POLITECNICO DI TORINO

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# Contemporary and future 5G wireless communication systems: A survey of basic physical layer techniques and performance analysis

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# Abstract

The rapid evolution of technologies and use cases cellular networks increased the necessity for next-generation cellular systems. To coup, this demand the 3GPP formed a task force and started to develops the next-generation systems.
In this work first, we have analyzed the next-generation mobile network, a.k.a. 5G, in terms of new technologies that are going to be adopted in its physical layer. One of the choke points of fast and reliable mobile networks is the handling of multiple users. Many models are studied or even used in the previous generations of mobile networks. But with the rapid growth of the damned data rate of those techniques can not handle the required rate within a good margin of performance. One of the main contenders to replace the current generation OFDMA technique is the use of Non-orthogonal multiple access techniques (NOMA). After a brief review of various types of NOMA, we focused on power Domain NOMA due to its performance and extensive study over it among the scholars and we demonstrated the preeminence of NOMA over conventional OMA techniques through computer simulations in various performance metrics.
In the final chapter, we presented some of the new possible development to NOMA to ever more increase its performance to stay along with newly developed needs.

Keywords: **5G; Non-orthogonal Multiple Access; NOMA; PD-NOMA; Ergodic Sum Rate;Outage Performance**

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# Acronyms

**CP** Cyclic Prefix.

**FDD** Frequency-division duplexing.

**IoT** Internet of Things.

**MIMO** multiple-input and multiple-output.

**NOMA** Non-orthogonal Multiple Access.

**NR** New Radio.

**OFDM** Orthogonal Frequency Division multiplexing.

**OFDMA** Orthogonal Frequency Division Multiple Access.

**OMA** Orthogonal Multiple Access.

**PAPR** Peak to Average Power Ratio.

**SNR** Signal to noise ratio.

**TDD** Time-division duplexing.

**TDMA** Time Division Multiple Access.

# Chapter 1

# Introduction

In this chapter we briefly review the main aspects of 5G systems in physical layer.

## 1.1 General Description of Next Generation of Cellular Networks

Fifth Generation Communication Systems or in short 5G is next generation of communication system designed to enhance user experience of User Equipment (UE) or Mobile device in many terms, such as Latency, Available Bandwidth and Data Rate. Also in other hand it introduces many other application to the current Mobile Broadband system. The governing body of 5G, 3GPP (Third Generation Partnership Project) is going to deploy system by 2020 in phase 1. Anyhow 3GPP published its release 15 which corresponds to the 5G phase one. Currently 3GPP is finalizing the release 16 which corresponds to the 5G phase 2. 3GPP put following verdict on the difference of the two phases:
Phase one[3]:

* Design New Radio
* Massive Machine to Machine communication
* Internet of Things (IoT)
* Using unlicensed spectrum specially in high frequencies
* Network slicing and Software defined networking

* Latency critical and Ultra reliable systems such as Vehicle to Vehicle transmission

Phase two[3]:

. Vehicle to X with added features

. Industry wide IoT

. Further enhancement in ultra-reliable and low latency Systems

. Further enhancement in New Radio

. Improved efficiency in general system of 5G

. SDN networking

As it said before, the roadmap published by 3GPP, illustrated that they want to finalize the Release 16 by end of 2020 so it can be commissioned from 2022. As you can notice the phase 2 of 5G is generally designed to enhance the phase 1 which they want deploy it rapidly before 2020 by improving it installed infrastructure instead of deploying new ones. After deployment of phase 1 and 2, the 3GPP wants to continue working on the 5G in the upcoming releases. Mainly in release 17. The release 17 in currently under discussion to embed more features into 5G such as:

+ Possible usage of more unlicensed spectrum

+ New radio system for IoT and other improvement

+ Power consumption enhancements

+ Smarter Control plane and many more feature which may or may not include in finale version of standard. 3GPP hopes to finalize Release 17 by 2021.

In next sections major aspects of 5G physical layer will be surveyed.

## 1.2 MIMO and Massive MIMO

A multiple-input and multiple-output (MIMO) technique in communication system is a method for increasing the capacity of user data rate with increasing number of channel which are transmitting and receiving. In modern definition of MIMO the data transmitted simultaneously with other signals in the same band. And at the receiver, the original data would be extracted. This technique although uses multiple amount of antenna but it is essentially different method to improve system performance. A simple MIMO system can be portrayed like in figure 1.1 , where multiple antenna at transmitter, send messages in different channels to antennas of receiver.

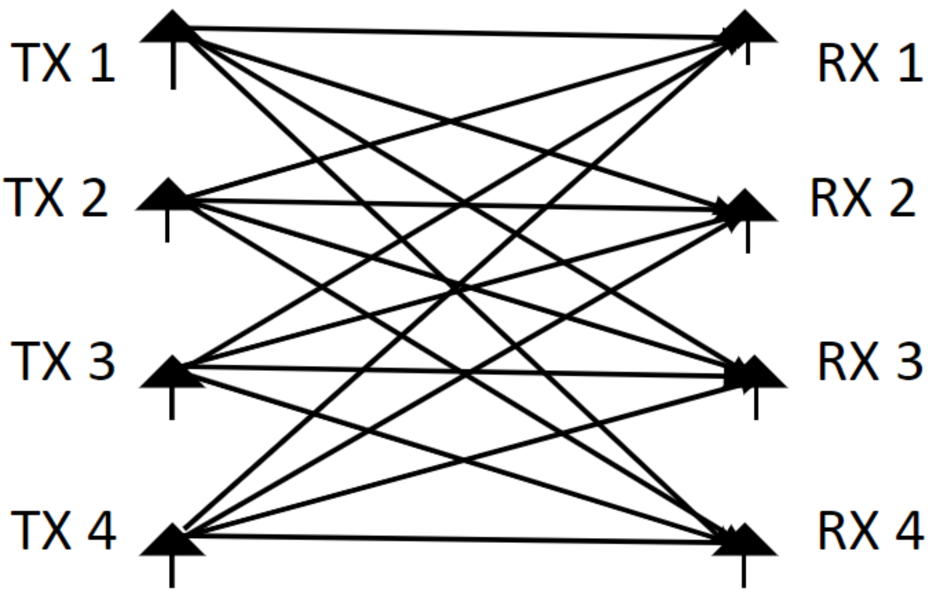


Figure 1.1. A simple $4 \times 4$ MIMO model

For each received signal we can write:

$$y = Hx + n \tag{1.1}$$

where

$y = [y_1, \cdots, y_{N_t}]^T$as received signal at receiver

$x = [x_1, \cdots, x_{N_t}]^T$as transmitted signal from each transmitter

$n = [n_1, \cdots, n_{N_t}]^T$as channel noise in each transmission channel

$H = \begin{bmatrix} h_{1,1} & \cdots & h_{1,N_t} \\ \vdots & \ddots & \vdots \\ h_{N_r,1} & \cdots & h_{N_r,N_t} \end{bmatrix}$ as channel response between transmitter and receiver

From information theory capacity of MIMO can be written as :

$$C_{MIMO} = \max\{H(y) - H(y|x)\} \tag{1.2}$$

The 1.2 , with assumption of a fixed channel medium, the only variation comes from noise so $H(y|x) = H(n)$,can be further simplified into:

$$C_{MIMO} = \max\{H(y) - H(n)\} \tag{1.3}$$

For computation of the channel capacity we only need to calculate $H(y)$ and $H(n)$. From [4], we have:

$$\begin{aligned} H(n) &= \frac{N_r}{2}\log_2\Big(2\pi e\Big) + \frac{1}{2}\log_2\Big|\sigma^2 I_{N_r}\Big| \\ max\{H(y)\} &= \frac{N_r}{2}\log_2\Big(2\pi e\Big) + \frac{1}{2}\log_2\Big|HR_{xx}H^T + \sigma^2 I_{N_r}\Big| \end{aligned} \tag{1.4}$$

with substituting formulas from 1.4 to 1.3 we can approximate the channel capacity in more realistic scenario.

$$\begin{aligned} C_{real} &= max\{H(y) - H(z)\} \\ &= \frac{1}{2}\log_2\Big|HR_{xx}H^T + \sigma^2 I\Big| - \frac{1}{2}I\log_2\Big|\sigma^2 I\Big| \\ &= \frac{1}{2}\log_2\left[\frac{\Big|HR_{xx}H^T + \sigma^2 I\Big|}{\Big|\sigma^2 I\Big|}\right] \\ &= \frac{1}{2}\log_2\left[\frac{\Big|HR_{ss}H^T + \sigma^2 I\Big|}{\sigma^2|I|}\right] \end{aligned} \tag{1.5}$$

And from matrix theory the determinant of $|I| = 0$ so above, transforms to:

$$C_{real} = \frac{1}{2}\log_2\left|I + \frac{1}{\sigma^2}HR_{xx}H^T\right| \frac{bits}{sec\ Hz} \tag{1.6}$$

The 1.6 gives us a straight forward solution but in realty estimating the channel proprieties are hard.
There are many approximation to channel matrix computed for different channel models. For instance in [5] the authors considered the channel as Rician channel and had written it like:

$$H = \bar{H} + R^{1/2}H_w T^{1/2} \tag{1.7}$$

where $\bar{H}$ stands mean value of channel in the essence of Line of sight signal in a multipath system and $R$ and $T$ respectively stands for the receive and transmit correlation matrix.
The equation 1.6 can be rewritten with preliminary knowledge of the Channel State Information at Receiver (CSIR) and $R_{xx} \triangleq E\{ss^H\} = \sigma_s^2 I_{N_t}$ as below[6]:

$$\begin{aligned} C &= \log_2 \left| I_{N_r} + \frac{1}{\sigma^2} H R_{ss} H^H \right| \\ &= \log_2 \left| I_{N_r} + \frac{\sigma_s^2}{\sigma^2} H H^H \right| \end{aligned} \tag{1.8}$$

Substituting $H = \sqrt{\rho} H'$ into 1.8 we have

$$C = \log_2 \left| I_{N_r} + \frac{\rho}{N_t} H' H'^H \right| \tag{1.9}$$

For its performance upgrade that MIMO offers, in many modern system including WI_FI, LTE-Advanced and etc. MIMO widely used. Likewise to the LTE in fifth generation of mobile networks, MIMO will be used. Although in 5G the use of MIMO will drastically increase and to avoid interference scholar are studying the use of Multi user MIMO (MU-MIMO) to achieve some part of the required performance in 5G. In [7] Gesbert et. al surveyed over the feasibility of MU-MIMO and had reached the conclusion of good resource allocation and precoding of messages, will improve the performance of system. Other point to consider is correct use of interference cancellation techniques to increase scattering diversity of users.
Main challenges that the researcher are currently facing can be summarized into following points:

A. channel estimation in downlink and uplink: One of main issues in the MIMO is channel estimation of transmission medium. With increasing number of antennas, the H matrix size will increase which increase numbers of coefficients that should be computed.

B. Antenna design: There are also challenges to design a proper directional antenna to increase its gain and also use some form of spatial multiplexing to decrease interference between adjacent devices.

  $>$ Phased Array Antenna

  $>$ Other Directional Antenna

C. Interference With increasing the number of antenna the interference between them may increase in which some mitigation should be implemented to avoid them.

D. Cost Increasing the number of antenna also will increase the development cost to properly implant it in the Mobile Devices. Which with current design trend of cell phones considered a hard and complex.

## 1.3 Beamforming

Beamforming is going to be one of the method to deal with interference and also for increasing the spatial diversity for increasing the MIMO channel gain. one of main benefits of Beamforming might be increasing the antenna gain so the total required transmission power will be decreased due to the fact the difference could compensated from the gain of antenna. But this may rise several issues. The most important one is how to acquire user position and then direct the beam toward it. Several solutions are suggested such as :

* Using a user acquisition plane in control plane which will be broadcasted like current generation of mobile networks.
* The user constantly broadcast its current location and then choosing from best possible signal to be its provider.

Each of these approaches cast some other issues to be solved. For instance, some of them are mentioned below:

A. Power efficiency

B. User acquisition

  $>$ Possible if we use two band, one for data and one for control plane

  $>$ User location estimation

## 1.4 New Radio

The new radio in 5G will retain some of the existing systems and methods from LTE while will open many more advanced technologies as part of NR. In this section we briefly surveyed the most prominent ones.

