USER PAIRING AND POWER ALLOCATION ALGORITHM OF N-USERS IN NOMA SYSTEMS 5G

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(**With Specialization in Communication Systems**)

By

PRADEEP K M

(Enrollment No. **17531013**)

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY, ROORKEE

ROORKEE-247667 (INDIA)

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CANDIDATE'S DECLARATION

I hereby declare that the work presented in this dissertation report entitled **"USER PAIRING AND POWER ALLOCATION ALGORITHM OF N-USERS IN NOMA SYSTEMS 5G"** towards the partial fulfilment of the requirements for the award of the degree **of MASTER OF TECHNOLOGY** with specialization in **Communication Systems**, submitted in the Department of Electronics and Communication Engineering, Indian Institute of Technology Roorkee, Roorkee (India) is an authentic record of my own work carried out during the period from May 2018 to June 2019, under the guidance and supervision of **Dr. Anshul Tyagi**, Assistant Professor, Department of Electronics and Communication Engineering, Indian Institute of Technology Roorkee, Roorkee (INDIA).

The matter presented in this dissertation has not been submitted by me for the award of any other degree of this or any other institution.

Date:

Place: Roorkee

(Pradeep K M)
Enrolment No. 17531013
ECE Department
IIT Roorkee

CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief.

Date:

Place: Roorkee

(Dr. Anshul Tyagi)
Assistant Professor
ECE Department
IIT Roorkee

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(PRADEEP K M)

Enrolment No. 17531013
ECE Department
IIT Roorkee

ABSTRACT

Non-orthogonal multiple access (NOMA) has been considered as one of the key technique for 5G wireless network systems. Here similar to the previous generation multiple access techniques, the available transmission bandwidth is divided into bands of different frequency. All the users in the system are allotted into the sub bands and transmitted by being superimposed and a power allocation is carried out. And at the receiver end, a special type of processing is carried out called Successive interference cancellation (SIC) to detect the desired signal which has been differentiated by the power allotted to it. In this dissertation, a sub-optimal user grouping scheme is being implemented by exploiting the differences in channel conditions between the base station and various users in a cluster and then allots them into sufficient number of clusters to maximize the throughput. This is done with the objective of enhancing the sum-throughput of the system. After cluster formation, we then derive the optimal power allocation scheme that enhances the sum-throughput per NOMA cluster and therefore in turn maximizes the overall throughput of the NOMA system. Closed-form solutions for optimal power allocations are then derived for any cluster size, for downlink NOMA systems using Karush-Kuhn-Tucker optimality conditions.

Contents

List of Figures

List of Tables

Abbreviations

MA	Multiple Access
NOMA	Non Orthogonal Multiple Access
MIMO	Multiple Input Multiple Output
OFDMA	Orthogonal Frequency Division Multiple Access
QoE	Quality of user Experience
RAT	Radio Access Technology
TDMA	Time Division Multiple Access
CDMA	Code Division Multiple Access
SCFDMA	Single Carrier Frequency Division Multiple Access
LTE	Long Term Evolution
HSDPA	High Speed Downlink Packet Access
WLAN	Wireless Local Area Network
MINLP	Mixed Integer Non Linear Programming
KKT	Karush Kuhn Tucker
BS	Base Station
SIC	Successive Interference Cancellation
CSI	Channel State Information
DPC	Dirty Paper Coding
SINR	Signal to Interference Noise Ratio
MCS	Modulation and Coding Scheme
AWGN	Additive White Gaussian Noise
EE	Energy Efficiency
SE	Spectral Efficiency

Symbols

α	Power or Bandwidth Allocation factor
N	Power Spectral Density
β_k	Power Assignment Ratio
h_i	AWGN Channel Gain
ε	Imperfect Cancellation Parameter
γ	Channel Gain
δ	Minimum Power Difference Parameter
λ	Lagrange Multiplier
μ	Lagrange Multiplier
ψ	Lagrange Multiplier

Chapter 1

Introduction

The design of radio access technology (RAT) is one essential aspect in enhancing and increasing the system capacity and is a cost-effective approach. As we know, RAT are classified into (FDMA) frequency division multiple access, (TDMA) time division multiple access, (CDMA) code division multiple access, and (OFDMA) Orthogonal frequency division multiple access, which provides the means for multiple users to access and share the radio spectrum simultaneously. In the Long-Term Evolution (LTE) and LTEAdvanced (LTE-A), orthogonal multiple access (OMA) which is based on OFDMA and single carrier (SC) FDMA are used to achieve satisfactory throughput performance with a comprehensible receiver design. But due to the dwindling spectrum resources, more complex receiver designs are needed in order to reduce intra-cell and or inter-cell interference.

1.1 Necessity of NOMA

Multiple access (MA) techniques can mainly be classified into orthogonal and non-orthogonal approaches. TDMA, FDMA and OFDMA are the three main orthogonal multiple access techniques. In contrast to the orthogonal approaches, non-orthogonal multiple access schemes allows the overlapping of the signals from different users in the system by exploiting the use of power domain or code domain etc., and thus providing much better results. First and second generation wireless systems using orthogonal multiple access approaches, avoids intra-cell interference between the users and simplifies the air interface design. But, the disadvantage of orthogonal multiple access approaches being, they themselves don't have the ability to oppose the disadvantage of inter-cell interference. So sophisticated interference management techniques or careful cell planning are required to oppose the inter-cell interference.

Second and third generation wireless systems is implemented on top of non-orthogonal CDMA techniques. Compared to its orthogonal counterparts, CDMA can strongly perform when it comes to inter cell interference but it is performs weakly against intra cell. Although CDMA has lots of pros including soft capacity and handover but it is not suited for data services for e.g., 3GPP high speed uplink/downlink packet access (HSUPA/HSDPA) standard) and wireless local area networks (WLANs) which requires better single-user data rates.

Over the coming decade, for ensuring the sustainability of wireless communication services, new technologies should be proposed which will provide further improvements that can efficiently tackle future challenges. In order to satisfy these above requirements, a wide array of new methods are required, such as novel architectures, and new multiple access schemes. Among such technologies, the improvement of MA from orthogonal to non-orthogonal is thought to be one optimistic move for 5G systems. So in this dissertation, we firstly discuss the concept and fundamentals of NOMA towards the improvements of spectral efficiency. After then, the key features of NOMA is discussed and implemented including multi user allocation of power and receiver design. After that proper user allocation algorithms are implemented for different users for classifying the users into user clusters to improve the overall throughput of the system.

1.2 Motivation behind Thesis

From the recent proposals regarding NOMA, effective user pairing and allocation of power to the users in the system are the most basic design problems. And from the proposals, we know that a proper power allocation algorithm for correctly analyzing the downlink NOMA is not available. Most of the research on this topic consists of a simple fixed power allocation algorithm where the lower and upper bounds of the power allocation factor is found using theoretical analysis and thus by varying the value from lower to upper bound for each user and then comparing the results with previous multiple access techniques. As a result, in this dissertation, we focus on implementing a proper power allocation scheme where the exact power allotted to each users is derived by considering an optimization problem.

The contributions of this dissertation are given as follows:

- Firstly we go through the necessity of NOMA, concept, system model and fundamentals of NOMA.
- For downlink NOMA, we pair all the users present in the system into different clusters on the basis of some practical considerations.
- After pairing the users into groups, each user is allotted different power levels based on its distance from the base station or its channel conditions.
- This is done by using a convex optimization problem of maximizing the throughput of the system by considering three main constrains such as the minimum rate necessity of users, the power constraints of the users and SIC constraints.
- Since the above problem is a mixed integer non-linear programming (MINLP) problem, it is carried out by firstly discussing and implementing a user pairing scheme and then allocation of the downlink power budget in a way to maximize not only the sum throughput of the system but also the individual throughputs of all the users in the NOMA system.
- After grouping the users into NOMA clusters using a grouping algorithm, we obtain the optimal power allocation algorithm that maximizes both the individual and sum-throughput of the wireless system and thus maximizing the overall rate. Using Karush Kuhn Tucker conditions, optimal powerallocations for any cluster size is evaluated.
- Simulations are done based on these methods and the results obtained after user pairing and power allocation is compared with that of an OFDMA system.

1.3 Existing Research in NOMA

In order to develop a new multiple access technique for Fifth Generation Cellular Systems, to overcome the disadvantages of the previous multiple access systems and to meet the requirements of the new generation system, a large amount of research proposals have been put forward.

In paper [1], [2], and [3], a brief overview of the concept and fundamentals of NOMA are explained and also the allocation of power by considering the distance between the base station and user equipment. Specifically in paper [2], the authors have reviewed the practical considerations regarding the working of NOMA and its disadvantages. They include mainly the allocation of power to different users, the mobility of users, scheduling of the users into different sub bands, overall system overhead, the dependence of all the users with less channel conditions in the detection of the desired signal and the adoption of MIMO technology in combination with NOMA. The simulations for overall fairness, outage probability of NOMA were carried out in [7] for 2-user NOMA.

In paper [4], a test bed for NOMA was carried out for the case of 2 user NOMA. Experiments were carried out taking into consideration various assumptions. And the results showed the practical analysis of NOMA and its improvement over various other multiple access schemes. In paper [8], the impact of combining the concept user pairing and power allocation of NOMA is studied.

Chapter 2

Literature Survey

2.1 Multiple Access Techniques

2.1.1 Frequency Division Multiple Access (FDMA)

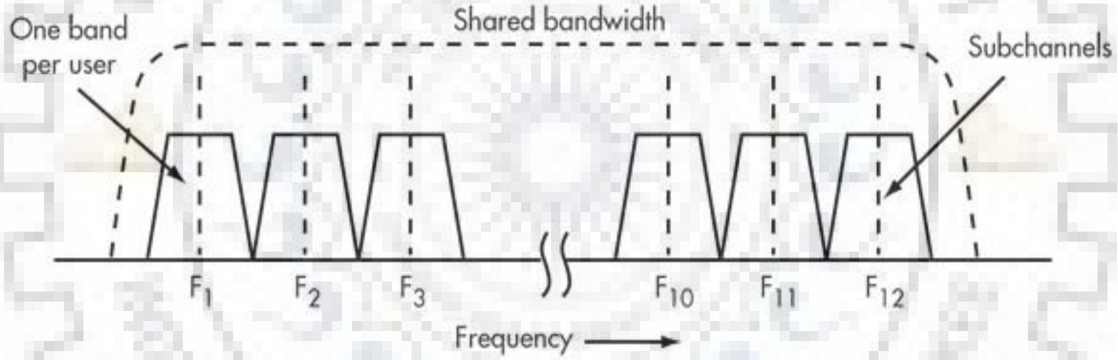

Fig. 2.1. FDMA.

FDMA, as the name suggests is a multiple access technique which divides the downlink transmission bandwidth into smaller frequency bands. And each small frequency band is considered as a channel for communication each user. When a user wants access to the channel, it requests the channel from the BS and BS allots the frequency channel to that user and no other user can access that particular channel until that user no longer uses it. It is the simplest form of multiple access technique. FDMA divides the frequency band and allocates it to the users for the amount of time required by the user and in this case there is no time multiplexing since only frequency is being multiplexed and each user data is modulated and send through the channel.

Disadvantages

- In FDMA, each user is allocated frequencies are permanently and so spectrum will be wasted when base stations or users are not transmitting or receiving.
- Network and spectrum planning is hectic, cumbersome and time consuming.
- FDMA uses guard bands in order to prevent interference wasting very useful and scarce frequency resources.
- In order to meet stringent adjacent channel rejection specifications, FDMA requires RF filters increasing cost of the system.
- Maximum bit rate per channel is constant in FDMA and therefore cannot be used for varying data rate requirements as per QoS.

2.1.2 Time Division Multiple Access (TDMA)

In TDMA, the bandwidth is divided into time slots and each user is allocated the time slots while transmission. The transmission occurs in digital bursts and is non continuous. This technique works better with slow voice signals, compressed video and other high-speed data. T1 transmission system is considered as an example of TDMA which is an important part of the company for many years. It carries up to 24 single voice phone calls on a single line shown in Fig. 2.2.

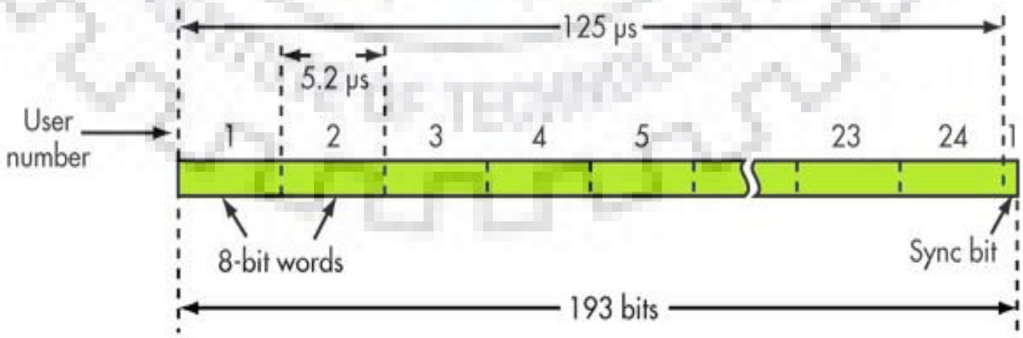

Fig. 2.2. TDMA Frame Structure.

Fig 2.3 showing T1 telephony frame illustrates TDM. The lack of simultaneity is made unaware to the user due to the high data rate. The now digitized voice data looks as individual serial bytes having a rate of 64-kHz.

