS-NOMA scheme all the 8 users are served in just 4 time slots, while it would have taken STBC-NOMA 8 time slots to serve all the users. Therefore, 4 time slots are saved in case of HS-NOMA as compared to STBC-NOMA, which can greatly increase the system throughput, while reducing the interference and system complexity. The throughput in case of STBC-NOMA for $M = 8$ is given by

$$Throughput_{(STBC-NOMA)} = \frac{1}{8} \sum_{i=1}^M B \log(1 + SINR_i) , \quad (6.1)$$

where the factor $1/8$, is the natural consequence of time sharing. The throughput in case of HS-NOMA for $M = 8$ can be obtained as

$$Throughput_{(HS-NOMA)} = \frac{5}{8} \sum_{i=1}^M B_{sub} \log(1 + SINR_i) . \quad (6.2)$$

From (6.2) it can clearly be seen that the throughput is increased by a factor of $1/2$ as compared to STBC-NOMA. The throughput and EE comparisons of both the schemes are given in Section 6.2, where it is shown that HS-NOMA has much greater performance in terms of throughput and energy efficiency as compared to STBC-NOMA. However, when the number of users become large, the throughput of HS-NOMA, though still greater than the STBC-NOMA, starts decreasing, which is due to the fact that with increasing number of users, the number of sub-groups also increase. Thereby, making the transmit power, P_{sub} and bandwidth, B_{sub} of each sub-band even smaller and thus reducing the overall throughput.

6.1.2 HS-NOMA Variant II

Considering for a system which is not power constrained and EE can be traded off for higher throughput, we propose a second variant of the HS-NOMA. In this variant, the BS sends superimposed signals for different sub-bands in separate time slots with maximum allowed transmission power for BS, i.e., $P_{sub} = P$. In case of $M = 8$, the BS transmits the first superimposed signal for first sub-band with $P_{sub} = P$ and in the next three time slots STBC-NOMA is implemented in the first sub-group. However, in the second time slot, the BS sends another superimposed signal for the second sub-band while STBC-NOMA is being implemented in the first sub-group simultaneously. The whole process is completed in 5 time slots and the throughput of this scheme can be obtained as

$$Throughput_{(HS-NOMA-2)} = \frac{4}{8} \sum_{i=1}^M B_{sub} \log(1 + SINR_i) . \quad (6.3)$$

From (6.3) it can clearly be seen that the throughput is increased by a factor of 3/8 as compared to STBC-NOMA.

6.2 Simulation Results

Figs. 6.2 and 6.3 illustrate the throughput and EE comparison between STBC-NOMA and two variants of the HS-NOMA respectively. Fig. 6.2 shows that the first variant of HS-NOMA outperforms both the other schemes in terms of EE performance. It can be observed from the graph that EE of the first variant of HS-NOMA tends to increase at first, but then the graph

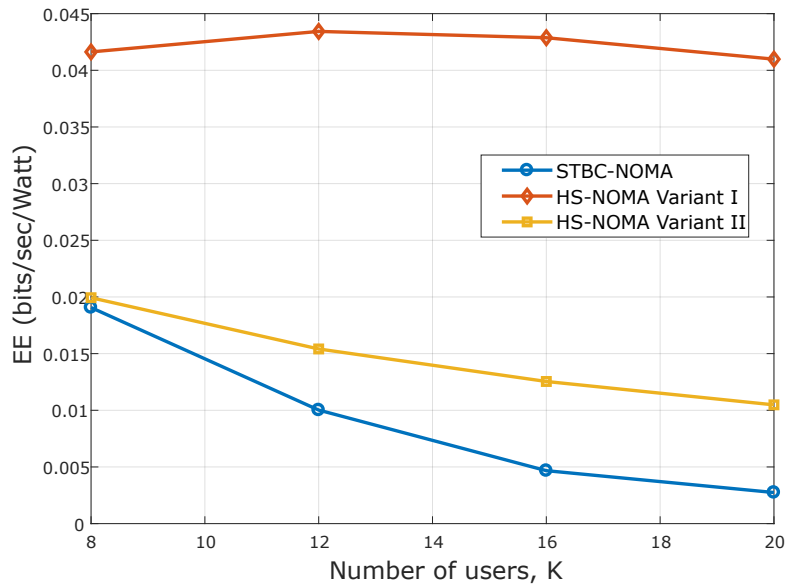


Figure 6.2: EE comparison between different variants of STBC-NOMA for $P=20$ dB and $\zeta=1.5$.