### 1.4.1 Orthogonal frequency-division multiplexing

One of major development of 5G is going to occur in new radio concept. The base structure will be inherited from the LTE meaning that some parts of the its radio structure will be used. The [8] suggests that radio resource management based on OFDM will be still used in 5G although this scheme has low power efficiency. The main issue of OFDM in energy efficacy due to its properties it has low Peak to Average Power Ratio (PAPR) which comes from the fact that the power amplifier should work in linear zones to effectively amplify signal while not disturbing it. But this comes with penalty that power amplifiers are generally much less efficient in linear zone than saturation zone.

The total energy consumption and generation in any system is zero. So the [9] derived following from conservation of energy in any closed system.

$$P_{IN}(W) + P_{DC}(W) + P_{OUT}(W) + P_{DISS}(W) = 0 \tag{1.10}$$

where $P_{IN}$ stands for our input signal power and $P_{DC}$ for bias of amplifier and $P_{OUT}$ output signal power and $P_{DISS}$ is for heat dissipation and other types of energy loss. The energy efficiency of a amplifier with good precision only can be written as

$$\eta = \frac{P_{OUT}}{P_{DC}} \approx 1 - \frac{P_{DISS}}{P_{DC}} \tag{1.11}$$

in the case of $P_{OUT} >> P_{IN}$. This shows that if the efficiency of amplifier reduced significantly it will act as heat pump which create thermal design problems. There are some solution are suggested such as using other modulation scheme or higher efficient amplifier using switching techniques as [8]suggests an example of it.

[10] notes the other major issues of OFDM. Firstly the shaping signal should roll off fast enough to avoid interference with other sub-bands. Secondly in 4G to avoid previous problem they introduce the Guard band for sub-carrier which will mitigate most of the leakage problem but this decrease the spectral efficiency(SE) also in addition to this the complexity of system will increase as the nodes should be synchronized to decrease inter carrier interference.

A common bock diagram of an OFDM system in both transmitter and receiver are shown respectively in figure 1.2 and figure 1.3. (From [11])

The data stream comes to the modulator in serial and then paralleled and each of them goes into constellation mapping with different frequency. The

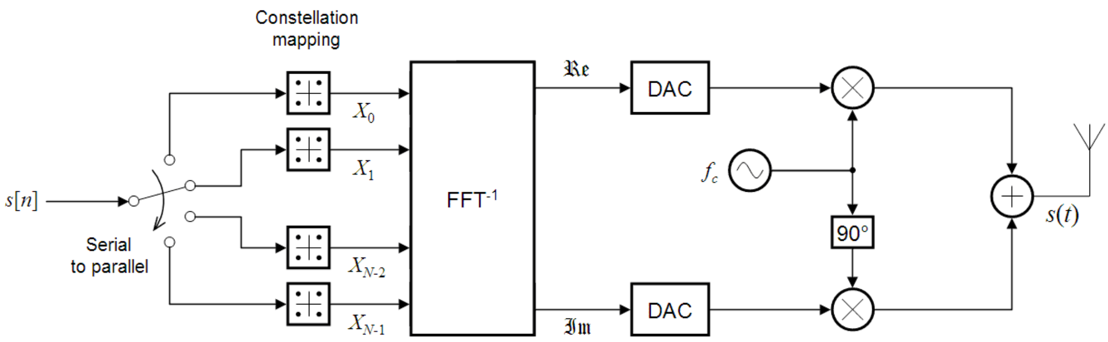


Figure 1.2. Ideal OFDM Transmitter.

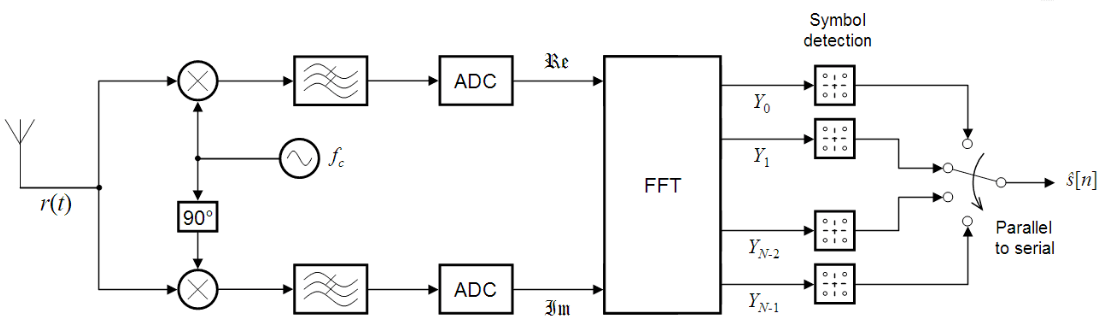


Figure 1.3. Ideal OFDM Receiver.

constellation mapping used in 5G can be changed due to different necessity and circumstance. Table 1.1 shows all possible modulation scheme in the 5G standard in both up-link and down-link that are used. After constellation mapping a inverse fast Fourier transform will be applied and then up converted to high frequency and transmitted in the channel.

Receiver side almost has similar structure to the transmitter. The received signal first demodulated and goes into Low Pass Filter(LPF) and then to get the transmitted symbol first a FFT will run and then data will be extracted and serialized. It worth to mention that different coding scheme could be used, But the most probable one is Low-density parity-check code(LDPC) which introduce good performance to complexity with respect to Cyclic redundancy check(CRC) code. Also the size of sub-carrier unlike LTE is variable and can change due to environmental circumstances. The amount of transmitted symbol depends on the constellation mapping and number of sub-carrier used. Let's consider if we use $N$ sub-carrier and transmit $M$

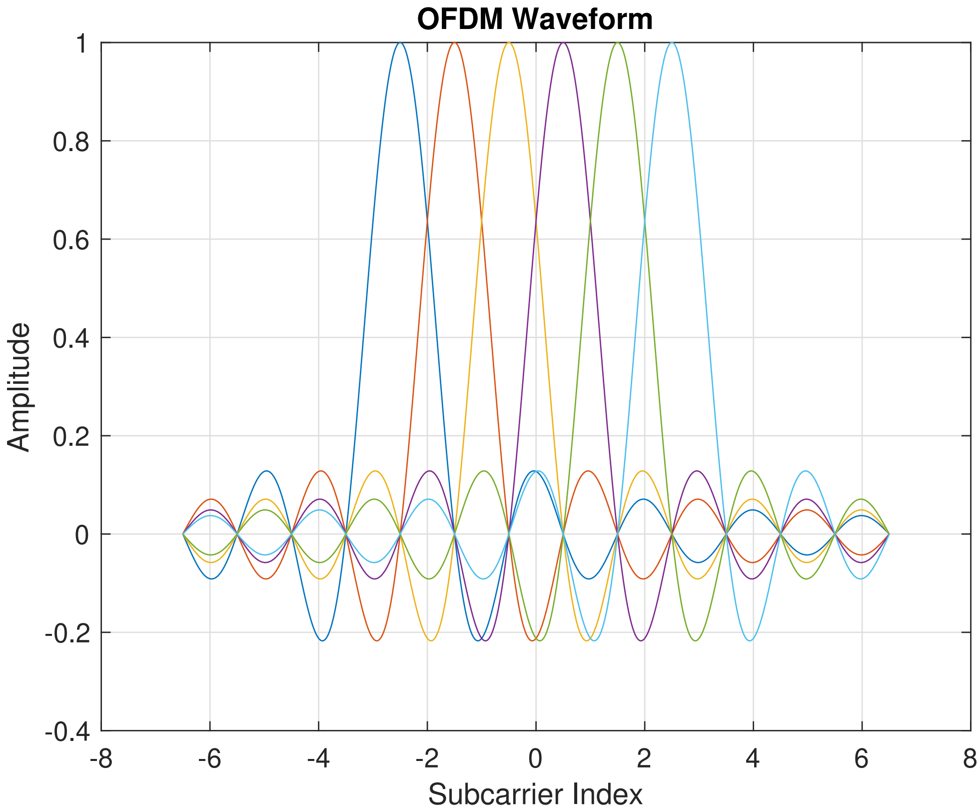


Figure 1.4. OFDM waveform and its orthogonality without considering the noise and Cyclic prefix.

symbol in our constellation mapper we can transmit up to $M^N$ symbols. So for $FFT{-}1$ with size of N and set data stream in each given time to it as $X_i(t)$ with with N element. So after inverse Fourier transform we have

$$f(t) = \sum_{i=0}^{N-1} X_i(t) e^{j2\pi it/T}, \quad 0 \leq t < T. \tag{1.12}$$

in which T stands for the OFDM symbol time which depends on the sub-carrier spacing($\Delta f = \frac{1}{T}$).
The orthogonality of the can be proven from following property. Let's consider two OFDM sub-carrier as $f_{k_1}(t)\, and\, f_{k_2}(t)$ over a period of $T$

$$\begin{aligned}\langle f_{k_1}(t), f_{k_2}(t)\rangle &= \int \overline{f_{k_1}(t)} f_{k_2}(t)dt \\ &= \frac{1}{T}\int_t^{t+T} (e^{j2\pi k_1 t/T})^* (e^{j2\pi k_2 t/T})dt \\ &= \frac{1}{T}\int_t^{t+T} e^{j2\pi(k_2-k_1)t/T}dt \\ &= \delta_{k_1k_2} = \begin{cases} 0 & k_1 \neq k_2 \\ 1 & k_1 = k_2 \end{cases}\end{aligned} \tag{1.13}$$

So as shown in figure 1.4 and proven mathematically above, every sub-carrier is orthogonal with other sub-carrier however due to small frequency size of sub-carrier its sensitive to the multipath fading. To solve the problem some guard band will be added known as Cyclic Prefix. The CP waveform will be taken from signal in $T - T_g \leq t < T$ and later added on $-T_g \leq t < 0$.

| | |
|---|---|
| Downlink | QPSk,16 QAM, 64 QAM, 256 QAM |
| Uplink-OFDMA | QPSk, 16 QAM, 64 QAM, 256 QAM |
| Uplink-SC-FDMA | $\pi/2$ BPSK, QPSk, 16 QAM, 64 QAM, 256 QAM |

Table 1.1. The Modulation possibility in 5G in both uplink and downlink.[1]

### 1.4.2 Orthogonal frequency-division multiple access

As the case with LTE 3GPP has decided to use Orthogonal Frequency Division Multiple Access (OFDMA) as a method of multiple access technique in both downlink and uplink although it has many flaws such as power efficiency. OFDMA uses OFDM as its modulation technique and as previously discussed,in OFDM the bandwidth divided into several sub-carrier transmitting a subset of data, so using this division the OFDMA assigns each or some of them to different users which allows simultaneous data transmission for users. Like LTE, Single carrier frequency division multiple access(SC-FDMA) is also possible to use as uplink multiple access scheme due to its higher power efficiency while the overall throughput is close. In SC-FDMA instead of transmitting the sub-carrier in parallel they will be transmitted in sequential form. Although this make the system sensitive to the inter symbol interference due to multipath. So at the base station some technique should be used to mitigate the problem.[12] Another problem for OFDMA is in uplink is frequency offset in different terminals that are transmitting in the same time thence the orthogonality of signal will be disrupted and interference will occur. [13] The resource allocation of although will happen at the the sub-carrier level but it is our smallest portion of sub-channel which we can access it. So we assign some sub-channel for each user. The number of assigned sub channel should be determined by higher layer and adjusted to the channel condition and required quality of service(QoS). The two prominent method of assignment are :

A. Adjacent sub-carrier method(ASM): The sub-channel created from a group of adjacent sub-carriers and then assigned to user.

B. Diversity sub-carrier method(DSM): The sub-channel created through a progress of selection of set of non adjacent sub-carriers and then assigned to user.

An example of it shown in figure 1.5.