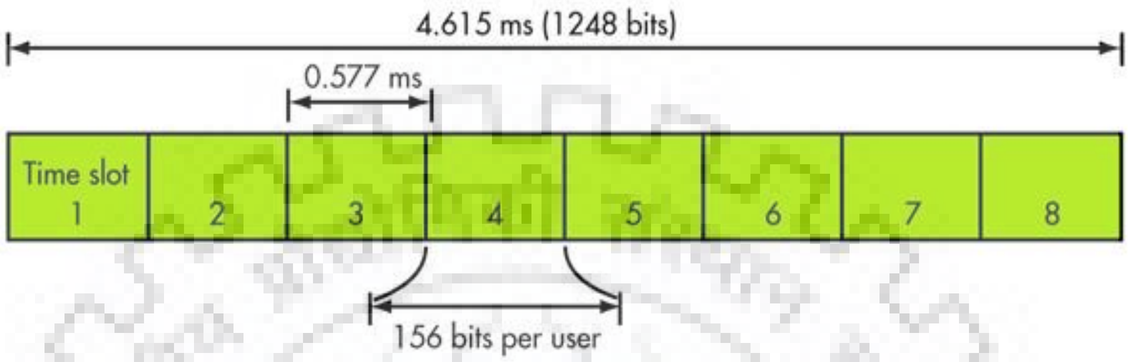

Fig. 2.3. TDMA Time Slot.

Disadvantages

- Network and spectrum planning is hectic, cumbersome and time consuming.
- Call quality is affected by multipath interference.
- Moving from one BS to the other cell will have an outcome of calls being dropped and thus reducing the efficiency.

2.1.3 Code Division Multiple Access (CDMA)

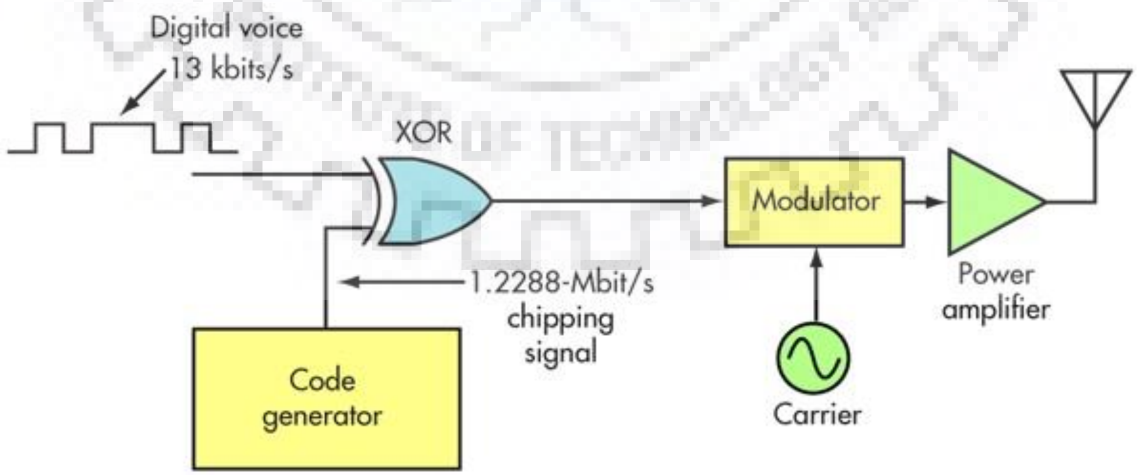

Fig. 2.4. CDMA Block Diagram.

Spread spectrum communication is the main technique used in CDMA systems. The voice data signal is given as input multiplied by a wide bandwidth signal called as the chipping signal. The chipping signal is actually a pseudorandom code signal generated by a shift register which assigns a unique code to each user. This code spreads the voice data signal. The signal obtained after this multiplexing is being transmitted and the same pseudo random code is required at the receiver end to demodulate the desired signals.

Disadvantages

- Network and spectrum planning is cumbersome and requires more efforts.
- Call quality is affected by multipath interference.
- Moving from one BS to the other cell will have an outcome of calls being dropped and thus reducing the efficiency.

2.1.4 Orthogonal Frequency Division Multiple Access (OFDMA)

OFDMA is the multiple access method used in Long-Term Evolution (LTE) so as to occupy multiple users in the given transmission bandwidth. It divides a channel into multiple small orthogonal bands that are spaced so they don't interfere with one another.

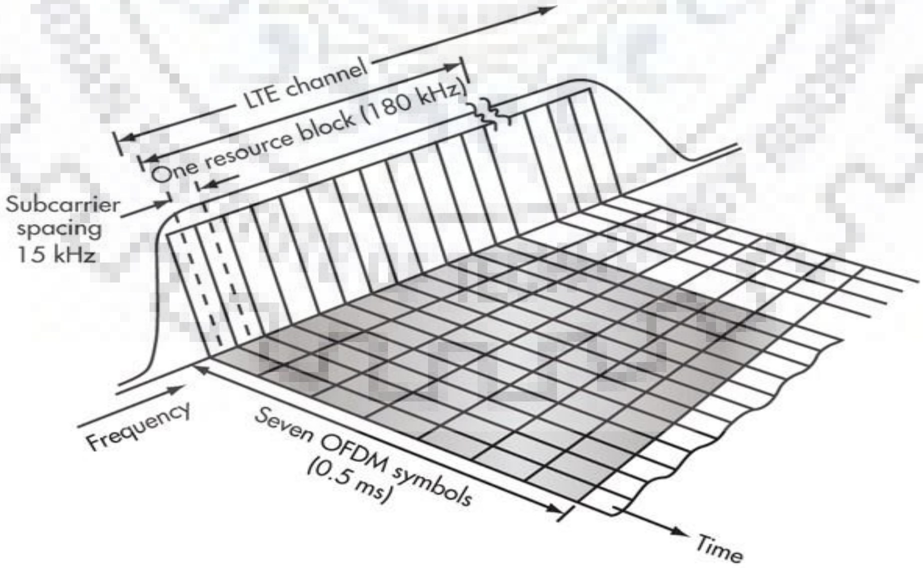

Fig. 2.5. OFDMA.

Here the frequency is being modulated orthogonally. Similar to FDMA, OFDMA divides the frequency band into smaller bands and each user is transmitted in the smaller bands. But in OFDMA, the division of the total available bandwidth is not equal, i.e. the bandwidth allocated to each user is different. And the signal which is going to be sent is modulated into sub carriers

Disadvantages

- OFDMA requires close spacing among sub carriers which might cause the losing of orthogonality due to frequency errors.
- OFDMA is vulnerable to the problem of carrier frequency offset.
- Orthogonal frequency division multiple access has high PAPR (Peak to Average Power Ratio).

2.2 User Clustering

User clustering or user pairing or cluster analysis is one the main techniques used in communication systems to increase the overall system performance because if clustering is done in the correct way such that the users being grouped have certain qualities that are beneficial in increasing the performance of not only of that particular user but also the other users that are grouped with this user and therefore increasing the overall performance of the system. It has been employed not only in the field of communication systems but various other fields as well such as data mining, and a common technique for statistical data analysis, used in many fields, including pattern recognition, machine learning, bioinformatics and computer graphics .

One of the main user paring algorithm that have been proposed in many fields and proving to be having lot of benefits is K- means clustering method. K means first decides some random cluster heads and groups the users together based on their distance and then take s a mean average to further improve the paring. But this method does not provide the necessary advantages in NOMA systems because the users having the same channel conditions will be grouped together thus reducing the performance of NOMA.

Chapter 3

Concept and Key Technologies of NOMA and its Comparative Study with OFDMA

3.1 Concept of NOMA

NOMA is an effective method for future wireless radio access. In theory, NOMA works on the principle of successive interference cancellation (SIC) or also known as dirty paper coding (DPC). The main property of NOMA is the usage of power domain which has been equally distributed in the previous generation systems. But here the users are distinguished by allotting them different power according to their distance from the BS or its channel conditions. At the receiver end, the user which is allocated higher amount of power can easily detect its own signal by considering all the others as interference. But the user which is allocated lower amount of power has to do SIC processing to remove the other signals having higher power levels.

Fig 3.1 shows signal the transmitter and receiver design of downlink NOMA by considering two users. Here, we assume that the first user is the cell center user and the second user is cell-edge user. And in NOMA, the base station sends a super imposed signal by allocating different powers for user1 and user2. Here, more power is distributed for user 2 or the cell edge user. And since user1 is having higher SINR compared to the other user, its capacity belongs to the bandwidth-limited. As a result, less power is allocated to user1. The addition of power allocated to user1 and user2 will be equal to the total transmission power budget available to the base station. And due to the different power allocated to the users, for successful demodulation, there is different processing at each of the users. We can see that user2 can easily detect its own signal by considering user1 signal as interference because the power allocated to the latter is less. But user1 cannot do this because user2 is allocated more power. So as a result user1 performs SIC where it detects the signal of user2 and then negates the signal from the super imposed signal and then with the improved SINR it can detect its own signal.

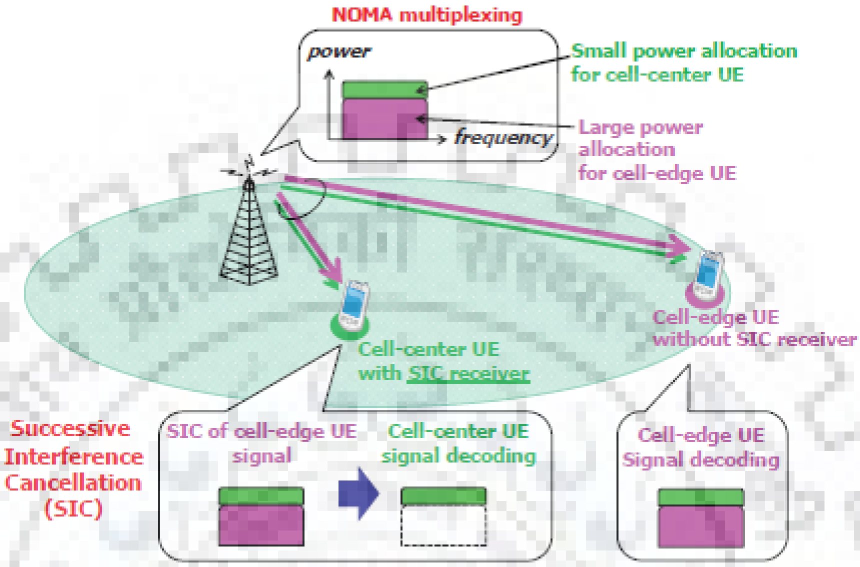

Fig. 3.1. Illustration of downlink NOMA with SIC (2 users).

For the sake of reduced complexity, let us assume that the system uses single transmitter and receiver antenna configuration. Further the system bandwidth is taken as 1 Hz. As we have explained before, in NOMA the signals are super imposed. And if we consider 2 users and let P_1 be the power allotted to user1 and P_2 be of user2, then the data which is transmitted is given as

$$x = \sqrt{P_1}x_1 + \sqrt{P_2}x_2 \quad (3.1)$$

And the signal which is obtained at each user is given by

$$y_i = x * h_i + w_i \quad (3.2)$$

where h_i is the AWGN channel coefficient between the BS and useri. And AWGN having a power spectral density of N_0, is denoted by term w_i.

Now at the receiver end, the users perform SIC. But it should be performed in an order for successful detection of the signals. Since the cell edge user is given more power it can easily detect its own signal by considering the cell center user as interference. But the cell center user cannot detect its signal when other users having less channel conditions are present because of the higher power allotted to it. So the cell center user must remove all such users first before decoding its own signal. Since we are considering a 2-user system, the cell center user must remove cell edge user first. So according to this constraint, it can be concluded that for successful and optimal SIC process, it should be done in the descending order of channel gain. Let us simplify the expression by normalizing channel coefficient by noise and interference denoted by $|h_i|^2/N_{0,i}$. And so we can see that in a multiple user system, the users having channel gain must remove those signals with lower channel gains or the users which comes after the decoding order mentioned before for successful SIC. But the disadvantage of NOMA is that the detection of one signal user depends on SIC process on the users having less channel conditions compared to the desired signal. By assuming perfect SIC, throughput can be calculated for user1 and user2 by the equation

$$R_1 = \log_2\left(1 + \frac{P_1|h_2|^2}{N_{0,1}}\right), R_2 = \log_2\left(1 + \frac{P_2|h_2|^2}{P_1|h_2|^2 + N_{\_0,2}}\right) \quad (3.3)$$

From the above equation (3.3), we see that the variables P1 and P2 directly affects the individual throughputs. And the throughput of the user2 has user1 as interference. This is because user2 has high power allotted to it and other users having high channel conditions have less power. But the throughput of user1 does not have any interference and only the noise resulting from AWGN channel is present. Because this is the outcome of SIC processing as the interference is detected and then negated from the super imposed signal. So by varying the ratio P_1/P_2, the throughput can be adjusted and also the user fairness. And since the power budget is assumed to be 1 dBm, if α power is allotted to user1, then 1- α is allotted to user2 in a two user system.

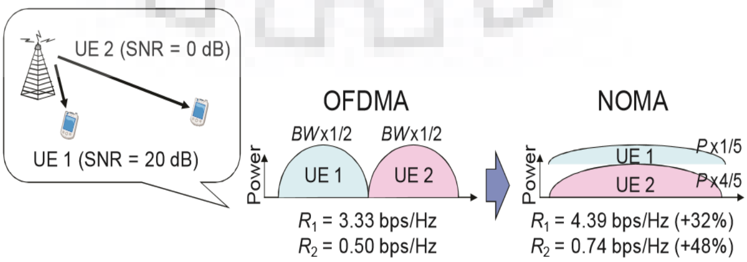

Fig. 3.2. Comparison between NOMA and OFDMA wireless systems.