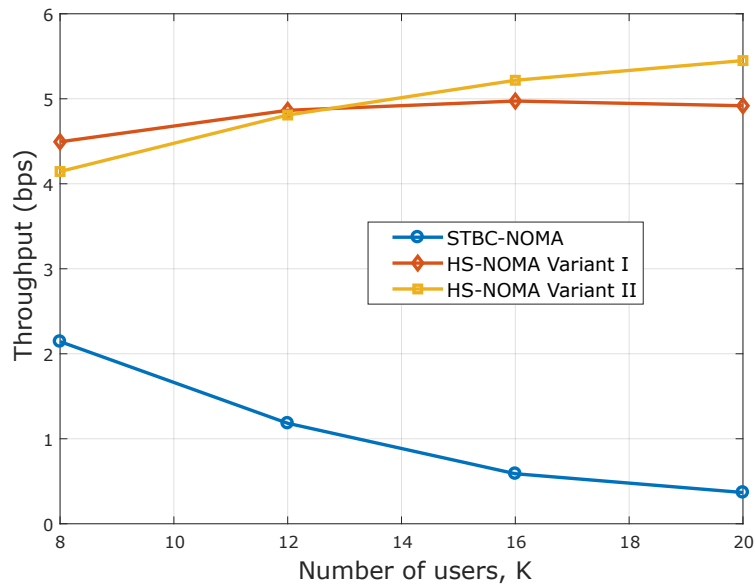


Figure 6.3: Throughput comparison between different variants of STBC-NOMA for $P=20$ dB and $\zeta=1.5$.

starts to decline as the number of users is increased. This is due to the fact that with large number of users, more orthogonal sub-bands are required thus reducing the amount of transmit power allocated to a single sub-band. From Fig. 6.3 it can be observed that the throughput of the first variant is also better than both the other schemes for small number of users, but as the number of users become large, the second variant takes lead. This is due to the extra amount of energy used in case of the second variant to transmit the different NOMA signals, which greatly degrades its EE performance. But still both the variants of HS-NOMA show better throughput and EE performance as compared to STBC-NOMA. However, HS-NOMA variant I is preferred when EE is of highest priority, while variant II is preferred when EE can be traded off for higher throughput.

Chapter 7

Conclusion & Future Works

In this thesis we presented an STBC-based cooperative NOMA scheme based on distributed Alamouti STBC. The proposed scheme reduced the system complexity due to reduced number of SICs performed overall in the system and also achieved higher system throughput as compared to conventional C-NOMA. The SIR and rate outage probability expressions are obtained based on the received SIR. The simulation results show that STBC-NOMA can significantly outperform both NOMA and conventional cooperative NOMA in terms of outage probability and sum rates. We also proposed a fair power allocation scheme based on the game-theoretic approach to maximize the system throughput and EE. Simulation results showed that STBC-NOMA with PPA achieves higher throughput as compared to STBC-NOMA with FPA. Finally, we introduced the concept of HS-NOMA, a hybrid scheme which incorporates the concept of SBD into the STBC-NOMA. The performance comparisons between different variants of STBC-NOMA illustrated that HS-NOMA can provide higher system EE and throughput with large number of

users.

As a future work, the analysis can be extended to MIMO-NOMA networks, where STBC-NOMA is implemented within each beam. Another important direction is the study of finding an upper limit on the number of cooperating users while keeping the required performance, and to study the effects of imperfect SIC and channel state information (CSI) on the performance of STBC-NOMA.

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