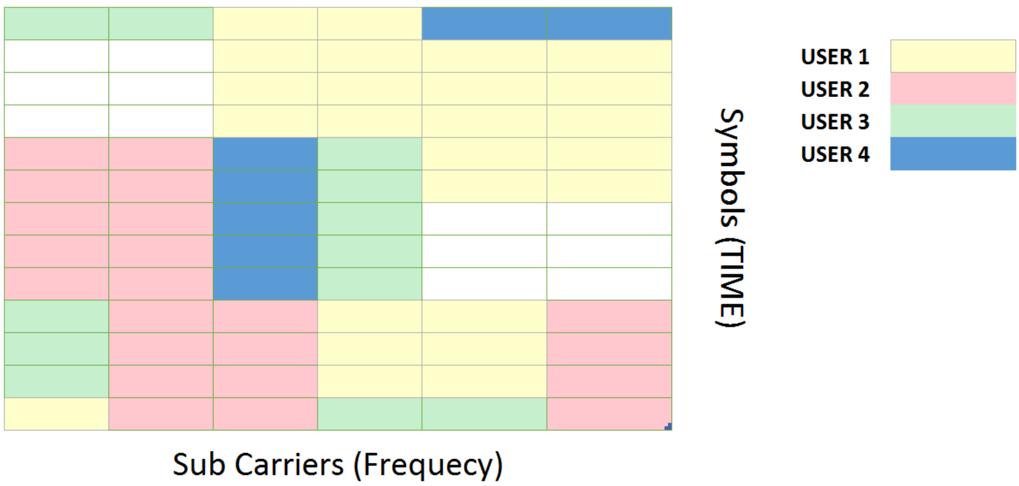


Figure 1.5. An example of OFDMA resource allocation.

### 1.4.3 Non orthogonal multiple access proposals

In recent years researchers have been working on the other multiple access scheme for improving outage performance and maximum assignable rate for users.
Many schemes are suggested by scholars to in where they use many available

| | 2G GSM | 3G WCDMA | 4G LTE | 5G |
|---|---|---|---|---|
| Downlink | TDMA | CDMA | OFDMA | OFDMA |
| Uplink | TDMA | CDMA | SC-FDMA | OFDMA/SC-FDMA |

Table 1.2. The Multiple Access Scheme used in different generation of mobile networks.[1]

options that signals are not strictly orthogonal. In general NOMA can offer better performance while keeping the fairness. In this work we studied the power domain non orthogonal multiple and analysed its performance versus the more conventional TDMA scheme.

### 1.4.4 Duplexing

In the 5G both Time-division duplexing (TDD) and Frequency-division duplexing (FDD) are possible to use to ease the deployment of it. But the prominent technology will be Time-division duplexing unlike LTE in which it was Frequency-division duplexing. The choice is done due to the extensive use of estimation for both Uplink and Downlink. In the TDD the amount of required processing will be reduced significantly due to possibility of previous channel estimation of in either UL or DL. Also in TDD is easier to manage the allocated capacity and resource for each node which is very beneficial in dense cells. The main issues with TDD is the increased amount of latency with comparison to FDD.
Some research have been done for solving the both issues of high amount of spectral usage in FDD and time latency in TDD. For instance in [14] the authors suggests a scheme for simultaneous transmission of data in both Uplink and Downlink. The main issue of In-band Full Duplex(IBFD) is interference and self interference which got worse in the edge of the cell. To avoid this issue the Base station knows its geographical location and its property and then determines a Radius that User Equipment(UE) can use this scheme. Then then BS create the a number of set of users so those users can frequency reuse. If the number of subsets are low, we can achieve high frequency reuse ratio. Then each subset divide all the band between themselves and allocate appropriately them into Uplink and Downlink.

### 1.4.5 Higher frequencies

With increment in the offered transmission speed required by the standard researcher have been researching in the modes of increasing them. One of the most obvious choices is the increasing the allocated bandwidth. A simple methodology can be reached from Shannon formula of channel capacity

$$C = B\log_2\Big(1 + \frac{S}{N}\Big) \tag{1.14}$$

in an additive white Gaussian noise (AWGN) channel. As you can see with increasing the Bandwidth the channel capacity will increase linearly. The trend of increasing the bandwidth has been used up to 4G. For example in GSM 900 in TDMA scheme each user had 200 KHz in their time, later in 3G CDMA 2000 this increased to 5 MHz and in LTE it is 20 MHz. But unfortunately this trend can not continue in 5G in usual radio frequencies that we use nowadays. There are several explanation for this. First the free and available band in those bands are scarce and many of them used in other technologies or limited by regulatory laws in different countries and even if they are available often they cost a lot. For resolving these issues the 3GPP declared its intention to move to high frequencies in two step. First to 6-26 GHz and later to 30-300 GHz. This way the cellular company can benefit from the commercially free bands or cheap bands while having very huge frequency bandwidth to serve their customer. However like every other thing in real world these moves come with some caveat. For instance in [15] authors surveyed some of those issues. The main issue is high path loss which can be categorize to different categories.

I. Free space path loss: With increasing the frequency the amount of attenuation of the electromagnetic wave will reduce by power of -2. The free space path loss(FSPL) can be derived from infamous Friis equation. The Friis equation describe the ratio of received power over transmitted power in free space as following :

$$\frac{P_r}{P_t} = D_t D_r (\frac{\lambda}{4\pi d})^2 \tag{1.15}$$

with taking the declivities as isotropic the we can rewrite it as:

$$\frac{P_r}{P_t} = (\frac{\lambda}{4\pi d})^2$$

then with considering the $c = \lambda f$ we have FSPL as:

$$FSPL = (\frac{4\pi f d}{c})^2$$

.

II. Atmosphere absorption:Generally speaking with increasing the frequency air absorption will increase significantly. In [16] they surveyed the amount of atmospheric absorption for different frequencies above 6 GHz and concluded that around the 60 GHz bands the amount of atmospheric attenuation is significant and thereof likelihood of using outdoor is very low. As you can see in figure 1.6 there are several spikes in different frequency ranges the first two are happening because of high absorption factor of vapor water and oxygen molecules in those frequencies thus they are unlikely to be used in 5G.

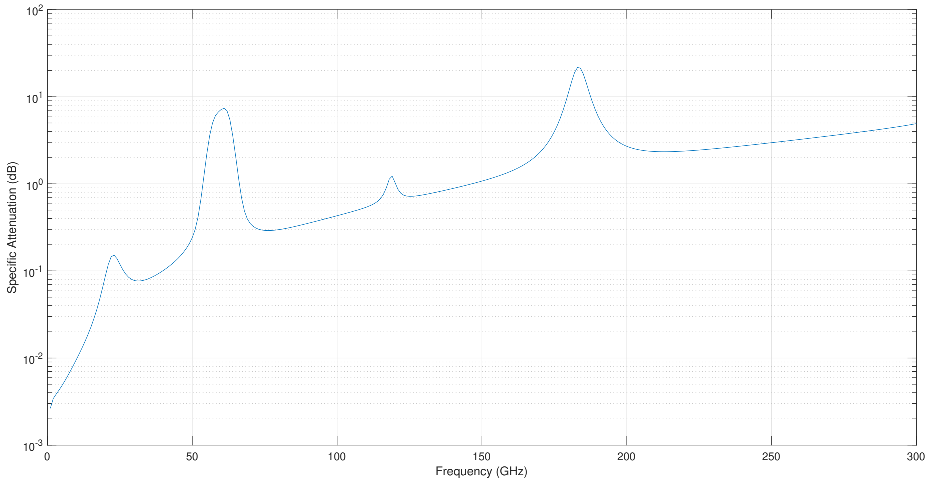


Figure 1.6. Atmospheric attenuation in relation to frequency in following condition. Air temperature 20 °c,Air pressure 1 Bar and Water vapor density is 12 $\frac{g}{m^3}$

III. Obstacle, foliage and rain loss: In the high frequencies objects like building, trees or even rain drops cause huge loss to radio waves. There are several models suggested for each of them in different circumstances and materials. For example in [17] 3GPP and its partners suggested a model for path loss due to obstacle and building in a urban area.

$$PL_{tw} = PL_{npi} - \log_{10} \sum_{i=1}^{N} p_i \times 10^{\frac{L_{material,i}}{-10}} \tag{1.16}$$

where $PL_{npi}$ is for non perpendicular cases , $L_{material,i}$ for penetration loss of each material which can be calculated from table 1.3 and $p_i$ for coefficient effectiveness of each compounded used in the building. It should be noted that the sum of coefficients should be one. For normal situation the above formulas can be simplified to following formulas, which probably are suitable for most European urban areas.

$$PL_{tw} = 5 - 10\log_{10}(0.3 \cdot 10^{\frac{-L_{glass}}{10}} + 0.7 \cdot 10^{\frac{-L_{concrete}}{10}}) \tag{1.17}$$

in low loss situation and for more lossy situation we have,

$$PL_{tw} = 5 - 10\log_{10}(0.7 \cdot 10^{\frac{-L_{L_{IRRglass}}}{10}} + 0.3 \cdot 10^{\frac{-L_{concrete}}{10}}) \tag{1.18}$$

The figure 1.7 illustrate the effect of frequency in the essence of building in path loss.

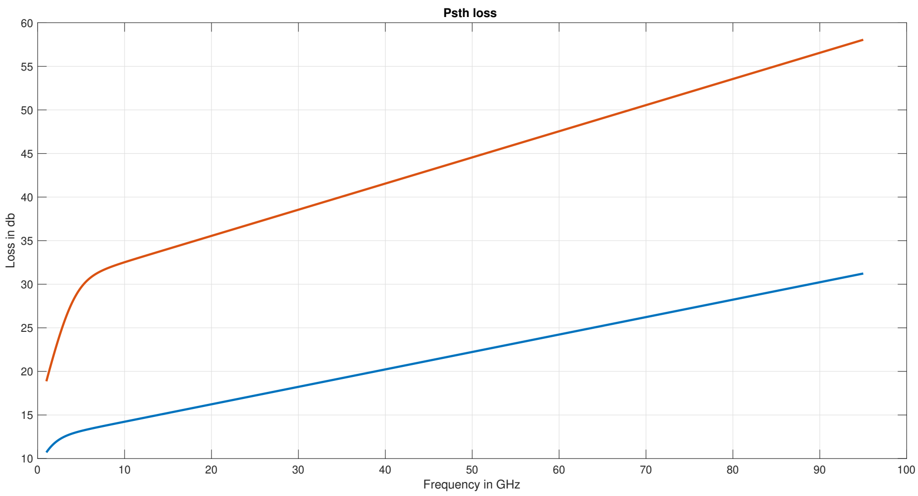


Figure 1.7. Path loss due to essence of building in both high loss model and low loss model

As mentioned before, the other major source of loss is trees and their leaves. Amount of this loss is very dependent on the depth of its leaves.

| Material | penetration loss |
|---|---|
| Standard multi-pane glass | $L_{glass} = 2 + 0.2f$ |
| IRR glass | $L_{IRRglass} = 23 + 0.3f$ |
| Concrete | $L_{Concrete} = 5 + 4f$ |
| Wood | $L_{Wood} = 4.85 + 0.12f$ |
| All frequencies in GHz | |

Table 1.3. Penetration loss for different construction material

In a survey conducted by United States Department of Defense in 1982 [18] Mark Weissberger suggested below formulas amid at modeling foliage attenuation factor for frequencies in range of 230 MHz to 95 GHz and foliage depth of up to 400 meters.

$$\alpha_f = \begin{cases} 1.33 \cdot f^{0.284} \cdot d_f^{-0.412}, \; 14 \leq d_f \leq 400 \\ 0.45 \cdot f^{0.284}, \; d_f \leq 14 \end{cases} \tag{1.19}$$

Where $\alpha_f$ is attenuation factor in db/m f is frequency in GHz and $d_f$ is foliage depth. so for calculating the path loss we can adjust the formulas to

$$LP_f = \begin{cases} 1.33 \cdot f^{0.284} \cdot d_f^{0.588}, 14 \leq d_f \leq 400 \\ 0.45 \cdot f^{0.284} \cdot d_f, d_f \leq 14 \end{cases} \tag{1.20}$$