Since we are comparing the performance of NOMA with OMA, for OMA let us assume that the bandwidth of 1 Hz is given for both the users. So contrast to NOMA, for OFDMA the bandwidth is varied for both the users, i.e., if α Hz frequency is allotted to user1, them 1- α Hz frequency is allotted to user2. So the throughput of user1 and user2 is denoted by

$$R_1 = \alpha \log_2\left(1 + \frac{P_1|h_2|^2}{\alpha N_{0,1}}\right), R_2 = (1-\alpha)\log_2\left(1 + \frac{P_2|h_2|^2}{(1-\alpha)N_{0,2}}\right) \tag{3.4}$$

Now the throughputs of both the systems are compared. From the Fig 3.2. Let us take the assumption that the channel gain normalized by noise and interference for both the users denoted by $|h_1|^2/N_{0,1}$ and $|h_2|^2/N_{0,2}$ are set to 20 dB and 0 dB. As explained before, for NOMA, the bandwidth of 1 Hz is equally distributed for the users and the power allotted to the user having channel gain 20 dB is $P_1 = 1/5P$ and to the user having channel gain 0 dB is $P_2 = 4/5P$. As it can be seen that the above power allocation, the property of NOMA is satisfied as less power is allotted to 20 dB user and more power is allotted to 0 dB user. And for OMA, both the power and bandwidth are equally distributed. And the throughputs are calculated using the equation 3.4 and we get the results as R_1 = 3.33 and R_2 = 0.50 bps for OMA and as R_1 = 4.39 bps and R_2 = 0.74 bps for NOMA. It is clear from the calculations that NOMA has significant advantage over OMA in a 2 user system.

3.2 Key Technologies of NOMA

3.2.1 System model

In the previous section, a two user NOMA system was considered using a cell center user and a cell edge user. Here let us discuss about the system model of NOMA by considering N number of users. In the Fig 3.3., the total number of users M are present and these M users are scheduled into different sub bands such a way that N number of users are simultaneously transmitted. In OFDMA also the similar division of bandwidth is carried out. But in OFDMA, the bandwidth allotted to each user is varied and only one user is present in a sub band. But in NOMA, multiple users are transmitted in a single sub band by using the principle of NOMA of using the power domain.

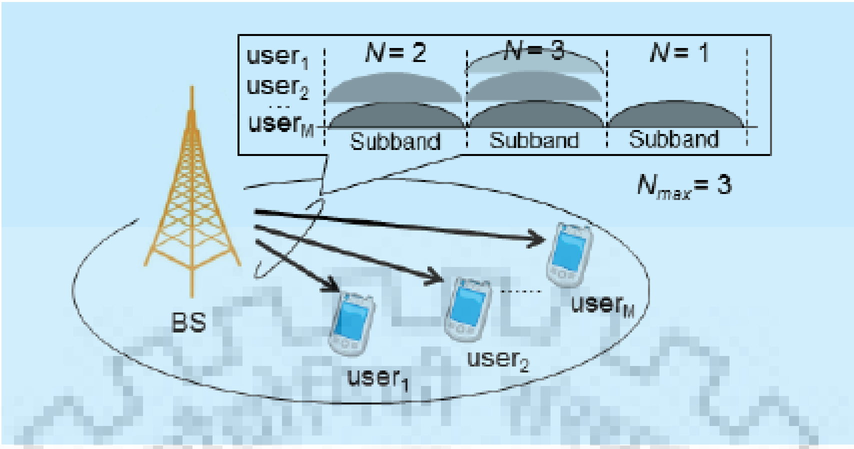

Fig. 3.3. Concept of NOMA with SIC receiver for downlink multiple access.

Let us consider a sub band having N uses simultaneously transmitted. One more assumption that is taken throughout the first portion of the dissertation is that the users are arranged in either descending order of SINR or ascending order of SINR. Here we are assuming the former, i.e., the user1 has the highest channel conditions and user2 has the lowest as it is the farthest from the user. So taking these assumptions the theoretical aspects of NOMA system model is defined. And the received signal at the nth user is given by

$$y_n = h_n \times \sum_{k=1}^{N} s_k . \sqrt{P_k} + I_n + w_n \tag{3.5}$$

where h_n denotes the AWGN channel coefficient and the data transmitted by each user is denoted by the symbol s and P is the power allotted to each signal. I_n denotes the inter cell interference and w_n denotes the AWGN which is present in the signal. And $n, k \in [1, N]$ denotes user index. The power allotted to $user_k$ according to the property of NOMA is given by the equation $P_k = \beta_k \times \frac{P_{BS}}{N_{SB}}$ where β_k lies between 0 and 1. And P_{BS} denotes the total power of the base station and N_{SB} denotes the total number of sub bands.

Now SIC is carried out according to the constraints of NOMA. Since the users are arranged in descending order of channel gain and the desired $user_n$ lies between the users having low and high channel gains compared to it, SIC is applied accordingly. Since all the users which comes after the desired $user_n$ has less channel conditions and therefore more power, they need to be removed at each stage. After successfully applying the SIC process, the signal obtained is given by the equation

$$y_n = h_n \times s_n\sqrt{P_n} + h_n \times \sum_{k=1}^{n-1} s_k.\sqrt{P_k}$$

Desired Signal Remained Interference (intra-cell)

$$+ h_n \times \sum_{k=n+1}^{N} s_k.\sqrt{P_k} + \quad I_n + n_n \tag{3.6}$$

To be removed by SIC Interference (inter cell)

It can be deduced from the equation that the super imposed term can be divided into two terms. First term where k is varying from 1 to n-1 is the remaining interference. Since all the users coming before the desired signal has higher channel conditions and therefore lower power compared to the desired signal, they can easily be considered as interference and the desired signal can be detected. But the users coming after the desired signal has more power allotted to it, so SIC should be done on each of those users and then removed from the super imposed signal. The SINR of the $user_n$ after SIC can then be denoted by

$$SINR_n^{Post} = \frac{\beta_n}{\sum_{k=1}^{n-1} \beta_k + \frac{1}{SINR_n}} \tag{3.7}$$

denotes the SINR of user when full transmission power is given to the user and P_{I+N} denotes total power including inter-cell interference and noise observed at $user_n$.

3.2.2 Multi-user transmission power allocation

In order to find the theoretical lower and upper bounds of the power allotted to the users satisfying the principle of NOMA, let us assume M number of users whose channel gain is ordered as $|h_1|^2 \le |h_2|^2 \le \cdots \le |h_M|^2$, where h_i denotes the AWGN channel gain. For simplicity let us take two users, a-th user and b-th user such that they are arranged in the system as $1 \le v<w<M$.

Individual throughput of user a and user b is given by the following equation

$$R_{a,D}^{N} = \log_2\left(1 + \frac{\alpha_a |h_a|^2}{\alpha_b |h_a|^2 + \frac{1}{\rho}}\right),$$

(3.8)

$$R_{b,D}^{N} = \log_2(1 + \alpha_b \rho |h_b|^2)$$

respectively, where ρ is the channel gain normalized by noise or called transmit SNR, α_a and α_b are the power allocation factor for user *a*.

In order to have a minimum rate requirement for NOMA system, the OMA throughput equation is taken given by

$$R_i^t = \frac{1}{2}\log_2(1 + \rho |h_i|^2),\ i \in \{a, b\} \quad (3.9)$$

We need two conditions on the rate of user *a* and user *b* to find the lower and upper bounds for the power allocation factor. So let us consider firstly user b which is having high channel conditions as the primary user and the since the minimum rate requirement is at user b is R_b^T , and so we can assume the constraint $R_{b,}{}^{N}{}_{D} \geq R_b^T$ need to be satisfied. Therefore,

(3.10)

$$\log_2(1 + \alpha_b \rho |h_b|^2) \geq \frac{1}{2}\log_2(1 + \rho |h_b|^2)$$

$$\alpha_b \geq \frac{1}{\sqrt{1+\rho|h_b|^2} + 1}$$

In order to get the next constraint, let us take user a having less channel condition as primary user, so

$$\log_2\left(1 + \frac{\alpha_a |h_a|^2}{\alpha_b |h_a|^2 + \frac{1}{\rho}}\right), \geq \frac{1}{2}\log_2(1 + \rho |h_a|^2) \quad (3.11)$$

$$\alpha_b \leq \frac{1}{\sqrt{1+\rho|h_a|^2}+1}$$

From the equation, we can confirm that the upper bound of α_b satisfies the condition that user b should be given more power. It is given by the following constraint

$$\frac{1}{\sqrt{1+\rho|h_a|^2}+1} < \frac{1}{2} \tag{3.12}$$

From both of the above constraints given by the equation (3.10) with (3.11) power allocation factor α_b can be expressed as:

$$\alpha_b = \frac{\beta}{W+1} + \frac{\beta}{V+1} \tag{3.13}$$

$$W = \sqrt{1+\rho|h_b|^2}, \mathrm{V} = \sqrt{1+\rho|h_a|^2}$$

We can see from the above equations that the power allocation factors α_a and α_b are fixed and does not change as the users channel gains changes, as long as the order of channel gain does not change. By allocating various value of the power allocation factors, the throughput can be varied and the performance of NOMA can be analysed.

3.3 Results

Results regarding the simulation of the rates of users in a NOMA system in symmetric and asymmetric channels and its comparison with OFDMA.

3.3.1 Simulation Parameters

To analyze the performance, a simulation setup was created in MATLAB 2019a. In the setup 2 users are considered with Power Spectral Density N_0 and various power is allocated both users and the throughputs are calculated. The major simulation parameters are given in Table 3.1.

Parameter	Value
Channel Coefficient between BS and User1	10 dB, 20 dB
Channel Coefficient between BS and User2	10dB, 0 dB
Power Spectral Density, N_0	−150 dBW/Hz
Total System Bandwidth, W	5 MHz
Total Downlink transmit Power Budget, P	1 dBm
Power Allocated to User1	α
Power Allocated to User2	1- α
α- Bandwidth Splitting Factor in NOMA	varies from 0 to 1
α- Bandwidth Splitting Factor in OFDMA	varies from 0 to 1
Rate of User1, Rate of User2	o/p

Table 3.1. Simulation Parameters for the comparison of Throughput of NOMA and OFDMA

3.3.2 Results of Comparison of NOMA and OFDMA in a Symmetric Channel

From equations (3.8), (3.9), (3.10), (3.11), (3.12), (3.13), the rates of two users in NOMA systems and OFDMA systems is compared. While running the simulation, we are assuming a 2 user system and analysing the achievable rate for 2 user system. For simulations, we firstly consider a channel such that the user are stationary and are at an equally placed to the base station, i.e., we are taking the SNR1=SNR2=10dB. By plotting the results, Fig 3.4 shows the achievable rate regions R1and R2 for both the systems. By varying the power allocation factor between 0 and 1, the rates of the two users are plotted for NOMA and for OFDMA the bandwidth allocated to the two users are varied but equal power is allocated.

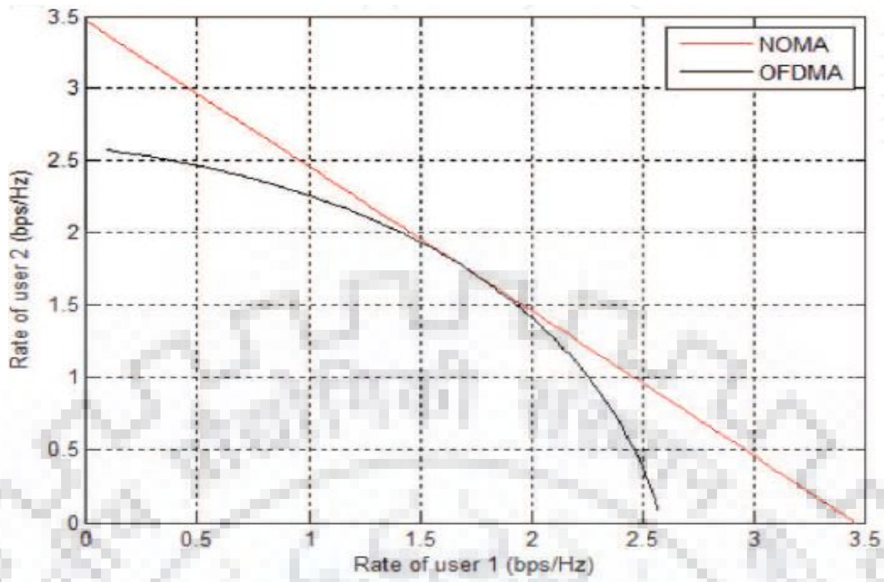

Fig. 3.4. Comparison of NOMA and OFDMA in a Symmetric Channel.

3.3.3 Results of Comparison of NOMA and OFDMA in an Asymmetric Channel

Fig 3.5 shows the results obtained when the users are stationary and are placed at unequal distances from the base station, i.e., SNR1 = 20dB and SNR2 = 0dB. This means that one user is closer to the base station and 2^{nd} user is farther.

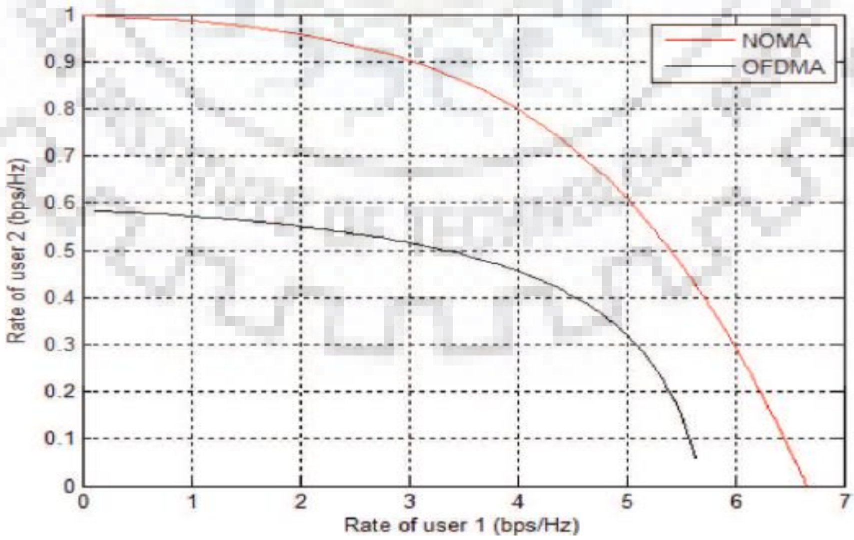

Fig. 3.5. Comparison of NOMA and OFDMA in an Asymmetric Channel.

Chapter 4

Imperfectness and Efficiency Analysis of NOMA

4.1 Imperfectness in NOMA

The discussions in the previous sections of the dissertation assumes the case of ideal SIC. That is the cell centre user will successfully detect the cell edge user and then negate the obtained signal from the super imposed signal. But the actual SIC processing works differently. It is actually quite difficult to attain perfect cancellation at the receiver. So if we consider practical considerations, there will be an imperfect cancellation term.

Here, we consider the downlink only. As mentioned earlier, the advanced receiver in NOMA decodes the data signals one by one and after each step the SINR is improved and finally the desired signal can be obtained. After each step, the interference of each user having higher power is removed but it cannot be perfectly removed. Some cancellation error would be present. Due to this cancellation error the SNR would have an additional term. So the SINR of the kth user is given by

$$SNR_k = \frac{P_k {h_k}^2}{N_0 W + \sum_{i=1}^{k-1} P_i {h_k}^2 + \epsilon \sum_{i=k+1}^{K} P_i {h_k}^2} \tag{4.1}$$

Comparing this equation to equation (3.2), we can see that an extra term is present. This is the interference that should be cancelled by SIC process. But during some cancellation error this term would be multiplied by the cancellation term given by the symbol ϵ.

4.2 Efficiency Analysis of NOMA

In this dissertation we are mainly focussing on the throughput of NOMA. In this section we analyse the spectral efficiency (SE) of NOMA as well as the energy efficiency (EE) of NOMA Here we also include the static power consumption of the system as well. This is because of the power amplifiers and the used power by the transmitted signal. And the power used by the signal is the additive product of the signal power and the one used by its circuits. This power can be given by the equation

$$P = P_{total} + P_{static} \tag{4.2}$$

Energy efficiency (EE) is defined as the ratio of sum rate to the total used power at the BS.

$$EE = \frac{R_T}{P_{total}} = SE\,\frac{W}{P_{total}} \quad \text{(bits/joule)} \tag{4.3}$$

where SE is the spectral efficiency in bps/Hz.

The EE-SE relationship is consequently monotonic if more is the SE value then it the EE value will be less. But we can see that, when the circuit power is taken into consideration, the EE increases in the low SE region and vice versa. From the figure, the highest point of the curve or the derivative of the EE-SE relationship is where the system is the most energy efficient. This point is referred to as the *green point*. For a fixed P_{total}, the EE-SE relationship is linear with a positive slope of R_T/P_{total}.

4.3 Results

Results regarding the simulation of the rates of users in a NOMA system considering the impact of imperfect cancellation and its efficiency analysis.

4.3.1 Simulation Parameters

To analyze the performance, a simulation setup was created in MATLAB 2019a. In the setup 2 users are considered in an AWGN channel with Power Spectral Density N_0 and power is allocated both users and the throughputs are calculated. The major simulation parameters are given in Table 4.1.

Parameter	Value
Channel Coefficient between BS and User1	10 dB, 20 dB
Channel Coefficient between BS and User2	10dB, 0 Db
Power Spectral Density, N_0	−150 dBW/Hz
Total System Bandwidth, W	5 MHz
Total Downlink transmit Power Budget, P	1 dBm
Power Allocated to User1	A
Power Allocated to User2	1- α
α- Bandwidth Splitting Factor in NOMA	varies from 0 to 1
α- Bandwidth Splitting Factor in OFDMA	varies from 0 to 1
Rate of User1	o/p
Rate of User2	o/p
Imperfectness Parameter, ε	0%, 1%, 5%, 10%
Power Consumed by circuitry, P_{static}	100 W
Energy Efficiency	o/p
Spectral Efficiency	o/p

Table 4.1. Simulation Parameters to show the impact of imperfect cancellation and SE-EE trade off of NOMA and OFDMA.

4.3.2 Results of the Impact of imperfect cancellation

From equation (4.1), we are simulating the impact of imperfect cancellation on the SNR of the 2 users. In Fig 4.1, we repeat the asymmetric downlink channel conditions but by considering the imperfect cancellation parameter. The case for perfect cancellation is the same as the results obtained in the previous section, i.e., Fig 3.5 and is given as reference. Here simulations are done to measure and review the effect of the cancellation parameter. The term (ε) is varied at values, i.e., 1, 5 and 10%.

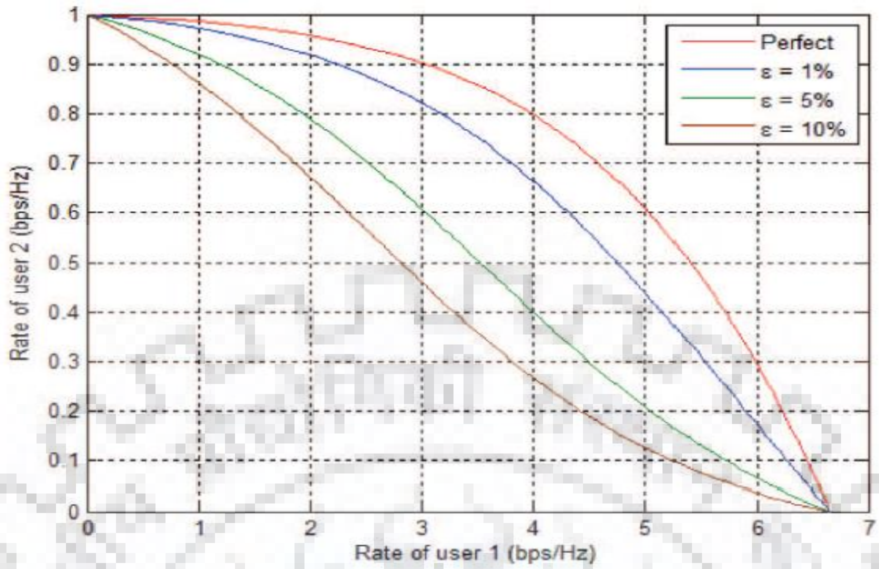

Fig. 4.1. Comparison of NOMA and OFDMA for various values of e

4.3.3 Results of SE-EE trade-off with NOMA

From equations (4.2) and (4.3), the SE –EE values of NOMA and OFDMA is plotted. And the results show significance advantage of NOMA and OFDMA. NOMA achieves higher SE and EE.

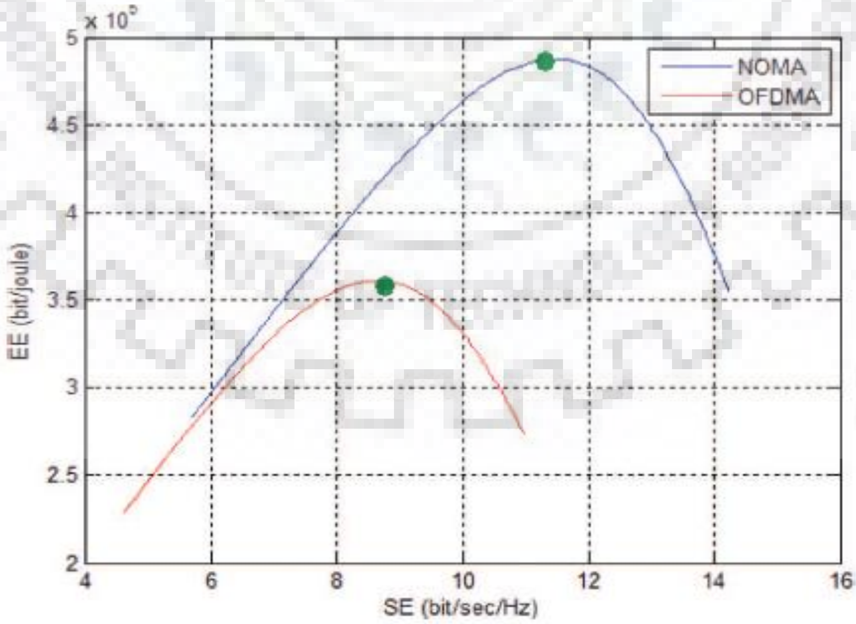

Fig. 4.2. SE-EE trade-off with NOMA and OFDMA

Chapter 5

Dynamic User Pairing For NOMA

5.1 Fundamentals of NOMA

In this section of the paper, the basics of downlink NOMA taking m number of users having different channel gains in a group are discussed. The superimposed signals are transmitted and a proper power is allocated to all the users and at the receiver end proper SIC mechanism is done to decode the signals.

In an m-user downlink user system, the transmitter sends the superimposed signals non-orthogonally over the same radio spectrum. And all the m receivers receive their desired signals and the interferences with noise of the channel. So to obtain the desired signal for a user, each user having the higher channel gain first decodes the users with dominant channel conditions and then negated them from the super imposed signal to improve the SINR.

In a multi user NOMA system, in order to detect the signal of a single user from the super imposed signal, SIC process should be done. All the users having higher channel conditions can be considered as interference and the signal can be detected because such users are allotted high power. But the users having less channel conditions are allotted high power and so they need to be removed by the desired user by SIC process until no such user is remaining. So in conclusion the lowest channel user or the user which is farthest from the BS does not need to perform SIC and can easily detect its own signal and the user having the highest channel conditions or the user which is closest to the BS need to do the SIC process highest amount of times. This is illustrated in the following figure.

Following Fig 5.1 shows a 3-user NOMA system where h_1, h_2, and h_3 are the channel gains of UE_1, UE_2, and UE_3, respectively. Also, it is assumed that x_1, x_2, and x_3 are the desired messages sent by

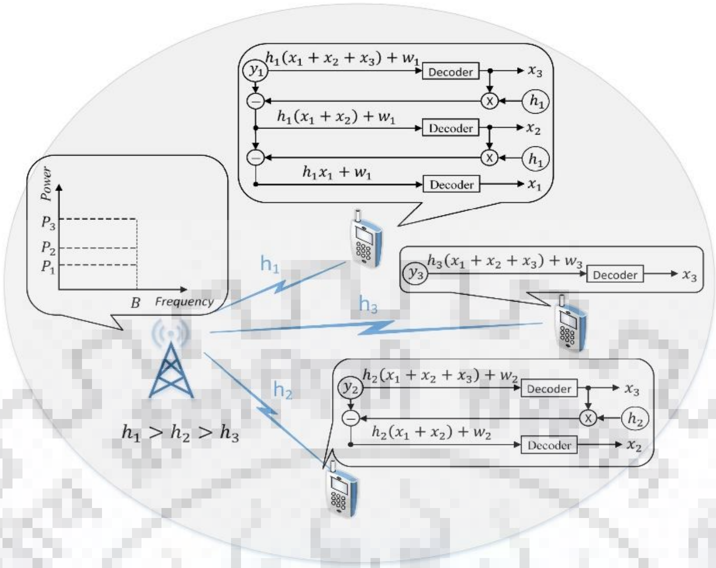

Fig. 5.1. Illustration of a 3-user downlink NOMA pairing with SIC at the UEs.

UE_1, UE_2, and UE_3, respectively, while w_1, w_2, and w_3 denote the additive white Gaussian noise (AWGN) of UE_1, UE_2, and UE_3, respectively.

If $h_1 > h_2 > h_3$, then UE_1 can successfully carry out SIC to remove both UE_2 and UE_3, whereas UE_2 can only remove interference from UE_3. Also, UE_3 suffers interferences from both UE_1 and UE_2, but cannot remove any of them because of relatively low power levels. Therefore, the achievable throughput for UE_i, $\forall i = 1,2,3, \ldots . n$ in an n-user NOMA can be given by

$$\hat{R}_i = \omega B \log_2\left(1 + \frac{P_i \gamma_i}{\sum_{j=1}^{i-1} P_j \gamma_i + \omega}\right), \forall i = 1,2,3, \ldots . n \quad (5.1)$$

where $\gamma_i = \frac{h_i}{N_0 B}$ the normalized channel gain with power spectral density denoted by N_0, ω is the number of radio channels and P_i is the power allotted to each user and B is the bandwidth of each channel.

The transmission power allotted to each user must be taken such a way that successful SIC takes place at the receiver. If P_1, P_2, and P_3 are the powers allotted for users UE_1, UE_2, and UE_3, then the following constraints must be satisfied the following for correct successive interference cancellation at UE_1

$$P_3\gamma_1 - (P_1 + P_2)\gamma_1 \geq P_{tol}, \tag{5.2a}$$

$$P_2\gamma_1 - P_1\gamma_1 \geq P_{tol}, \tag{5.2b}$$

where $P_1 + P_2 + P_3 \leq P_t$, P_t is the total power transmission budget. The above equations shows the conditions needed at UE_1 and user needs to remove the users UE_2 and UE_3 by SIC process before detecting its own. And it can be seen from the equations that the power allotted to the user to be detected first must be greater than the sum of all powers of the users which are having less power allotted to it. Similarly from equation (5.2b), it can be seen that the user to be detected is UE_2 and it should be greater than UE_1 by some value. This difference in both the cases to distinguish between the user to be detected and the users having less power allotted to it is given by P_{tol}.

So similarly if we consider that the SIC process is performed at UE_2 and then the equation can be rewritten in such a way that the power of UE_3 should be greater than the sum of users UE_1 and UE_2 by an amount denoted by P_{tol}. So the constraint that need to be satisfied at UE_2 is given by the expression

$$P_3\gamma_2 - (P_1 + P_2)\gamma_2 \geq P_{tol}. \tag{5.3}$$

Since the users are arranged in descending order of channel gains, we know that $\gamma_1 > \gamma_2$, and comparing the previous equations , it can be seen that if equation (5.3) is satisfied then equation (5.3) holds.

So the necessary constraints for proper allocation of power can be given by the equations (5.2b) and (5.3).