As you can see in figure 1.8 with increase of foliage depth the effect of frequency will increase dramatically. So in the selection of mm-wave bands in the foliage depth is very important.
For calculating the effect rain drops over radio wave attenuation several models are proposed such as Specific attenuation model for rain for use in prediction methods by ITU in [19]. This model measures the attenuation of rain relative to the rain rate and their propagation polarization. The attenuation factor $\gamma_R$ (db/m) is defined as

$$\gamma_R = kR^{\alpha} \tag{1.21}$$

where k and $\alpha$ are coefficients relative to frequency and propagation polarization and R is rain rate in mm/hour. k and $\alpha$ are calculated from

$$log_{10}k = \sum_{j=1}^{4} a_j exp[-(\frac{log_{10}f - b_j}{c_j})^2] + m_k log_{10}f + c_k$$

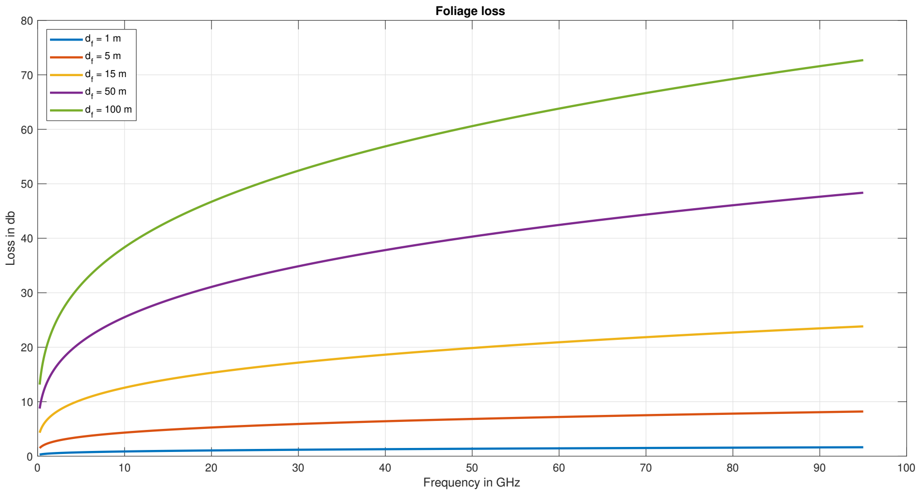


Figure 1.8. Path loss due to trees and leaves in different foliage depth

and

$$\alpha = \sum_{j=1}^{5} a_j exp[-(\frac{log_{10}f - b_j}{c_j})^2] + m_\alpha log_{10}f + c_\alpha$$

the value of a, b, c and m should extracted from tables 1, 2, 3, 4 and f is frequency in GHz in the range of 1 GHz to 1000 GHz. In figure 1.9 with increasing the frequency and rain rate the attenuation will increase. For heavy rains the possibility of using mm-wave is very low due to the very large attenuation rate. For simulation of snowfalls also we could use rainfall model although this may result to overestimation of system.

Other important issue that to be considered is how the millimeter wave will behave in outdoor or indoor application in presence of multipath and diffraction. In [20] a model for a conference room has been studied. In their model authors used combination of ray tracing and empirical models to get the benefits of both method and from it they found out that the spatial of environment in which the waveform are propagating are very important and every channel model should consider them also. Also good to note that due to very high attenuation and loss which surveyed in previous parts, use of antenna with high gain and directionally or beam-forming become necessity to establish a reliable connection. Probable use of beam-forming leads to use of active array antenna for gain both beam-forming and high

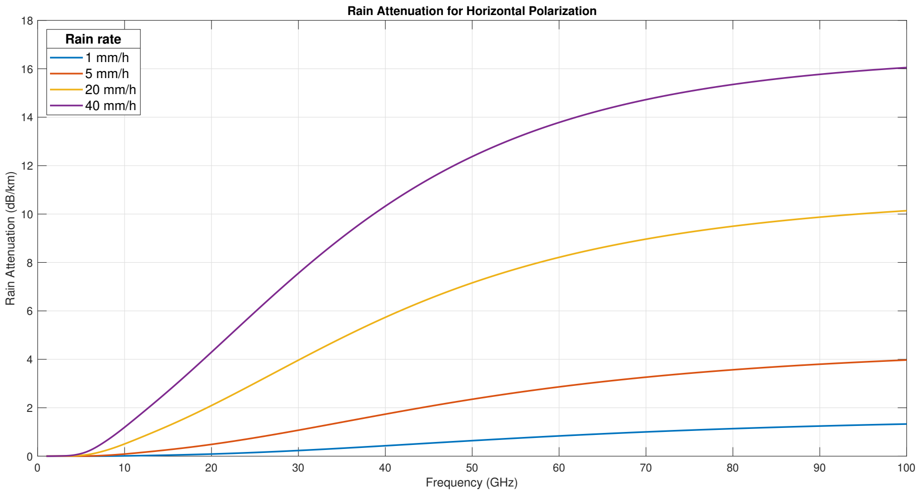


Figure 1.9. Rain Attenuation for Horizontal Polarization

gain. nevertheless the size of arrays should be limited so power consumption of its elements can be constrained to an acceptable level.
There are a lot of proposal about practical usage and applicability of high frequency ranges. In general those applications can be categorized into two major group:

A. Indoor and local area applications: Due to high loss of millimeter wave in free space, increasing the radius of cell will decrease received power significantly, to mitigate this issue cell size should be reduced.thereof it is possible to create a local area networks consisting of several mini base station for very high data transmission rate working in the millimeter waves and then a more traditional base station covering much larger area and o be used as backup, administrative and controlling the mobile station and mini stations. For instance in [21] they surveyed such architecture.

B. Outdoor applications: Although the millimeter wave has very huge loss and their characteristic in urban area not studied extensively their large amount of free spectrum makes them very appealing for the cellular network industry. Due to increase in the demand bandwidth and increase number of users, densification of network is inevitable. The major issue for densification of network is how to create back-haul networks. Traditionally this duty was done by fiber optic network, but with increase number nodes this process become increasingly costly. To avoid this there are proposal of use of millimeter wave as transmission medium of between nodes. To proper use of this method the use of directional antenna, beamforming and MIMO to moderate the loss due to various reasons.

### 1.4.6 Spectral efficiency And Carrier aggregation

As discussed in previous section the rationale behind moving toward to access huge set of available frequency. For the time being most cellular industry works in sub 6 GHz bands. But with increase number of users and massive demands by them, they can not satisfy them so it is necessary to move upward. The assigned frequencies varies between countries but they are at least in current phase of deployment, within range of 26 to 28 GHz.[22]

The allocated bandwidth per user in sub 40 GHz could be increased to much higher amount by means of aggregating the multiple frequency blocks. This method is part LTE-A is thought to be part of 5G with adding possibility of aggregating different bands into one larger band. In recent years many

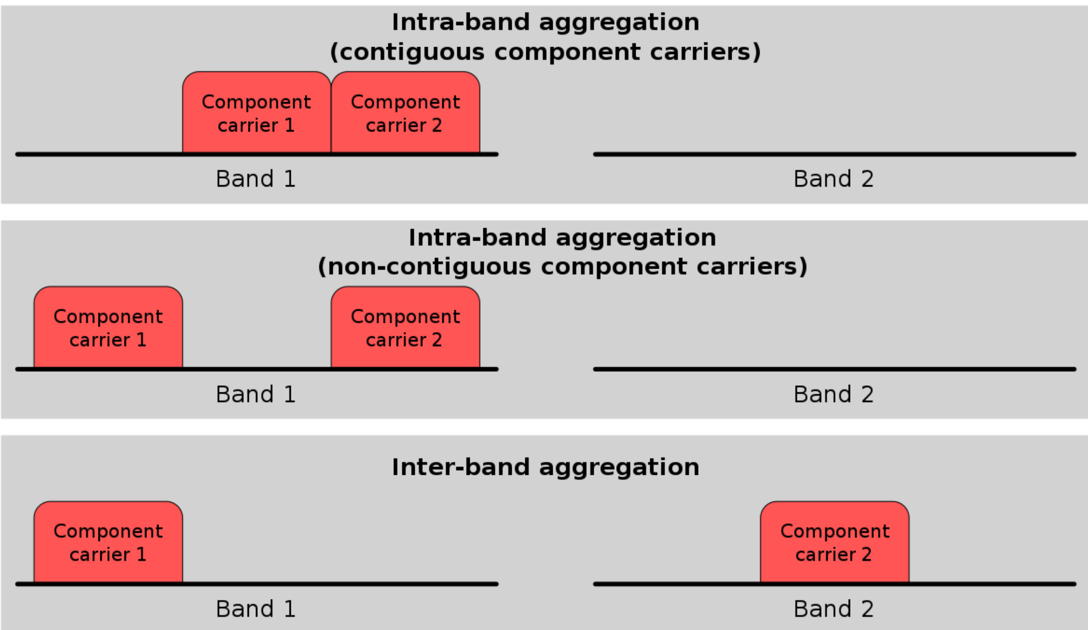


Figure 1.10. Types of carrier aggregation with regard how the bands are chosen [2]

mobile network operators started to shutting down their old GSM and 3G systems. This will open some what considerable amount of bandwidth in sub 3 GHz frequencies. For instance in USA operators already started to shut down their systems or announced they are scheduling for close them in near future. There are also other suggestion to use unlicensed band in sub 6 GHz in mobile devices which will open new level of possibilities in how we can allocate band width. Although this come with caveat of very huge amount of interference with other devices which are using these spectrum such as WiFi.

### 1.4.7 Interference management

One of the issues of using higher bands for 5G, is its interference with contemporary systems. This systems exists in wide range of applications such as satellite communication, fixed point to point networks like mobile back haul systems and last but not least military applications. The other source of interference may come from simultaneous use of mm-wave frequencies in 5G between multiple operators. In [23] the authors suggested some sort of biasing during the initial steps of association of user equipment to the base station proportional to alignment of beam and the User equipment to mitigate the interference effect. So the statement can be written as

$$(g^*, b^*) = \arg \max_{(g,b)\in A} B_{g,b} \cdot P_{R,g,b} \tag{1.22}$$

Where (g , b ) stands for each pair of user terminal and gNb (base station) and $P_R$ received power from base station and B the offset value which we assign and $A$ is the set of all available pairs of UE and gNb. The authors proposed two method for computing the value of bias. The using technique depends on the architecture and system requirement of system. They claim with using their methods it is possible to protected against the interference while not affecting the 5G coverage range.

### 1.4.8 Densification of the network

With increase number of users in a given cell and more demand in bandwidth, the capacity of network should be increased in that cell. The other reason can be attributed to the use of mm-wave spectrum because those frequencies have much higher path loss in comparison with conventional mobile frequencies. The issue with more dense network, the interference will also

increase thereof the SINR (signal to interference and noise) will decrease. One solution is to select the Base station with the highest receiving power at the user equipment. This solution is easy to implement but is not an optimal optimal solution for resource allocation among the users. The ultra dense network are heterogeneous due to different characteristic of used spectrum, transmitted power and antenna's gain, therefore are complicated to design the cells in the network.
In [24] the writers presented a simple model for simulating the number of serviceable users in a given area in correlation with different transmitting power, different UE and base stations density. Their model is based on the infamous Shannon capacity formula.

$$C = B_k \log_2(1 + SINR_k) \tag{1.23}$$

where $B_k = \frac{B_{tot}}{N}$ and SINR is the signal to interference and noise ratio which is defined as:

$$SINR_k = \frac{P_{rx,j,k}}{\sum_{n=1}^{M} P_{rx,n,k} - P_{rx,j,k} + P_n} \tag{1.24}$$

where $P_{rx,j,k}$ stands for received power from base station in a given frequency and $P_n$ is the total noise in given frequency which will increment with increasing frequency.

# Chapter 2

# Non-Orthogonal Multiple Access

In this chapter is about the brief description of multiple access techniques used in previous generation of mobile then we continue why new multiple access technique would be vital in near future cellular systems.