The above equations can be generalized as the SIC constraints as

$$P_i\gamma_{i-1} - \sum_{j=1}^{i-1} P_j\gamma_{i-1} \geq P_{tol}, i = 2,3,\cdots,m. \tag{5.4}$$

And the SIC constraints can be proved by the following Lemma

Lemma1(Maximum Transmit Power for the Highest Channel Gain User in a Downlink NOMA Cluster): "The maximum transmission power allocation to the highest channel gain user in the downlink NOMA system cluster must be smaller than $\frac{P_t}{2^{m-1}}$, where m is the total no of users in the cluster and P_t is the total downlink transmission power budget for the given NOMA cluster".

Proof: In order to prove the Lemma, let us consider a 2 –user system and applying the SIC conditions to it, we get the following equations

$$P_2\gamma_1 - P_1\gamma_1 \geq P_{tol}, \tag{5.5}$$

$$P_1 + P_2 \leq P_t, \tag{5.6}$$

The maximum allotted power to the user with the best channel condition can be given by

$$P_{1(max)} \leq \frac{P_t - \delta}{2}, \tag{5.7}$$

where $\delta = \frac{P_{tol}}{\gamma_1}$ is defined as the minimum power difference required for efficient SIC. Similarly maximum power for 2nd highest and the highest is given as

$$P_{2(max)} \leq \frac{P_t - \delta}{2},$$
$$P_{1(max)} \leq \frac{P_t - \delta}{2^2} - \frac{\delta}{2}. \tag{5.8}$$

Therefore, for an *m*-user

$$P_{1(max)} \leq \frac{P_t - \delta}{2^{m-1}} - \frac{\delta}{2^{m-2}} - \cdots - -\frac{\delta}{2} \approx \frac{P_t}{2^{m-1}}. \tag{5.9}$$

This is the result given in **Lemma 1**.

5.2 Key issues for User Pairing in Downlink NOMA

The practical considerations considered for user pairing or clustering is given below.

After performing SIC at the receiver end, we can see from the equation of the rate of the highest channel gain that it depends on its own channel conditions and power allotted to it. And so even if low amount of the available power is allotted to this user, the impact of the low power level on the sum throughput will be minimal. As a result the highest channel gain user has a very high dependency on the sum throughput. For this reason, every high channel gain user should be put into different clusters while using user pairing algorithm since it will vastly increase the individual rate.

Similarly to improve the rate of the users having poor conditions, it is better to group them with users having good channel conditions. This is because, as we explained before, the throughput of the high channel gain users depend only on the power levels and the channel conditions and not the interference of other users. So low power level is required for such users thereby leaving a large portion of the total power for the users having low channel conditions. So the main conclusion of the user pairing algorithm is the user having highest channel conditions with the user having lowest channel conditions into the same NOMA cluster, while the user having 2^{nd} highest channel gain conditions is paired with the user having 2^{nd} lowest channel gain conditions into another NOMA cluster, and so on.

And the rate of the rest of the users follows the same method. Since we can see that the channel gain in the numerator and denominator of the throughput equation is the same. And we can also see that the power level in the numerator is greater than the sum of the power of the users having higher channel conditions as said by the SIC constraints mentioned in the previous section. So, the individual and sum rate of the rest of the users in a NOMA depends mainly on the power levels.

By taking these considerations into account a user paring algorithm is designed for NOMA system which improves the rate further.

5.3 User Pairing Algorithm

Based on discussions in the previous section, we can categorize the users into 2 classes. The users in the first class, denoted as α, are having high channel conditions and users in the second class is having less channel conditions, i.e.

$$\gamma_1, \gamma_2, \cdots, \gamma_\alpha \gg \gamma_{\alpha+1}, \gamma_{\alpha+2}, \cdots, \gamma_N.$$

Then, the implemented optimal user pairing algorithm can be given as

- Sort users : $\gamma_1 \geq \gamma_2 \geq \cdots \geq \gamma_\alpha \gg \gamma_{\alpha+1} \geq \gamma_{\alpha+2} \geq \cdots \geq \gamma_N$
- Selection of number of clusters, κ:

  if (α < N/2) then select κ = α:

  else (α ≥ N/2) then select, κ = N/2.

  (a) After selecting the number of clusters, group the users into the cluster according the following pattern

  1st cluster $= \{\gamma_1, \gamma_{\kappa+1}, \gamma_{2\kappa+1}, \cdots, \gamma_N\}$

  2nd cluster $= \{\gamma_2, \gamma_{\kappa+2}, \gamma_{2\kappa+2}, \cdots, \gamma_{N-1}\}, \cdots$

  κth cluster $= \{\gamma_\kappa, \gamma_{2\kappa}, \gamma_{3\kappa}, \cdots, \gamma_{N-\kappa-1}\}$

- if ((Nmod κ) == 0), Group the users into uniform cluster
  else, then uniform cluster size else different cluster size.

Illustration of user pairing of for different NOMA clusters is shown in Fig 5.2. We can see from the figure that the practical considerations discussed in the previous section has been followed. It can be seen that the highest channel user is grouped with the lowest one and so on. So the overall rate improvement can be seen from the simulation results in the following section proving the discussed statements.

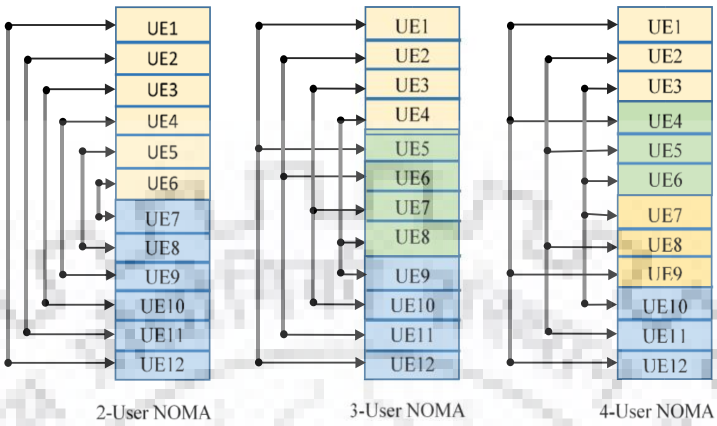

Fig 5.2. Representation of 2-user, 3-user, and 4-user downlink NOMA pairing for transmission of 12 users.

5.4 Results

In order to show the performances of NOMA systems, simulations are done for user pairing and optimal power allocations. Results of NOMA and OMA systems are compared to show the improvement of NOMA over OMA.

5.4.1 Simulation Parameters

To analyze the performance, a simulation setup was created in MATLAB 2019a. In the setup multiple users are considered in an AWGN channel with Power Spectral Density N_0 and the users are grouped into clusters according to the user clustering algorithm and power is allocated for all the users both users and the throughputs are calculated. The major simulation parameters are given in Table 5.1.

Simulation Parameters	**Values**
Total Bandwidth	20 MHz
Bandwidth of each sub band, B	180 kHz
No of sub bands, w	100
Downlink Power Budget, txpower	45 dBm
Uplink Power Budget, $P_{T'}$	32 dBm
Minimum Power required between the users, P_{tol}	9 dBm
Minimum Data Rate	100 Kbps
Number of Users	2, 3, 4...
Power Allocated to Each User	p1, p2, p3...
Throughput of Each User	r1, r2, r3...
Number of Clusters	2, 3, 4...
Number of Users per Cluster	2, 3, 4...
Channel Gain Coefficient	g1, g2, g3...

Table 5.1. Simulation parameters for downlink NOMA.

5.4.2 Results of Throughput Comparison of various Downlink NOMA

Since the transmit power level of the user having highest channel conditions is more than the sum of the power levels of other users, it is evident that as the no of users increases in an NOMA, drastically lowers the power for the user with highest channel conditions. So selecting the appropriate cluster size is required to maximize the throughput. Table 5.3 shows the comparison of 4UE, 3UE, 2UE NOMA and OFDMA of 12 users in a cell. In Table 5.3, we can see that the users are arranged in the descending order of channel conditions.

Cases 12 and 14 (Less distinct channel conditions of users): We can see from the Fig 5.7., in both the cases the throughputs for 4UE, 3UE, and 2UE are the same. But 4UE NOMA shows higher throughput for case 12 having better channel conditions and while the 2UE gets a higher rate even at lower channel conditions (case 14). From these observations we can say that higher cluster size would give better throughput for higher channel gain users and small cluster size would be better for lower channel gains.

Case 13 (More distinct channel conditions): Here we can see from the Fig that NOMA systems outperformances their OMA parts. And further we can see that the 4UE NOMA achieves a better throughput compared to its NOMA counterparts and OMA counter parts. Therefore, in a higher cluster size can be preferred in such cases.

Cases 3, 4, 6 (Number of users having higher channel conditions is equal to the number of clusters): In case 3, we can see that 3 users are having high channel conditions and therefore the number of clusters can be taken as 3 and number of users per cluster is 4. And here the 4UE NOMA produces maximum relative throughput. In case 4 we can see that, 4 users are having high channel conditions and therefore number of clusters can be taken as 4 and the number of users per cluster is 3 and. And here the 3UE NOMA produces maximum relative throughput. Thus, we can conclude that for higher channel condition system, the number of clusters can be selected in such a way that it is equal to the high channel users.

In cases 6 to 12, the throughputs are similar because more than half of the users have good channel conditions. But here we can see that in cases 1 to 3 higher cluster size should be picked since the number of higher channel condition users are. Finally, Fig. 5.3, 5.4, 5.5 and 5.6 shows individual and sum users' throughputs for 3-user downlink NOMA.

From the Figures we can compare the rate of individual user in the system and the corresponding rate of OMA users when the channel conditions are varied. The results obtained from simulations shows the performance of NOMA over OMA and at the same time its disadvantage can also be seen where in some cases, OMA has better performance than NOMA. This is due to the low power allotted to some users where as in OMA, equal power is allotted thereby increasing the throughput.

No	**Normalized Channel Gain (dB)**												**Sum- Throughput**			
	g1	**g2**	**g3**	**g4**	**g5**	**g6**	**g7**	**g8**	**g9**	**g10**	**g11**	**g12**	**4UE**	**3UE**	**2UE**	**OMA**
1	40	15	14.5	14	13.5	13	12.5	12	11.5	11	10.5	10	**10.3**	9.5	8.2	6.2
2	40	39.5	15	14.5	14	13.5	13	12.5	12	11.5	11	10.5	**15.9**	14.2	11.8	9.8
3	40	39.5	39	15	14.5	14	13.5	13	12.5	12	11.5	11	**19.7**	17.3	14.7	11
4	40	39.5	39	38.5	15	14.5	14	13.5	13	12.5	12	11.5	20.3	**20.9**	15.6	11.5
5	40	39.5	39	38.5	38	15	14.5	14	13.5	13	12.5	12	20.8	**21.2**	15.8	12.7
6	40	39.5	39	38.5	38	37.5	15	14.5	14	13.5	13	12.5	21	**21.7**	18	14.4
7	40	39.5	39	38.5	38	37.5	37	15	14.5	14	13.5	13	21.4	**21.9**	19.7	15
8	40	39.5	39	38.5	38	37.5	37	36.5	15	14.5	14	13.5	**21.8**	21.8	20.2	15.2
9	40	39.5	39	38.5	38	37.5	37	36.5	36	15	14.5	14	**22.1**	22.1	21	16
10	40	39.5	39	38.5	38	37.5	37	36.5	36	35.5	15	14.5	**22.8**	22.7	21.3	16.3
11	40	39.5	39	38.5	38	37.5	37	36.5	36	35.5	35	15	**22.8**	22.7	21.3	16.6
12	40	39.5	39	38.5	38	37.5	37	36.5	36	35.5	35	34.5	**22.9**	22.6	21.7	16.7
13	40	37	34	31	28	25	22	19	16	13	10	7	**19.1**	18.9	16.6	10.5
14	11	10.5	10	9.5	9	8.5	8	7.5	7	6.5	6	5.5	3.1	**3.3**	**3.4**	2.9

Table 5.2 sum-throughput of different NOMA and OMA systems with 12 downlink users for different channel conditions.

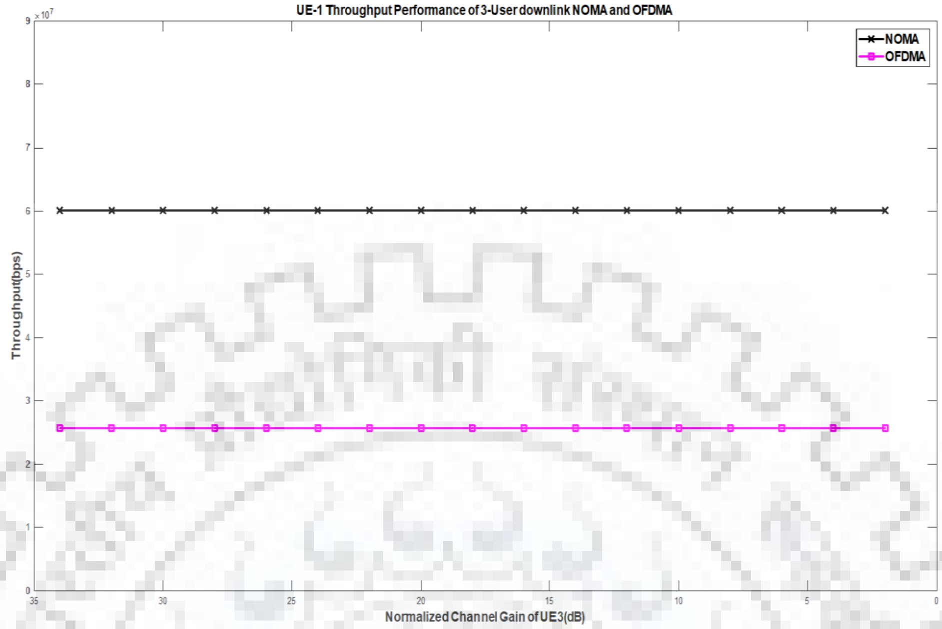

Fig. 5.3. Throughput performances of UE-1 in 3-User Downlink NOMA and OMA.

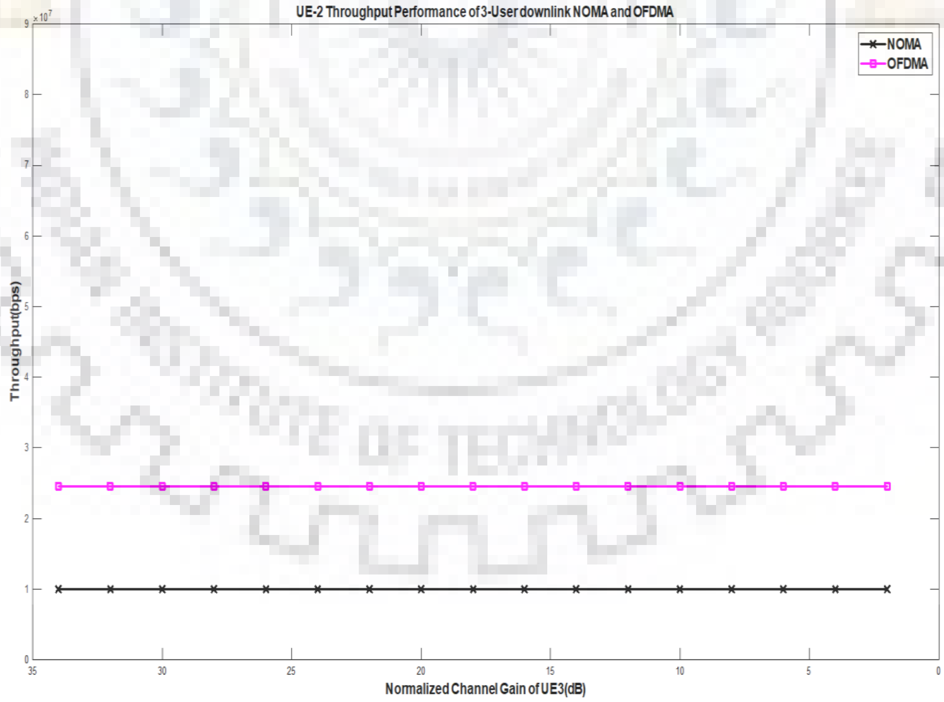

Fig. 5.4. Throughput performances of UE-2 in 3-User Downlink NOMA and OMA

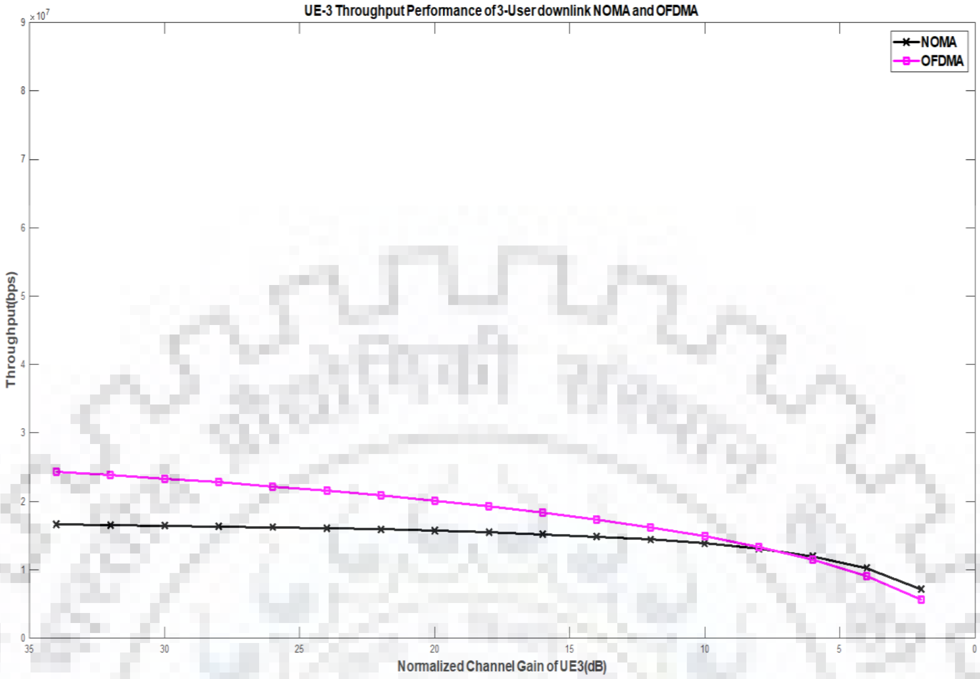

Fig. 5.5. Throughput performances of UE-3 in 3-User Downlink NOMA and OMA.

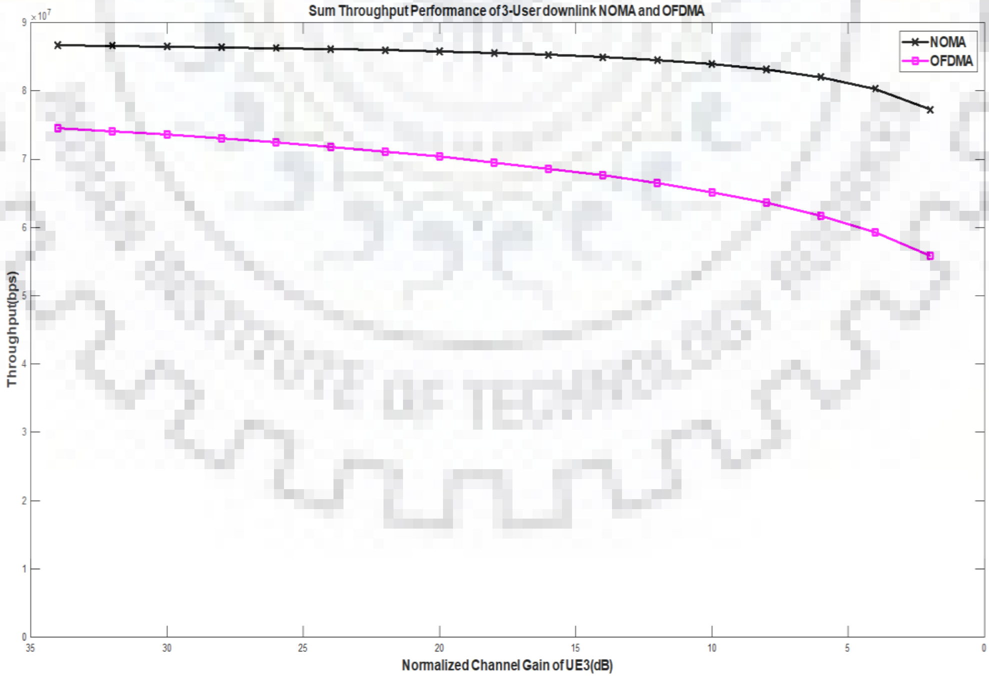

Fig. 5.6. Sum Throughput performances of 3-User Downlink NOMA and OMA.

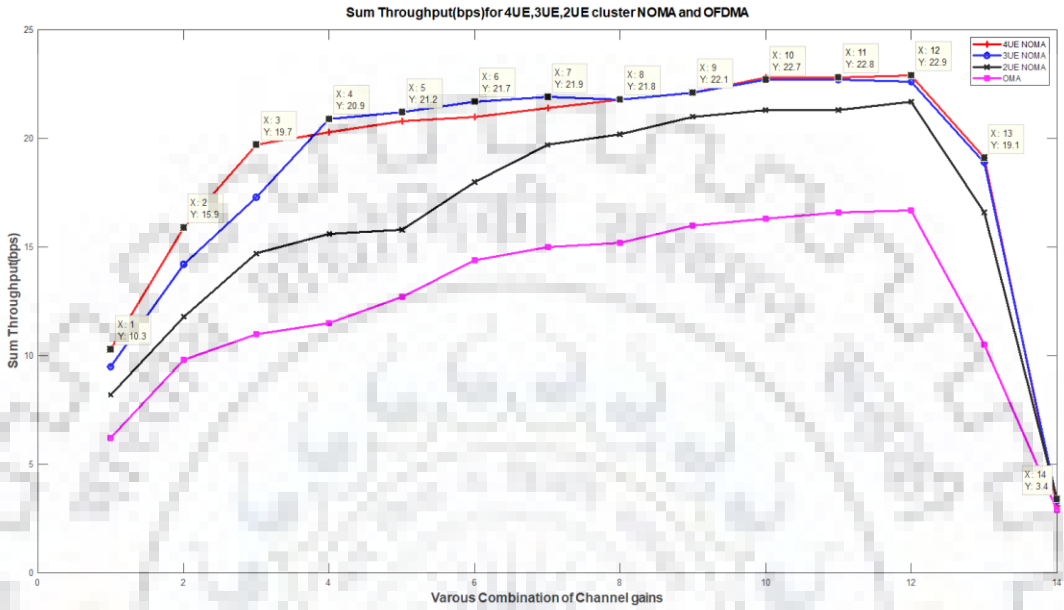

Fig. 5.7. Sum Throughput performances of 4Ue, 3UE, 2UE and OMA for 12 users.

Fig 5.7 shows the simulation results of the user clustering algorithm for 12 users. Here the 12 users are grouped into either a 2UE cluster, 3UE cluster and 4UE cluster and the power allocations are done accordingly and the results of the above system are compared with OMA system.

Chapter 6

Optimal Power Allocations in NOMA

6.1 Network Model and Assumptions

Here let us discuss about the system model of NOMA by considering N number of users. In the system, total N number of users are present and these N users are scheduled into different sub bands such a way that N number of users are simultaneously transmitted. The number of sub bands is denoted by $\Omega = B_T/B$ where B_T is the total bandwidth and B is the bandwidth of each sub band. Inside each sub band the users are transmitted non orthogonally which forms a cluster. One of the constraints of NOMA is that at least one user should occupy a cluster and on user should be in more than one cluster. From the above statement we can conclude that the no of clusters should lie in the region $1 \le k \le N/2$ and thus we can say that the no of users per cluster should lie between $2 \le m \le N$. And the no of sub bands for each cluster lies between $1 \le \omega \le \Omega$.

By taking into consideration the above two constraints mentioned in the previous statements, we then introduce a variable $\beta_{i,j}$ which becomes 1 when i-th user is paired with j-th user in a cluster. And so according with the presence of this variable, the constraints will be satisfied. Now for the sake of simplicity, let us arrange the users in a descending order of their channel gains represented as $\gamma_1 > \gamma_2 > \gamma_3 > \cdots > \gamma_N$.

Now, let us define a variable $\beta_{i,j}$ as follows:

$$\beta_{i,j} = \begin{cases} 1, & \text{if a user i is paired into cluster j} \\ 0, & \text{ow} \end{cases} \tag{6.1}$$

where $j = 1,2,,\cdots,N/2$ and $i = 1,2,\cdots,N$.

Now we are formulating a maximizing problem by considering user pairing and optimal power allocation and it is given as

$$\max_{\omega,\beta,P} \sum_{j=1}^{\frac{N}{2}} \sum_{i=1}^{N} \omega_j \beta_{i,j} \log_2 \left(1 + \frac{P_i \gamma_i}{\sum_{k=1}^{i-1} \beta_{k,j} P_k \gamma_i + \omega_j} \right)$$

$$\text{subject to } \mathbf{C_1}: \sum_{i=1}^{N} \beta_{i,j} P_i \le P_T,$$

$$\mathbf{C_2}: \sum_{j=1}^{\frac{N}{2}} \omega_j \beta_{i,j} \log_2 \left(1 + \frac{P_i \gamma_i}{\sum_{k=1}^{i-1} \beta_{k,j} P_k \gamma_i + \omega_j} \right) > R_i, \forall i, \tag{6.2}$$

$$\mathbf{C_3}: \left(\beta_{i,j} P_i - \sum_{k=1}^{i-1} \beta_{k,j} P_k \right) \gamma_{i-1} \ge P_{tol}, \forall i,$$

$$\mathbf{C_4}: \left(\sum_{j=1}^{\frac{N}{2}} \beta_{i,j} = 1, \forall i \right)$$

$$\text{AND} \left(\left(2 \le \sum_{i=1}^{N} \beta_{i,j} \le N \right) \text{OR} \left(\sum_{i=1}^{N} \beta_{i,j} = 0, \forall j \right) \right)$$

$$\mathbf{C_5}: \sum_{j=1}^{\frac{N}{2}} \beta_{i,j} \omega_j \le \Omega, \forall i, \mathbf{C_6}: \omega_j \in \{1,2,\cdots,\Omega\}, \forall j,$$

$$\mathbf{C_7}: \beta_{i,j} \in \{0,1\}, \forall i, j,$$

where R_i is minimum target rate, i.e., the throughput should be at least R_i which is given by the constraint C2. We know that the sum of the power allotted to the users should be equal to the total budget. This is given by the constraint C1. The SIC constraints are denoted by C3. The two constraints mentioned in this chapter which is satisfied by the variable $\beta_{i,j}$ is given by C4. C5 denotes the number of sub bands per cluster constraint and C6. C7 denotes integer variables.

6.2 Power Allocation using Convex Optimization

All the constraints discussed in the previous maximization problem are not needed for throughput maximization because the constraint denoted as C4 can be neglected due to the introduction of the variable $\beta_{i,j}$. And after the selection of number of clusters and allocation of users into them, the rate can be maximized inside the cluster itself, thereby taking the range of the number of users per cluster as $2 \leq m \leq N$.