## 2.1 Multiple Access in previous Generation of Cellular Network

The choice of the proper multiple access for mobile networks primarily determined by the user requirement and available technology at the time. In the first generation of mobile networks there wasn't an unique standard and many countries adopted their respective standards. The most common feature of those standards was reliance on Analogue Voice Transmission unlike modern system. For archiving the Multiple access predominantly they used Frequency Division Multiple Access(FDMA) with short allocated bandwidth [25]. With increase in the usage of cellular phones Second Generation of Mobile transformed into digital world with increase in carrier frequency and some increase in overall allocated bandwidth, to mitigate this issue in GSM standard they have used Time Division Multiple Access (TDMA) with creating 8 time slot with duration of almost 0.557 ms. For each slot a ID from 0 to 7 will be assigned and data modulated in GMSK (Gaussian Minimum Shift Keying) modulator. The time slots themselves also separated with each other with aid of Guard Time.[26] In 3G the used technique is Wideband Code Division multiple Access (W-CDMA) to permit the users to have

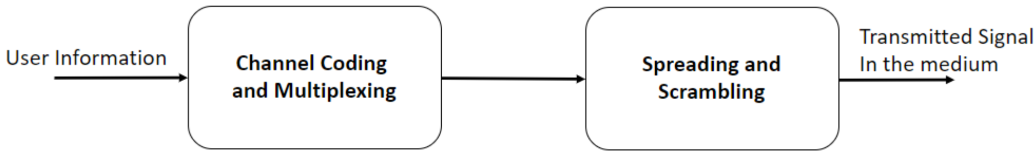


Figure 2.1. System model of a W-CDMA transmitter

more data rate with contrast to GSM. To enable it, 3GPP implemented a Direct-sequence spread spectrum (DSSS) to modulate the signal. The multiple access is achieved through spreading code to widen the band of the data signal and then using scrambling, each user separate its message from spreaded message. To minimize the interference between user, the scrambing code designed to be orthogonal to each other. [27]

The CDMA is dropped in 4G/LTE due to its very high required chip rate to achieve the required transfer rate by the standard so the 3GPP body changed the Multiple Access to new form of FDMA where the carrier bands are divided into orthogonal sub bands which allow high data rate while keeping the complexity at reasonable amount. As discussed in previous chapter, also in Fifth Generation of Mobile networks e.g. 5G, the governing body of 3GPP decided to continue to use the OFDMA likewise 4G/LTE with some improvement in the scheme which allows the multiple subcarrier to each user.

## 2.2 Non orthogonal Multiple Access

As mentioned in previous chapters, It would be more demand for bandwidth in future communication systems. To mitigate the issues, more robust and efficient multiple access schemes are required. One of the well-known solutions is to use a non-orthogonal multiple access scheme. Scholars suggested different approaches to achieve specified requirements, the two prominent approaches are

- Power Domain NOMA
- Code Domain NOMA

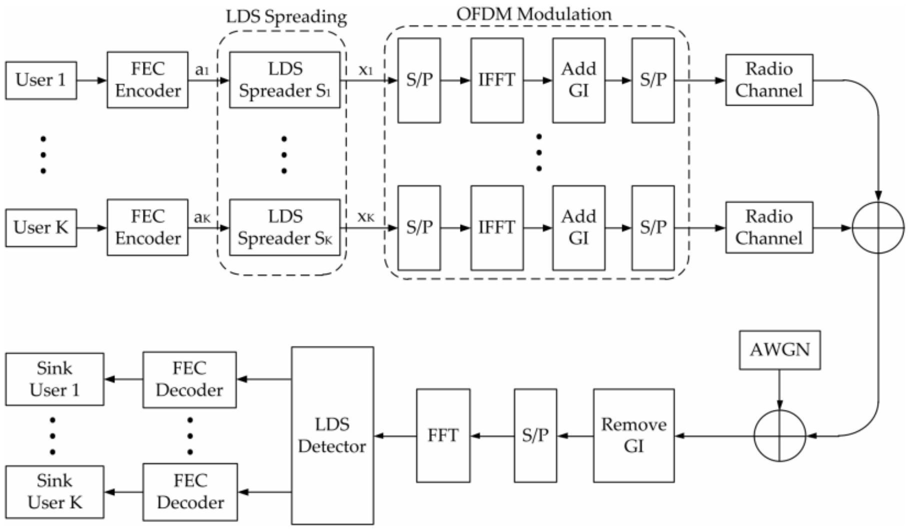


Figure 2.2. System Diagram of MC- LDSMA

## 2.2.1 Code Domain NOMA

In the CD-NOMA the multiplexing is done likewise CDMA through spreading codes, but unlike conventional CDMA, the CD-NOMA guarantees the accessibility of resources in time or frequency domains. The used sequence in the CD-NOMA is sparse and features a low correlation non-orthogonal coefficient [28]. There are many classes of CD-NOMA are defined. For instance, in [29] the authors suggested a Multicarrier-Low density Spreading code multiple access technique(MC- LDSMA) in which each users spread their information to a group of subcarriers and in each subcarrier it is allowed to multiple users transmit in it. To mitigate the interference at the receiver, each user will not transmit in all the sub carriers. Then to achieve SINR better algorithms can be used. Due to the different number of active users in a subcarrier, the performance of users will vary in each of them. In the [30] they could achieve better performance in bit error rate(BER) and thereafter better Quality of Service (QoS) at less transmitting power thence saving more battery in user equipment. In some work, it has been shown it is possible to couple the code spreader/detector with an OFDM modulator/demodulator. As it is shown in 2.2 the transmitter a Code spreader is placed to multiply the spreading the sequence in the OFDM subcarriers. Then at the receiver after demodulation of the incoming OFDM signal, the data detection could be done by using the known spreading sequence at each subcarrier. As discussed before, in MC-LDSMA it not necessary to satisfy

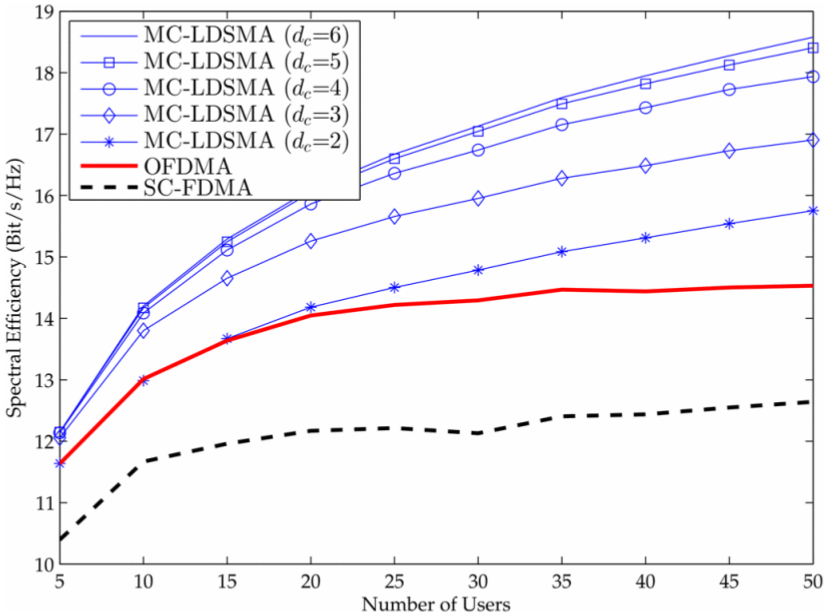


Figure 2.3. Spectral efficiency of MC-LDSMA with respect other OFSMA and SC-OFDMA with increasing the number of users.

any auto-correlation and cross-correlation restraint therefore the code design would be more flexible . Due to limitation over spectrum and power in MC-LDSMA it is possible to dynamically allocate them to boost both system fairness and optimal usage of resources in each cell. In the [31] the authors studied the performance of MC-LDSMA reached our previous anticipation.

As an improvement over MC-SCDMA in[32] a novel and more simple method for encoding the spreading codes in data by using the combination of the QAM modulator and spreading encoder proposed. This approach will simplify the design of system but increase the mathematical complexity by introducing multidimensional constellation matrix at the encoder/modulator block. The SCMA encoder, maps the K dimensional code word $x$ into into $N$ dimensional complex constellation set points where the the mapping is a binary mapping. In the process of mapping we do not permute the size of $N$ but we fill the rest of the space $x$ with zero bits, so the size of $N$ and $x$ would be equal and the output codebook shall consist of $M$ codewords with each contain $k$ complex value in a space $V$ with size of $N$ . Then the encoder will encode the $C_J$ with $M_j$ alphabets into a ,ultidimensional vecotor $V$ with J layer, then the transmitting message would be

$$
\begin{aligned}
y &= \sum_{j=1}^{J} diag(h_J)xj + n \\
&= \sum_{j=1}^{J} diag(h_J)V_j gj(b_j) + n
\end{aligned}
\tag{2.1}
$$

where $x_j = (x_{1j}, \ldots, x_{kj})^T$ is SCMA codeword and $h_j = (h_{1j}, \ldots, h_{kj})^T$ is channel gain in layer $j$ and $n \sim CN(0, N_0 I)$ is channel's noise. The number of transmitting layer can be computed through factor graph matrix computation. At the demodulator for extracting the data, the MPA(Message Passing Algorithms) method would be applied to decode the received message. At the decoder with presumption of knowledge of channel properties, the transmitted message approximated as :

$$\hat{X} = \arg \max_{x \in (X_{j=1}^{J})\mathrm{X_j}} P(X|y) \tag{2.2}$$

Then with conversion of problem into a Marginalize product of Functions(MPF), the solution become easier but increase complexity with increase number of layers. For improving the accuracy, it is better to have a prairie knowledge layers with some pilot messages and then iterate the algorithm several time to obtain better result. There are more robust and less complex solution for decoding the received message is suggested in academia, for instance in [33] less complex method proposed. Other important part in design of SCMA, is to design of an optimal while satisfying following properties for constituent vectors in the transmitting message.

$$\mathcal{V}^*, \mathcal{G}^* = \arg\max_{\mathcal{V},\mathcal{G}}\ m(\mathcal{S}(\mathcal{V}, \mathcal{G}, J_r M, N, K)) \tag{2.3}$$

whereas $m$ is design condition with undefined definition[33].

### 2.2.2 Power Domain NOMA

As mentioned in previous section, on of the most promising NOMA technique for multiple access is the use of it in the power domain which is currently under extensive study by the researcher and academia all over the world.
In the Power Domain NOMA (PD-NOMA) the users signal are generated by superposing their respective signal in different power, meaning that each user data is buried under sum of other sum of other users data and for getting the intended data, first users should extract and remove the irrelevant

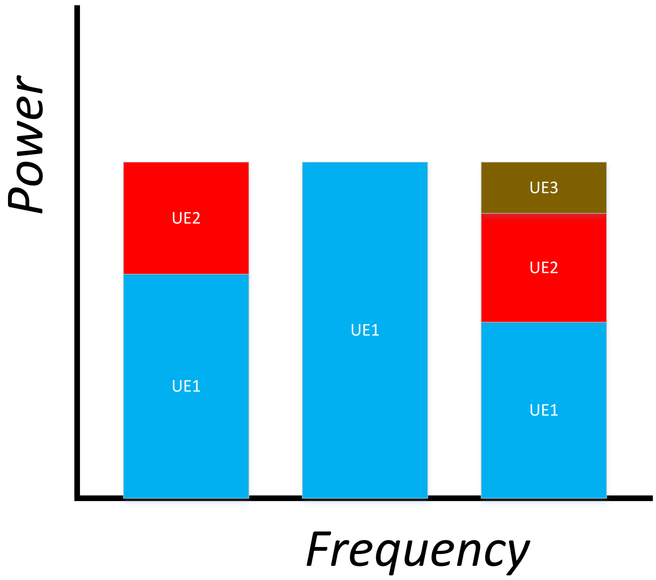


Figure 2.4. Distribution of power in Power Domain NOMA in different band with diverse number of users in each ban.

data by means of Successive Interference Cancellation (SIC). In this format discrepancy between the power level of each user in received message is very important and low level discrepancy leads to very poor system performance and bit error rate(BER).

Using the theorem of technique we can write :

$$y_m = h_m \sum_{i=1}^{M} \sqrt{a_i P} s_i + n_m \tag{2.4}$$

where $m$ denotes the number of users, $h$ Channel and it is described for $m_{th}$ user as $h_m = \frac{\tilde{g_m}}{\sqrt{(1+d)^\alpha}}$ where $\tilde{g_m}$ is Rayleigh fading channel gain and $\alpha$ the path loss factor and $a$ the power allocation coefficient and finally $n$ stands for channel additive noise. As explained before the $m-th$ user should be able to distinguish its message with any user with $i < m$ so it can decode its own message. With assuming this, we can write achievable data rate for $m_{th}$ user as below:

$$R_m = \log\Big(1 + \frac{\rho |h_m|^2 a_m}{\rho |h_m|^2 \sum_{i=m+1}^{M} +1}\Big) \tag{2.5}$$

where $\rho$ stands for transmission signal to noise ratio(SNR) and presumption of $R_{j\hookrightarrow m} \leq \tilde{R}_j$ and $\tilde{R}_j$ represent targeted data rate of the $j_{th}$ user. and $R_{j\hookrightarrow m}$ is rate of transmission for $m_{th}$ user while the $j_{th}$ user can decode its own data. With these assumption the actual rate for the last user i.e. $M_{th}$ user can be written as,

$$R_M = \log\left(1 + \rho|h_m|^2 a_M\right) \tag{2.6}$$

.

In the PD-NOMA there are several major performance metric to determine its superiority to more conventional orthogonal multiple access in certain situations and conditions. In the next chapters PD-NOMa is deeply studied and then its performance will be analyzed using a simulation program written in the MATLAB.

## 2.3 Advantage of NOMA over Orthogonal Multiple Access techniques:

Many aspects can be studied to demonstrate the superiority of the NOMA over the OMA. One is maximum achievable data rate of NOMA is higher than OMA in same condtions. Let's ponder following, there are two networks, each consists of two users and one base station, in one network the OMA used and in other one NOMA has been used. With denoting $\rho$ as the signal to noise ration (SNR) and using Shannon capacity theorem we can write rate for users $m$ and $n$ as:

$$R_m^{OMA} = \beta \log_2\left(1 + \rho|h_m|^2\right) \tag{2.7}$$

and

$$R_n^{OMA} = (1-\beta)\log_2\left(1 + \rho|h_n|^2\right) \tag{2.8}$$

where $\beta$ is resource allocation coefficient and it should satisfy $\frac{\alpha_m}{\beta} = \frac{\alpha_n}{1-\beta} = 1$. Likewise we can write:

$$R_m^{NOMA} = \log_2\left(1 + \frac{\rho\alpha_m|h_m|^2}{1+\rho\alpha_m|h_m|^2}\right) \tag{2.9}$$

$$R_n^{NOMA} = \log_2\left(1 + \rho\alpha_n|h_n|^2\right) \tag{2.10}$$

In both cases the $\alpha_m$ and $\alpha_n$ are the power allocation (PA) coefficient and their total sum should be 1. With approximating in high SNR region, the overall throughput of OMA and NOMA can expressed as:

$$\begin{aligned} R_{sum,\infty}^{OMA} &\approx \log_2\left(\rho\sqrt{|h_m|^2|h_n|^2}\right) \\ R_{sum,\infty}^{NOMA} &\approx \log_2\left(\rho|h_n|^2\right) \end{aligned} \tag{2.11}$$

from 2.11 we can compute obtainable sum-rate, in comparsion to OMA:

$$R_{sum,\infty}^{Gain} = R_{sum,\infty}^{NOMA} - R_{sum,\infty}^{OMA} = \frac{1}{2}\log_2\left(\frac{|h_n|^2}{|h_m|^2}\right) \tag{2.12}$$

With these considerations and building system to always stratify $|h_m|^2 < |h_n|^2$, the sum of rates for the NOMA is higher than OMA.

# Chapter 3

# Power Domain NOMA

In this chapter the theoretical fragment of Power domain non orthogonal multiple access will be studied with reviewing selected and renown work in this field. But before diving into the full description of PD-NOMA, the two vastly used term are briefly explained.

## 3.1 Superposition Coding

Up to recent years the idea to transmitting two signal in one band considered absurd and the researcher were studying many methods to cancel or limit it but in [34] Cover had mathematically proven that the achievable transmission rate can be maximised in broadcast mode with intend of serving multiple number of users, although this research until recent times was neglected. In the original article Cover suggested and later proved that with packing the message of several users together and later generating a series of codewords for transmitting signal for each user we can achieve on average higher rates. The act of combining different codes of each user and later creating new codeword called superpositioning. It should be kept in mind that in this case the rate of two signal should vary by large margins to not affect the overall performance. The rational behind this can be explained with consideration of two binary channel. The first channel is noiseless (denoted with $H_1$ ) and other one is a symmetric binary channel(denoted with $H_2$ ). With this consideration, let assume that in each channel we want to transmit a set of code $X = \{M_1 M_2\}$ defined to transmitted in both channel and in each channel there two receiver to receiver relevant codeword. In figure 3.1 the scenario is drawn.

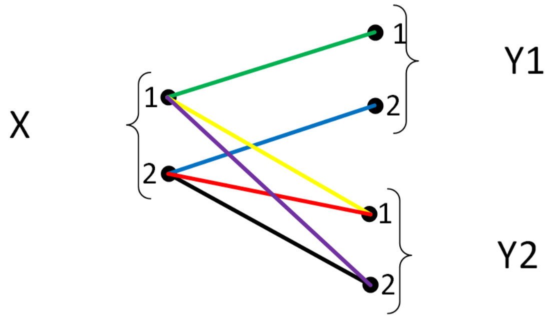


Figure 3.1. Two binary symmetric channel with different channel

The above assumption can be shown as:

$$H_1 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \qquad H_2 = \begin{bmatrix} \bar{p} & p \\ p & \bar{p} \end{bmatrix}$$

With knowledge of channel matrices it possible to calculate the channel capacity for each one:

$$C_1 = 1 \quad \& \quad C_2 = C_p = 1 - H(p)$$

but the maximum channel rate for $C_1$ only achievable when the TDD is applied therefore limiting the transmitting time, which will cause huge problems with increasing the number of users. Although in second channel the maximum achievable rate for each alphabet is less than first case but the in total it is possible to transmit more data with using appropriate coding scheme. With cascading n number of second channel, we obtain set of codeword of $S \subseteq X^n = 1{,}2^n$. Therefore it becomes feasible to transmit an arbitrary number $r$ to both receivers where $r \in \{1{,}2{,}\cdots{,}2^{n(C(\alpha\bar{p}+\bar{\alpha}p)-\epsilon)}\}$ and the receiver get an a set of a arbitrary integer:

$$s \in \{1{,}2{,}\cdots{,}(\genfrac{}{}{0pt}{}{n}{[\alpha n]})\}$$

And if the all the n transmitted codes can be correctly decoded we can write :

$$(\genfrac{}{}{0pt}{}{n}{[\alpha n]}) \approx 2^{nH(\alpha)}$$

per each codeword, so it is possible to write the transmission rate for first channel as:

$$R_1 \triangleq \frac{1}{n} \log 2^{nH(\alpha)} 2^{n(C(\alpha\bar{p} - \bar{\alpha}p) - \epsilon)} = C(\alpha\bar{p} - \bar{\alpha}p) + H(\alpha) - \epsilon \tag{3.1}$$

and for second with selection of this codeword we can compute the rate as:

$$R_2 = C(\alpha\bar{p} - \bar{\alpha}p) + H(\alpha) - \epsilon \tag{3.2}$$

In figure 3.2 achievable rate for both case is drawn, as you can see in case of superpositioning the code the overall achievable rate would be higher than any time sharing scheme. For imagining the code word in superpositioning scheme, we can consider that the original data are in the cloud of auxiliary codewords which helps decoding the signal at the receiver.The final codeword anyway should satisfy the superposition coding bound.

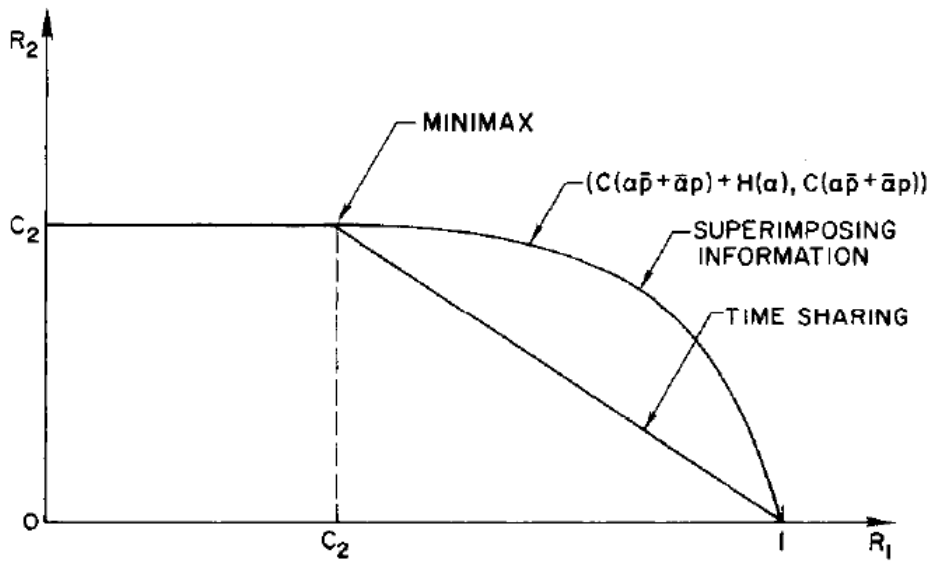


Figure 3.2. Achievable data rate for the set of studied symmetric channel

Many scholars are working toward the obtaining the must optimum codeword with consideration the superposition idea. For example in [35], the authors studied the possibility of using polar coding for instead of more traditional methods of coding and they show that with use of polar it is possible to obtain the better rate with less computational resources in comparison with time sharing scheme discussed in the [34].The authors of [36] proposed a method for generation of Low Density Parity Code(LPDC) with superposition idea and in another subsequent [36] work the writers proposed quasi-cyclic LPDC code with the superposition construction.

## 3.2 SIC(Successive Interference Cancellation)

The Successive Interference Cancellation (SIC) is the set of techniques to detect and later allow to decode the concurrent incoming messages at the receiver. These techniques are widely studied in the literature and number use case and methods for them are developed. For instance in [37] the authors suggested a hybrid SIC technique. In their technique, it is necessary to use an optimal power allocation scheme, then the decoding successively start from the strongest user, with least complexity assigned to it. Then for ensuring the reliability of it, mean square error (MSE) will be performed over several iterations.

$$MSE \triangleq \frac{1}{n}\sum_{t=1}^{n}|X_{k,t} - \widehat{X_{k,t}}|^2 \tag{3.3}$$

As with all MSE techniques, approaching toward zero means better predication and toward one means increased error in the message predication. With aid of the power difference between users, a virtual decoding window of size $w$ will be aligned with present $w$ strongest users for joint processing. Then with decoding the most strong signal and then if it is successfully decoded then the algorithm will continue to decode the second most strong signal and so on. Until a new user join the window. The authors of this scheme claim that, it is less complex while being offering no error propagation. The rationale is that the decoding window would not go forward until it correctly decode the previous one. SIC can be categorized based on the type of decision taking algorithm used in the receiver.

1. Hard SIC:
   In this technique the receiver is sensitive to decision errors, so if the channel quality is not good the performance will deteriorate comparing with non cancellation method which also not possible due to necessity of SIC in NOMA.

2. Soft SIC:
   In this approach the estimates are being based in the bit likelihood value provided by the decoder. So the decoder iterates many number of time between different parts of receiver to improve the estimation and therefore cancellation process. Then at each step the the decoder will assign a log likelihood ratio (LLR) to all bit to ensure that the estimates are correct and cancellation process can be done over signal and at the end the final signal could be decoded.

In the.3.3 the basic application SIC in the NOMA decoder is shown.