In the system having m users whose normalized channel gains of $UE_1, UE_2, \cdots, UE_m$ are assumed to be $\gamma_1, \gamma_2, \cdots, \gamma_m$, respectively, and their respective target rates are represented as $R_1, R_2, \cdots, R_m$, where $R_i > 0$. $P_1, P_2, \cdots, P_m$ are the transmission powers for $UE_1, UE_2, \cdots, UE_m$, respectively. Again the rate maximization can be done using convex optimization and solutions satisfied by KKT conditions are formulated. Now the equation (6.2) can be rewritten by reducing the constraint C4 and the integer constraints as

$$
\begin{aligned}
&\max_{P} \omega B \sum_{i=1}^{m} \log_2 \left(1 + \frac{P_i \gamma_i}{\sum_{j=1}^{i-1} P_j \gamma_i + \omega}\right) \\
&\text{subject to:} \mathbf{C_1}: \sum_{i=1}^{m} P_i \leq P_t, \\
&\mathbf{C_2}: \omega B \log_2 \left(1 + \frac{P_i \gamma_i}{\sum_{j=1}^{i-1} P_j \gamma_i + \omega}\right) \geq R_i, \forall i, \\
&\mathbf{C_3}: P_i \gamma_{i-1} - \sum_{j=1}^{i-1} P_j \gamma_{i-1} \geq P_{tol}, \forall i = 2,3,\cdots,m,
\end{aligned}
\tag{6.3}
$$

where $\sum_{j=1}^{i-1} P_j \gamma_i$ is the inter ference of i-th user. R_i is minimum target rate, i.e., the throughput should be at least R_i which is given by the constraint C2. We know that the sum of the power allotted to the users should be equal to the total budget. This is given by the constraint C1. The SIC constraints are denoted by C3. And this problem is convex under the three constraints.

Closed Form Power Allocation:

In order to convert the optimization problem into algebraic solutions, Lagrange multiplier for each constraint is taken as λ, μ, ψ and the solution is given as

$\mathcal{L}(P, \lambda, \mu, \psi)$

$$
\begin{aligned}
&= \omega B \sum_{i=1}^{m} \log_2 \left(1 + \frac{P_i \gamma_i}{\sum_{j=1}^{i-1} P_j \gamma_i + \omega}\right) \\
&= \lambda\left(P_t - \sum_{i=1}^{m} P_i\right) + \sum_{i=1}^{m} \mu_i \left\{P_i \gamma_i - \left(\sum_{k=1}^{i-1} P_k \gamma_i - \omega\right) \right. \\
&\quad \left. \times (\varphi_i - 1)\right\} + \sum_{i=2}^{m} \psi_i \left(P_i \gamma_{i-1} - \sum_{l=1}^{i} P_l \gamma_{i-1} - P_{tol}\right),
\end{aligned}
\tag{6.4}
$$

where λ, μ_i, and ψ_j are the Lagrange multipliers, $\forall i = 1,2,3,\cdots, m$ and $\forall j = 2, 3, 4, \cdots, m$. Also, $\varphi_i = 2^{\frac{R_i}{\omega B}}$. Derivatives of equation (6.4) w.r.t. P_i, λ, μ_i, ψ_j, is taken as follows:

$$\frac{\partial \mathcal{L}}{\partial P_1^*} = \frac{\omega B \gamma_1}{P_1\gamma_1 + \omega} - \sum_{k=2}^{m} \frac{\omega B P_k \gamma_k^2}{(\sum_{l=1}^{k} P_l \gamma_k + \omega)(\sum_{l'=1}^{k-1} P_{l'}\gamma_k + \omega)} - \lambda + \mu_1\gamma_1 - \sum_{j=2}^{m}(\varphi_j - 1)\,\mu_j\gamma_j - \sum_{j=2}^{m}\psi_j\,\gamma_{j-1} \leq 0, \text{if} P_1^* \geq 0, \tag{6.5}$$

$$\frac{\partial \mathcal{L}}{\partial P_i^*} = \frac{\omega B \gamma_i}{\sum_{j=1}^{i} P_j\gamma_i + \omega} - \sum_{k=i+1}^{m} \frac{\omega B P_k \gamma_k^2}{(\sum_{l=1}^{k} P_l \gamma_k + \omega)(\sum_{l'=1}^{k-1} P_{l'}\gamma_k + \omega)} - \lambda + \mu_i\gamma_i - \sum_{k=i+1}^{m}(\varphi_k - 1)\,\mu_k\gamma_k + \psi_i\gamma_{i-1} - \sum_{j=i+1}^{m}\psi_j\gamma_{j-1} \leq 0, \text{if} P_i^* \geq 0, \forall i = 2,3,\cdots,m, \tag{6.6}$$

$$\frac{\partial \mathcal{L}}{\partial \lambda^*} = P_t - \sum_{i=1}^{m} P_i \geq 0, \text{if} \lambda^* \geq 0, \tag{6.7}$$

$$\frac{\partial \mathcal{L}}{\partial \mu_i^*} = P_i\gamma_i - (\sum_{j=1}^{i-1} P_j\gamma_i + \omega)(\varphi_i - 1) \geq 0, \text{if} \mu_i^* \geq 0, \forall i = 1,2,3,\cdots,m, \tag{6.8}$$

$$\frac{\partial \mathcal{L}}{\partial \psi_i^*} = P_i\gamma_{i-1} - \sum_{j=1}^{i-1} P_j\gamma_{i-1} - P_{tol} \geq 0, \text{if} \psi_i^* \geq 0, \forall i = 2,3,4,\cdots,m. \tag{6.9}$$

Firstly according to the number of constraints in the convex optimization problem, the number of Lagrange multipliers are taken and all the combinations of the multipliers needs to be satisfied by the KKT conditions. For 2m Lagrange multipliers, 2^{2m} combinations of the Lagrange multipliers needs to be checked. But this is very complex to accomplish. Because for m = 3, 4, ⋯, 10, then 64,256, ⋯, 1048576, needs to be considered respectively [18]. In this problem $P_i > 0$, ∀i = 1, 2, 3, ⋯, m; so as to obtain a fixed number of solutions for m variables we need exactly m equations [16]. So we need to check only $\binom{2m}{m}$ combinations. By considering the above statement, we can conclude that for 2-, 3-, 4-, and 6-user NOMA clusters, the Lagrange multiplier combinations satisfying the KKT conditions are 2, 4, 8, and 32, respectively. So this can be generalized to give 2^{m-1}.

By solving the solutions for different values of m by considering the primal feasibility and dual feasibility property of KKT conditions by setting the values of all the combinations of Lagrange multipliers greater than or equal to zero and then checking if the constraints remain true. By doing this the solutions are obtained for different values of m giving the optimal power equations.

$$
\begin{gathered}
P_t - \sum_{i=1}^{4} 1\, P_i = 0 \\
P_i\gamma_i - \left(\sum_{j=1}^{i-1} 1\, P_j\gamma_i + \omega\right)(\varphi_i - 1) = 0, \ \ \forall i = 2,3,4, \\
P_i\gamma_i - \left(\sum_{j=1}^{i-1} 1\, P_j\gamma_i + \omega\right)(\varphi_i - 1) > 0, \ \ \forall i = 1 \\
P_i\gamma_{i-1} - \sum_{j=1}^{i-1} 1\, P_j\gamma_{i-1} - P_{tol} > 0, \ \ \forall i = 2,3,4,
\end{gathered}
\tag{6.10}
$$

Equations (6.10) gives the solution by converting the algebraic solutions by satisfying both the feasibility condition of KKT.

$$\begin{aligned}
P_1 &= \frac{P_t}{\varphi_2\varphi_3\varphi_4} - \frac{\omega(\varphi_2-1)}{\varphi_2\gamma_2} - \frac{\omega(\varphi_3-1)}{\varphi_2\varphi_3\gamma_3} - \frac{\omega(\varphi_4-1)}{\varphi_2\varphi_3\varphi_4\gamma_4},\\
P_2 &= \frac{P_t(\varphi_2-1)}{\varphi_2\varphi_3\varphi_4} + \frac{\omega(\varphi_2-1)}{\varphi_2\gamma_2} - \frac{\omega(\varphi_2-1)(\varphi_3-1)}{\varphi_2\varphi_3\gamma_3}\\
&\quad - \frac{\omega(\varphi_2-1)(\varphi_4-1)}{\varphi_2\varphi_3\varphi_4\gamma_4},\\
P_3 &= \frac{P_t(\varphi_3-1)}{\varphi_3\varphi_4} + \frac{\omega(\varphi_3-1)}{\varphi_3\gamma_3} - \frac{\omega(\varphi_3-1)(\varphi_4-1)}{\varphi_3\varphi_4\gamma_4},\\
P_4 &= \frac{P_t(\varphi_4-1)}{\varphi_4} + \frac{\omega(\varphi_4-1)}{\varphi_4\gamma_4}.
\end{aligned} \tag{6.11}$$

The exact power allocation equations for m=4 is given in the equation (6.11) in terms of the minimum power difference between users, channel gain, minimum rate and no of sub bands.

6.3 Results

In order to show the performances of NOMA systems, simulations are done for user pairing and optimal power allocations. Results of NOMA and OMA systems are compared to show the improvement of NOMA over OMA. The major simulation parameters are shown in Table 6.1.

6.3.1 Simulation Parameters

To analyze the performance, a simulation setup was created in MATLAB 2019a. In the setup multiple users are considered in an AWGN channel with Power Spectral Density N_0 and the users are grouped into clusters according to the user clustering algorithm and power is allocated for all the users both users and the throughputs are calculated.

Simulation Parameters	Values
Total Bandwidth	20 MHz
Bandwidth of each sub band, B	180 kHz
No of sub bands, w	100
Downlink Power Budget, txpower	45 dBm
Uplink Power Budget, $P_{T'}$	32 dBm
Minimum Power required between the users, P_{tol}	9 dBm
Minimum Data Rate	100 Kbps
Number of Users	2, 3, 4…
Power Allocated to Each User	p1, p2, p3…
Throughput of Each User	r1, r2, r3…
Number of Clusters	2, 3, 4…
Number of Users per Cluster	2, 3, 4…
Channel Gain Coefficient	g1, g2, g3…

Table 6.1. Simulation Parameters to show the multi user throughput of NOMA and OMA

6.3.2 Results of multiple user throughput of NOMA and its comparison with OMA

Fig. 6.1. 6.2 and 6.3 shows the results obtained from simulation of the sum-throughput and individual throughput of 2-user downlink NOMA cluster and it is compared with and OMA system where equal power and bandwidth is allotted to all the users in the system. Fig 6.1. shows the rate achieved by UE1 and it can be seen that it an high advantage over OMA case where the target rate of rate constraint is set as 100 Kbps. UE1 is the user which is having the highest channel condition or it is the user which is closest to the base station, And so as mentioned in the section 5.2 we can see that this UE1 has a very high significance on the individual rate and the sum rate because after SIC process all the users will be removed and its rate depends only on the power allotted to it and its channel conditions. And we can see from the results that although very low power is given to this user, its throughput is much better than the case of OMA. Fig 6.3. shows the sum rate which is also much higher and shows the performance of NOMA.

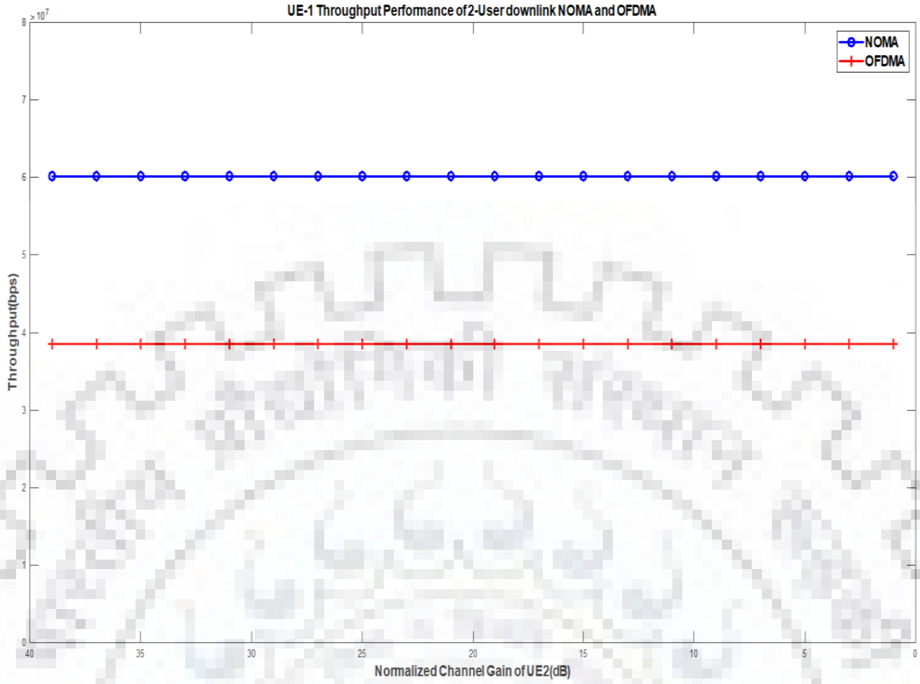

Fig. 6.1. Throughput performances of UE-1 in 2-User Downlink NOMA and OMA

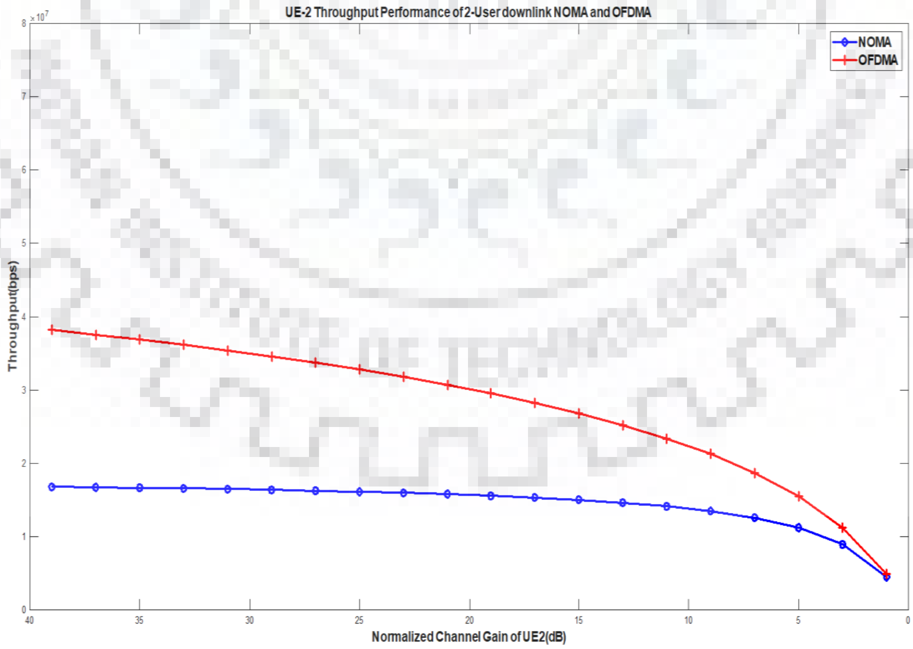

Fig. 6.2. Throughput performances of UE-2 in 2-User Downlink NOMA and OMA.