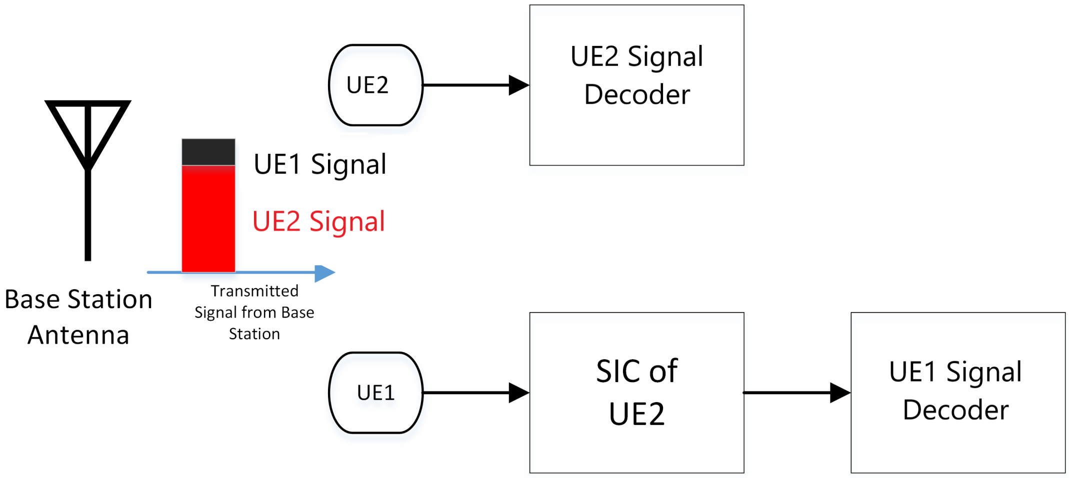


Figure 3.3. The method of using SIC in the multiple access mode for PD-NOMA. The UE1 enjoys more SNR while receiving less power

## 3.3 Comparison Parameters

For comparing the NOMA with its OMA counterparts, some parameters should be defined and investigated to determine whether it is superior or not.

### 3.3.1 Outage Probability

Outage probability defined as the probability when the data rate is less than specified threshold for the rate in other word an outage happens when the specified number of bit errors appears in given transmission so from that it is possible to say outage probability is the probability of occurring such an event. The outage probability of a channel heavily depended on the channel modeling and therefore its impairments. In our case, the outage probability defined as probability of not detecting all of messages with higher power allocation coefficient.

$$P^{out} = P(R_m > \sum_{i=1}^{m} R_i) \tag{3.4}$$

where $R_i$ is the rate at the $i_{th}$ user and $R_m$ is the rate of the user where we want compute outage probability.

### 3.3.2 Ergodic Sum rate

Ergodic sum rate is defined as the maximum viable rate averaged for over all channels. In our case of study we define it as the average rate of viable rate in a unscrupulous way[38]. And from definition of NOMA, the last user should able to decode the all message before him, in other word, it can be said that if we calculate the rate for final user we calculate average sum rate for whole set. Therefore it is possible to write:

$$R_{sum} = \sum_{m=1}^{M-1} \log_2 \left(1 + \frac{\rho\alpha_m|h_m|^2}{1+\rho\alpha_m|h_m|^2}\right) + \log_2\left(1+\rho\alpha_M|h_M|^2\right) \tag{3.5}$$

## 3.4 System Model

Two system model can be described for the PD-NOMA, first as non cooperative network of UEs and secondly the cooperative networks of UEs. In this work, we mainly focused on the non-cooperative mode.

In the our model we work on the performance of NOMA system in downlink(DL) in a Rayleigh Fading channel.

Raleigh fading channel is one of the vastly used model for simulation of the propagation loss over channel medium. its PDF for random variable $r$ can be wrriten as[39]:

$$p(r) = \frac{2r}{P_{avg}} exp(\frac{-r^2}{P_r}) \quad \forall r \geq 0 \tag{3.6}$$

where $P_{avg}$ is the average channel power.

In our studied medium, there are M users and a base station whom serves them as shown in figure 3.4. The channel for each user and base station denoted as $h_i$ with a Raleigh fading channel with aforementioned PDF. The users with best channel condition should get the most power by using the power allocation coefficient denoted as $\alpha_i$. With using these assumption we can transmitted signal from base station will be:

$$x = \sum_{i=1}^{M} \sqrt{\alpha_i P} s_i \tag{3.7}$$

where M is the number of active users served by the base station and $P_{S_i}$ is the transmitted power of message $S_i$ ongoing to a user $i$.

From above, we can assume that in each receiver the received message will be:

$$y_m = h_m \sum_{i=1}^{M} \sqrt{\alpha_i P} s_i + n_m \tag{3.8}$$

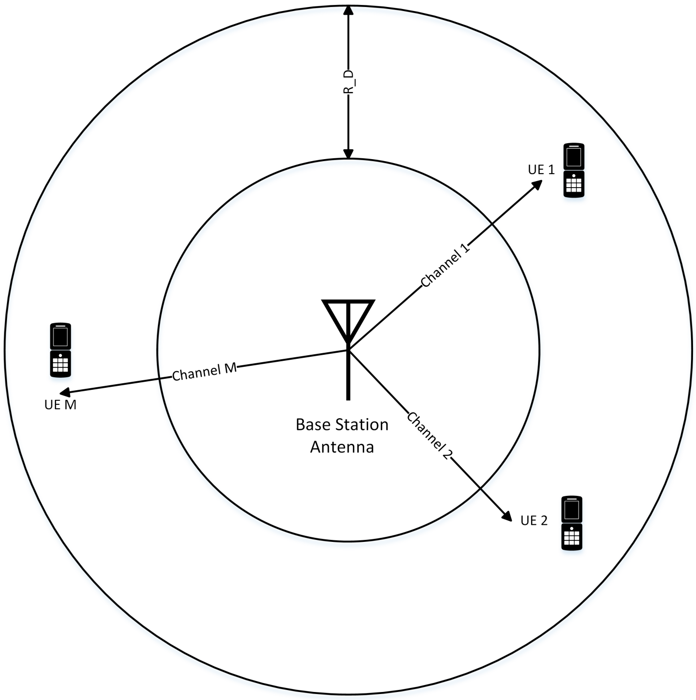


Figure 3.4. Architecture of system in Downlink. The users are randomly deployed in a disk with width of $R_D$

where $y_i$ is received signal at the user $i$ and $n_m$ is channel noise for channel of user $m$ a.k.a. $h_m$ . In our model, each user device comes with Interference Cancellation technique included in the device. So using the formula derived in previous chapter we can write the achievable rate for each users as:

$$R_m = \log_2\left(1 + \frac{\rho|h_m|^2\alpha_m}{\rho|h_m|^2\sum_{i=m+1}^{M}\alpha_i + 1}\right) \tag{3.9}$$

on prerequisite of $R_{j\to m} \geq \tilde{R}_j$ where $\rho$ is the signal to noise ratio (SNR) and $R_{j\to m}$ denotes the rate in which user $m$ can still decode $j_{th}$ user messages and can be calculated from:

$$R_{j\to m} = \log_2\left(1 + \frac{\alpha_j|h_m|^2}{|h_m|^2\sum_{j=1}^{m-1}\alpha_j}\right) \tag{3.10}$$

Similarly for the user $M$, the rate can be written as:

$$R_M = log(1 + \rho|h_M|^2\alpha_M) \tag{3.11}$$

As said before the goal is showing the supiority of NOMA over OMA in two meters defined above.

### 3.4.1 Outage performance of NOMA

In previous section, the outage probability was defined as:

$$P^{out} = P(R_m > \sum_{i=1}^{m} R_i)$$

This means that the user $m$ should be able to decode all the users with higher channel gain than itself. For instance user $m$ should be able to decode user $i$ for $m < i$, if the user index are ordered through channel gain i.e. $|h_1|^2 < |h_2|^2 \cdots < |h_M|^2$ and we denote such events as:

$$\begin{aligned}
\hat{E}_{m,i} &= \left\{\frac{\alpha_i(\rho|h_m|^2)}{\rho|h_m|^2 \sum_{j=i+1}^{M} \alpha_j + 1} > \phi_i\right\} \\
&= \left\{\left(\rho|h_m|^2\right)\frac{\alpha_i}{\rho|h_m|^2 \sum_{j=i+1}^{M} \alpha_j + 1} > \phi_i\right\} \\
&= \left\{\left(\rho|h_m|^2\right)\alpha_i > \phi_i(\rho|h_m|^2 \sum_{j=i+1}^{M} \alpha_j + 1)\right\} \\
&= \left\{\left(\rho|h_m|^2\right)\alpha_i - (\phi_i\rho|h_m|^2 \sum_{j=i+1}^{M} \alpha_j) > \phi_i\right\} \\
&= \left\{\left(\rho|h_m|^2\right)(\alpha_i - \phi_i \sum_{j=i+1}^{M} \alpha_j) > \phi_i\right\}
\end{aligned} \tag{3.12}$$

where $\phi_i = 2^{\hat{R}_J} - 1$ and $\alpha_i - \phi_i \sum_{j=i+1}^{M} \alpha_j > 0$.
So by definition outage when occurs in which there any of aforementioned events does not occur,

$$\begin{aligned}
P_m^{out} &= 1 - P\Big(\bigcap_{i=1}^{m} \hat{E}_{m,i}\Big) \\
&= 1 - P\Big(\bigcap_{i=1}^{m}((\rho|h_m|^2)(\alpha_i - \phi_i \sum_{j=i+1}^{M} \alpha_j) > \phi_i)\Big) \\
&= 1 - P\Big(\bigcap_{i=1}^{m}(|h_m|^2 > \frac{\phi_i}{\rho(\alpha_i - \phi_i \sum_{j=i+1}^{M} \alpha_j)})\Big)
\end{aligned} \tag{3.13}$$

for sake of simplification of the formulas, $\psi$ defined as:

$$\psi_i = \frac{\phi_i}{\rho(\alpha_i - \phi_i \sum_{j=i+1}^{M} \alpha_j)} \tag{3.14}$$

rewriting the 3.13,

$$P_m^{out} = 1 - P(\bigcap_{i=1}^{m}(|h_m|^2 > \phi_i) \tag{3.15}$$

it is possible to further simplify the formula,

$$\begin{aligned} P_m^{out} &= 1 - P(|h_m|^2 > \psi_m^*) \\ &= F_{h_m^2}(\psi_m^*) \end{aligned} \tag{3.16}$$

where $\psi_m^* = \max_{m+1 \le i \le M} \psi_i$ and $F_{h_m^2}(\psi_m^*)$ is the Cumulative Distribution Function (CDF) of Rayleigh fading channel for channel $h_m$ for the users located in the disk of $\mathcal{D}$ with radius of $R_D$ is rendered by [40]:

$$\begin{aligned} F_{|\hat{h}|^2}(z) &= \frac{2}{R_D^2}\int_0^{R_D}(1 - e^{-(1+z^\alpha)y})zdz \\ &= 1 - 2\binom{M}{m}\sum_{i=0}^{M-m}\binom{M-m}{i}\frac{(-1)^i}{D^{2(m+i)}}\int_0^{R_D} e^{-zx^a}x^{2(m+i)-1}dx \\ &= 1 - 2\binom{m}{M}\sum_{i=0}^{M-m}\binom{i}{M-m}\frac{(-1)^i}{D^{2(m+i)}}\frac{z^{-\frac{2(m+i)}{\alpha}}}{\alpha}\gamma(\frac{2(m+i)}{\alpha}, zD^\alpha) \end{aligned} \tag{3.17}$$

Where $x = \psi_{max}^*$ and $\gamma(x, y) = \int_0^y t^{x-1}e^{-t}dt$. With some simplification and substitution from [41], below reached:

$$P_m^{out} = \int_0^{\psi_{max}^*} \frac{M!(F_{|\hat{h}|^2}(x))^{m-1}(1 - F_{|\hat{h}|^2}(x))^{M-m} f_{|\hat{h}|^2}(x)}{(m-1)!(M-m)!}dx \tag{3.18}$$