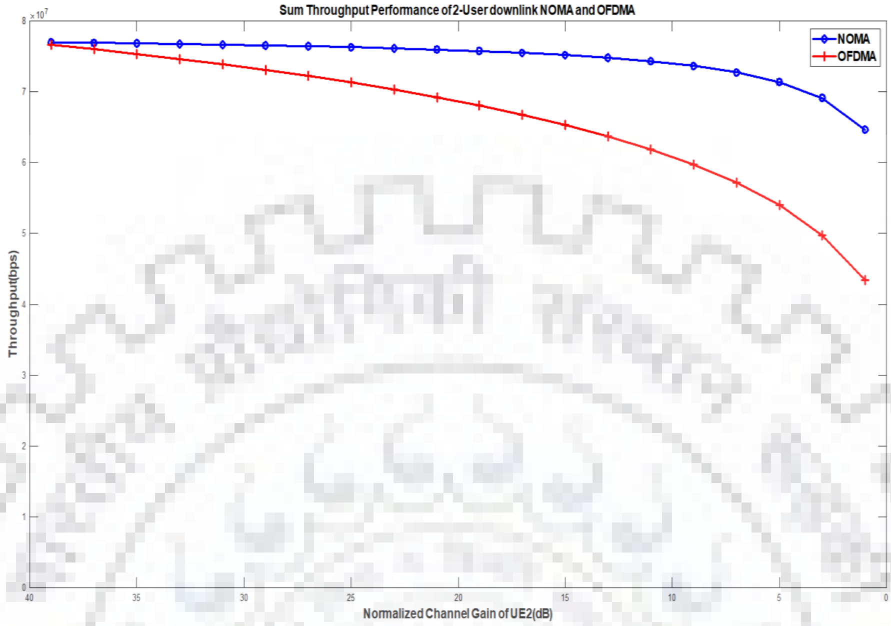

Fig. 6.3. Sum Throughput performances of 2-User Downlink NOMA and OMA.

Similarly to improve the rate of the users having poor conditions, it is better to group them with users having good channel conditions. This is because, as we explained before, the throughput of the high channel gain users depend only on the power levels and the channel conditions and not the interference of other users. So low power level is required for such users thereby leaving a large portion of the total power for the users having low channel conditions. So the main conclusion of the user pairing algorithm is the user having highest channel conditions with the user having lowest channel conditions into the same NOMA cluster, while the user having 2nd highest channel gain conditions is paired with the user having 2nd lowest channel gain conditions into another NOMA cluster, and so on.

So following these practical considerations we can see clearly from the simulation results the performance of NOMA is improved.

From the results we can conclude that OMA does not work efficiently at low channel conditions but NOMA shows improvement because the poor channel user is paired with high channel user to increase the individual as well as sum rate of the system.

6.3.2 Results of optimal power allocation of N-User NOMA

Table 6.2. Shows the optimal power allocation algorithm equations for 2-, 3-, 4-, 5-, and 6-user NOMA systems required to allocate the downlink transmit power budget to various users.

Cluster Size	**Optimal Power equations**
2 - Users	$txpower - p_1 - p_2 == 0$ $g_2 * p_2 - (si - 1) * (w + g_2 * p_1) == 0$
3 - Users	$txpower - p_1 - p_2 - p_3 == 0$ $g_2 * p_2 - (si - 1) * (w + g_2 * p_1) == 0$ $g_3 * p_3 - (si - 1) * (w + g_3(p_1 + p_2) == 0$
4 - Users	$txpower - p_1 - p_2 - p_3 - p_4 == 0$ $g_2 * p_2 - (si - 1) * (w + g_2 * p_1) == 0$ $g_3 * p_3 - (si - 1) * (w + g_3(p_1 + p_2) == 0$ $g_4 * p_4 - (si - 1) * (w + g_4(p_1 + p_2 + p_3) == 0$
5 - Users	$txpower - p_1 - p_2 - p_3 - p_4 == 0$ $g_2 * p_2 - (si - 1) * (w + g_2 * p_1) == 0$ $g_3 * p_3 - (si - 1) * (w + g_3(p_1 + p_2) == 0$ $g_4 * p_4 - (si - 1) * (w + g_4(p_1 + p_2 + p_3) == 0$ $g_5 * p_5 - (si - 1) * (w + g_5(p_1 + p_2 + p_3 + p_3) == 0$

6 - Users	$txpower - p_1 - p_2 - p_3 - p_4 == 0$ $g_2 * p_2 - (si - 1) * (w + g_2 * p_1) == 0$ $g_3 * p_3 - (si - 1) * (w + g_3(p_1 + p_2) == 0$ $g_4 * p_4 - (si - 1) * (w + g_4(p_1 + p_2 + p_3) == 0$ $g_5 * p_5 - (si - 1) * (w + g_5(p_1 + p_2 + p_3 + p_4) == 0$ $g_6 * p_6 - (si - 1) * (w + g_6(p_1 + p_2 + p_3 + p_4 + p_5) == 0$
13- Users	$txpower - p_1 - p_2 - p_3 - p_4 - p_5 - p_6 - p_7 - p_8 - p_9 - p_{10} - p_{11} - p_{12} - p_{13} - p_{14} - p_{15} == 0$ $g_2 * p_2 - (si - 1) * (w + g_2 * p_1) == 0$ $g_3 * p_3 - (si - 1) * (w + g_3(p_1 + p_2) == 0$ $g_4 * p_4 - (si - 1) * (w + g_4(p_1 + p_2 + p_3) == 0$ $g_5 * p_5 - (si - 1) * (w + g_5(p_1 + p_2 + p_3 + p_4) == 0$ $g_6 * p_6 - (si - 1) * (w + g_6(p_1 + p_2 + p_3 + p_4 + p_5) == 0$ $g_7 * p_7 - (si - 1) * (w + g_7(p_1 + p_2 + p_3 + p_4 + p_5 + p_6) == 0$ $g_8 * p_8 - (si - 1) * (w + g_8(p_1 + p_2 + p_3 + p_4 + p_5 + p_6 + p_7) == 0$ $g_9 * p_9 - (si - 1) * (w + g_9(p_1 + p_2 + p_3 + p_4 + p_5 + p_7 + p_8) == 0$ $g_{10} * p_{10} - (si - 1) * (w + g_{10}((p_1 + p_2 + p_3 + p_4 + p_5 + p_6 + p_7 + p_8 + p_9) = 0$ $g_{11} * p_{11} - (si - 1) * (w + g_{11}(p_1 + p_2 + p_3 + p_4 + p_5 + p_6 + p_7 + p_8 + p_9 + p_{10}) == 0$ $g_{12} * p_{12} - (si - 1) * (w + g_{12}(p_1 + p_2 + p_3 + p_4 + p_5 + p_6 + p_7 + p_8 + p_9 + p_{10} + p_{11}) == 0$ $g_{13} * p_{13} - (si - 1) * (w + g_{13}(p_1 + p_2 + p_3 + p_4 + p_5 + p_6 + p_7 + p_8 + p_9 + p_{10} + p_{11} + p_{12}) == 0$

Table 6.2. Optimal Power Equation for 2-, 3-, 4-, 5-, 6-, and 13- User NOMA.

Table 6.2. Shows the results obtained after simulations of 2, 3, 4, 5, 6 and 13 Users in a downlink NOMA system. Firstly the equations required to derive the optimal power allocation algorithm is obtained by considering various parameters such as downlink transmission power budget from the Base station to the users, the power allocated to each of the users, the minimum power difference required to properly decode the signals at the receiver end, the number of resource blocks in the system and the channel gain from the base station to each user.

After deriving the equations containing all the above parameters and satisfying all the constraints mentioned in the previous sections, these equations are solved to obtain all the different powers allocated to each of the users for a 15 user downlink NOMA system. And it is evident that the power is allocated such a way that the user with higher channel gain will be given low amount of power and the user with lower channel gain will be given higher amount of power from the total downlink transmission power budget.

Similarly optimal power equations can be derived for n number of users and can be plotted. But for demonstration purposes a random number of users as 2, 3, 4, 5, 6 and 15 has been taken. Finally Fig 6.4 shows the user clustering and power allocation scheme for 15 Users in a NOMA system and is compared with an OMA system.

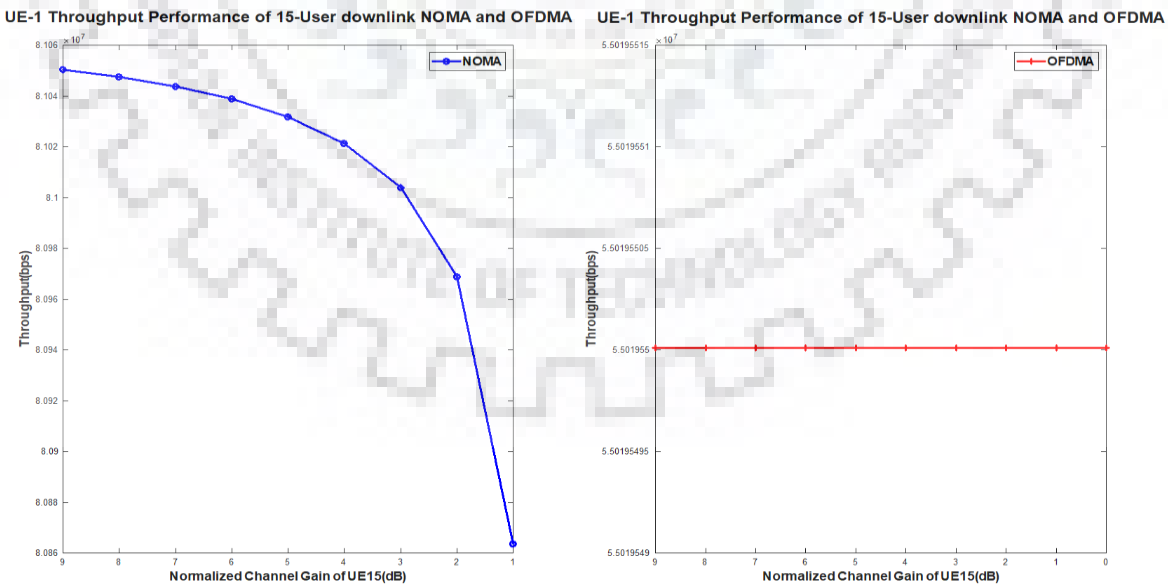

Fig. 6.4. Throughput performances of UE-1 for 15 Users of NOMA and OMA.

Conclusions and Future Scope

Firstly we go through the necessity of NOMA, concept, system model and fundamentals of NOMA. For downlink NOMA, we pair all the users present in the system into different clusters on the basis of some practical considerations. After pairing the users into groups, each user is allotted different power levels based on its distance from the base station or its channel conditions. This is done by using a convex optimization problem of maximizing the throughput of the system by considering three main constrains such as the minimum rate necessity of users, the power constraints of the users and SIC constraints. Since the above problem is a mixed integer non-linear programming (MINLP) problem, it is carried out by firstly discussing and implementing a user pairing scheme and then allocation of the downlink power budget in a way to maximize not only the sum throughput of the system but also the individual throughputs of all the users in the NOMA system. After grouping the users into NOMA clusters using a grouping algorithm, we obtain the optimal power allocation algorithm that maximizes both the individual and sum-throughput of the wireless system and thus maximizing the overall rate. Using Karush Kuhn Tucker conditions, optimal power allocations for any cluster size is evaluated. Simulations are done based on these methods and the results obtained after user pairing and power allocation is compared with that of an OFDMA system.

From the results we observed that the user having distinctive channel conditions are giving impressive throughput performance for NOMA systems in comparison with its OMA counterparts. And as the cluster size is increased after a particular value, then the performance of NOMA degrades. And as a result some issues may occur such as SIC error propagation and inter cell interference which are still under consideration. In this dissertation, we have obtained the results of NOMA in the case of ideal SIC, i.e., we are assuming that the interference is canceled perfectly by each user. But if that is not the case then, the performance may deeply affect the throughput of the system. Another disadvantage of NOMA is that, each signal that is transmitted has to be encoded, modulated at the base station while the advanced SIC receiver should be able to successfully and efficiently demodulate, decode and re-modulate the signals which are having higher allotted power to it. Due to this reason, for large NOMA clusters, error propagation will be a problem which will adversely affect the performance of NOMA. Furthermore, inter cell interference is also a major drawback of NOMA.

Further, in the future, non-orthogonal multiple access using SIC principle can be used corroboration with multiuser multiple-input multiple-output (MIMO) wireless systems In MIMO systems, in order to increase the performance the no of antennas used is increased and as a result the data will be further strengthened. This is done by making the no of antennas as the user end greater than the no of antennas at the BS. Since this is the case, we can successfully group the antennas at the user side into clusters such a way that they are either equal to or greater than the no of antennas at the base station side.

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