In [38] the authors showed whem the $y \to 0$ the CDF of disordered channel gains can be approximated as :

$$F_{|\hat{h}|^2}(y) \approx \frac{1}{R_D}\sum_{n=1}^{N}\beta_n y \tag{3.19}$$

and from it, the PDF can be obtained as:

$$f_{|\hat{h}|^2}(y) \approx \frac{1}{R_D}\sum_{n=1}^{N}\beta_n(1 - c_n y) \tag{3.20}$$

where $N$ is the complexity trade-off factor, $c_n = 1 + \frac{R_D}{2}(\theta_n + 1)^\alpha$, $\beta_n = \omega_n\sqrt{1 - \theta_n^2}\frac{R_D}{2}(1 + \theta_n)c_n$, $\omega_n = \frac{\pi}{N}$ and $\theta_n = \cos(\frac{2n-1}{2N}\pi)$. Rewriting equation

(3.18) :

$$
\begin{aligned}
P_m^{out} &= \int_0^{\psi_{max}^*} \frac{M!(\frac{1}{R_D}\sum_{n=1}^{N}\beta_n x)^{m-1}(1-\frac{1}{R_D}\sum_{n=1}^{N}\beta_n x)^{M-m}\frac{1}{R_D}\sum_{n=1}^{N}\beta_n(1-c_n x)}{(m-1)!(M-m)!}dx \\
&= \frac{M!}{(m-1)!(M-m)!}\int_0^{\psi_{max}^*}(\zeta x)^{m-1}(1-\zeta x)^{M-m}\frac{1}{R_D}\sum_{n=1}^{N}\beta_n(1-c_n x)dx \\
&\approx \frac{M!}{(m-1)!(M-m)!m}\zeta^m(\psi_{max}^*)^m
\end{aligned}
\tag{3.21}
$$

where $\zeta = \frac{1}{R_D}\sum_{n=1}^{N}\beta_n$.
The above result can be used for assessing the outage performance in high SNR regions. It can be noticed that in that regions the outage probability tends to solely depend on the SNR and the user order in the network. meaning the first users should have very SNR ratio, to be capable of decoding their messages. In the next chapter, in the simulation it showed that the above used scheme offer better performance in comparison to the Orthogonal multiple accesses while offering more fairness into system in high SNR regimes.

## 3.5 Ergodic Capacity Performance

In this section the performance of the NOMA mathematically evaluated in two part, first it studied over high frequencies and later we try to find out the asymptotic approximation of ergodic sum rate when the number of users grow to large numbers. In the [38] authors suggested that we can compute the ergodic from :

$$
R_{ave} = \sum_{m=1}^{M-1}\int_0^{\infty}\log_2(1+\frac{x\rho a_m}{1+x\rho\tilde{a}_m})f_{|h_m|^2}(x)dx+\int_0^{\infty}\log_2(1+x\rho a_M)f_{|h_M|^2}(x)dx
\tag{3.22}
$$

when the the user $j$ can correctly decode its own message at its given rate.

### 3.5.1 High SNR Approximation

In the equation 3.5, Ergodic sum rate calculated for specific condition. In [38] the authors demonstrated that for the Raleigh fading channel the upper formula can be altered into:

$$R_{ave} = \sum_{m=1}^{M-1} \int_0^\infty \log_2(1+\frac{a_m}{\tilde{a}_m}) f_{|h_m|^2}(x)dx + \int_0^\infty \log_2(1+x\rho a_M) f_{|h_M|^2}(x)dx \tag{3.23}$$

when the $\rho \to \infty$. Rewriting the latter part of equation as:

$$T_1 = \frac{\rho a_M}{\ln 2} \int_0^\infty \frac{1 - F_{|h_M|^2}(x)}{1 + x\rho a_M} dx \tag{3.24}$$

where $F_{|h_M|^2}(x)$ is the CDF of channel gain. In [38] the authors the $F_{|h_M|^2}(x)$ calculated as:

$$F_{|h_M|^2}(x) = \frac{1}{R_D} \sum_{n=0}^{N} b_n e^{-C_n x} \tag{3.25}$$

whereas:

$$b_n = -\omega_N n \sqrt{1-\theta_n^2} (\frac{R_D}{2}\theta_n + \frac{R_D}{2}) \; for\ 2 \ \le n \le N$$
$$b_0 = -\sum_{n=1}^{N} b_n$$
$$c_0 = 0$$

so we have for the $M_{th}$:

$$F_{|h_M|^2}(x) = (F_{|\tilde{h}|^2}(x))^M$$

So the $T_1$ will be:

$$T_1 = \frac{\rho a_M}{\ln 2} \int_0^\infty \frac{1}{1+x\rho a_M} (1 - \frac{1}{R_D} \sum_{k_0+\cdots+k_N=M} \binom{M}{k_0+\cdots+k_N} (\prod_{n=0}^{N} {b_n}^{k_n}) e^{-\sum_{n=0}^{N} k_n c_n x}) dx \tag{3.26}$$

note that $\binom{M}{k_0+\cdots+k_N} = \frac{M!}{k_0!\cdots k_N}$.

So we can rewrite 3.26 by multiplying its inner elements and then using the above:

$$T_1 = \frac{\rho a_M}{\ln 2} \int_0^\infty \frac{1}{1+x\rho a_M} dx - \frac{\rho a_M}{R_D \ln 2} \int_0^\infty \sum_{k_0+\cdots+k_N=M} \binom{M}{k_0+\cdots+k_N} (\prod_{n=0}^{N} {b_n}^{k_n}) e^{-\sum_{n=0}^{N} k_n c_n x}) dx \tag{3.27}$$

The first part of $T_1$, it can be calculated through:

$$\frac{\rho a_M}{\ln 2}\int_0^\infty \frac{1}{1+x\rho a_M}dx = \frac{\rho a_M}{\ln 2}[\frac{\ln(x\rho a_M+1)}{\rho a_M}]_0^\infty$$

which clearly shows it does not exist in its bounds.
But for second part, under consideration of $F_{|\tilde{h}|^2}(\infty) = 1$ we can assume:

$$\binom{M}{k_0 \cdots K_N}(\prod_{n=0}^{N} b_n k_n)e^{-\sum_{n=0}^{N} k_n c_n x} = R_D^M \tag{3.28}$$

where:

$$k_0 = M$$
$$k_i = 0 \ \ , \ for\ 1 \geq i \geq N$$

with the above:

$$T_1 = -\frac{\rho a_M}{R_D \ln 2}\int_0^\infty \sum_{k_0+\cdots+k_N=M} \binom{M}{k_0+\cdots+k_N}(\prod_{n=0}^{N} {b_n}^{k_n})e^{-\sum_{n=0}^{N} k_n c_n x})dx \tag{3.29}$$

is true for every input that does not zero the exponential power exponent to zero.
So with using 3.29, in [38] the equation 3.23 approximated to:

$$\begin{aligned} R_{ave} &= (\sum_{m=1}^{M-1} \log_2 1 + \frac{a_m}{\tilde{a}_m}) \\ &- \frac{1}{R_D^M \ln 2}\sum_{k_0+\cdots+k_N=M, K_0\neq M} \binom{M}{k_0+\cdots+k_N}(\prod_{n=0}^{N} {b_n}^{k_n})e^{\frac{\sum_{n=0}^{N} k_n c_n}{2\rho a_M}} \\ &\times (\frac{\sum_{n=0}^{N} k_n c_n}{\rho a_M})^{-\frac{1}{2}} W_{(-\frac{1}{2},0)}(\frac{\sum_{n=0}^{N} k_n c_n}{\rho a_M}) \end{aligned} \tag{3.30}$$

where $W_{(k,u)}(z)$ is Whittaker $W$ function, Which itself is a solution to its equation and can be written as:

$$W_{k,u}(z) = e^{\frac{-z}{2}} z^{u+\frac{1}{2}} U(u-k+\frac{1}{2}, 1+2u, z)$$

where is $U(a,b,z)$ is Tricomi's (confluent hypergeometric) function.
It is important to note that other approximation equations also studied in recent years. For instance in [42] the authors suggested much less resource

consuming approximation equation for calculating ergodic sum rate. This important for better resource allocation techniques in case of large number of users. So we have:

$$R_{ave}^{sum} = \underbrace{\sum_{n=1}^{N-1} E(\frac{1}{2}\log_2(1+\gamma_{RD_N}))}_{R_{ave}^{\hat{N}}} + \underbrace{E(\frac{1}{2}\log_2(1+\gamma_{RD_N}))}_{R_{ave}^{N}} \tag{3.31}$$

where,

$$R_{ave}^{\hat{N}} \approx \log_2(1+\frac{a_n}{\hat{a}_n}) \tag{3.32}$$

and

$$R_{ave,UB}^{N} = \frac{1}{2\ln 2}\sum_{k=1}^{N}(-1)^{k+1}\binom{k}{N}\{P_1+P_2+P_3+P_4\} \tag{3.33}$$

with substituting the values of 3.33 and 3.32 into 3.31 we can obtain the ergodic sum rate for last user.
note that in 3.32 the values of $P_1, P_2, P_3$ *and* $P_4$ obtained through followings:

$$P_1 = -e^{\frac{\theta}{\Omega_{SR}}}$$

$$p_2 = \sum_{l-=0}^{\infty} \frac{\rho_k^{l+1}}{l!(l+1)!}(\ln\rho_k + 2C - \sum_{a=1}^{l}\frac{1}{x} - \sum_{a=1}^{l+1}\frac{1}{x})$$

$$P_3 = (-2)^l e^{\frac{\theta}{\Omega_{SR}}} Ei(\frac{\theta}{\Omega_{SR}}) + \sum_{t=1}^{l+1}(-1)^{l+1-t}(t-1)!(\frac{\theta}{\Omega_{SR}})^{-t}$$

$$P_4 = \sum_{l-=0}^{\infty} \frac{\rho_k^{l+1}}{l!(l+1)!}^{l+1}[\psi(l+1) - ln(\frac{\theta}{\Omega_{SR}})]$$

where Ei(x) is Special Exponential integral and in [43] defined as the integral of the ratio of exponential power to its exponent in known bound. Other used functions and variables are very similar to what used before.

### 3.5.2 Asymptotic analysis of large users numbers

We can analyze the asymptotic behavior when the number of user goes to infinity i.e. $M \to \infty$. Likewise previous section with approximation of equation 3.22 with defining growth function as $G(x) \triangleq \frac{1-F_{|\hat{h}|}^2(x)}{f_{|\hat{h}|}^2(x)}$, which in appendix 1, below, it is proven that the $\lim_{x\to\infty} G(x)$ exists.

$$\lim_{x\to\infty} G(x) = \lim_{x\to\infty} \frac{1-\frac{1}{R_D}\sum_{n=0}^{N} b_n e^{-c_0 x}}{\frac{1}{R_D}\sum_{n=0}^{N}\beta_n e^{-c_0 x}} = \frac{-b_n}{\beta_N} \tag{3.34}$$

In 3.34, the result obtained in following condition:

$$\frac{1}{R_D} b_0 e^{-c_0 x} = 1$$
$$c_N \leq c_i \; for \; all \; 1 \leq i \leq N$$

With asymptotic behaviour of channel gain, we have a unique solution to the

$$1 - F_{|\hat{h}|^2}(u_M) = \frac{1}{M}$$

with rewriting it:

$$-\frac{1}{R_D} \sum_{n=1}^{N} b_n e^{-c_n u_M} = \frac{1}{M} \tag{3.35}$$

when $u_m \to \infty$ :

$$-\frac{b_n e^{c_N u_M}}{R_D}(1 + O(\frac{1}{u_M}) = \frac{1}{M} \tag{3.36}$$

from [44], the solution for $u_m$ found as:

$$u_M = \frac{1}{C_N} \log(M) + O(\log \log M) \tag{3.37}$$

so from previous results the [38], formulated asymptomatic ergodic rate bound to:

$$R_{ave} \to \log(\rho \log \log M) \tag{3.38}$$

and when $M \to \infty and \, \rho \to \infty$ it approaches to one. In opportunistic scenario the performance of the NOMA will be same with OMA but with much better fairness.

# Chapter 4

# Simulation

In this chapter we analyse the NOMA in several scenarios in previously discussed parameter that we analysed mathematically.

## 4.1 Simulation Part 1:

In this section we have demonstrated that power domain non orthogonal multiple access will almost match our theoretical models. In Figure 4.1 we compared outage performance of 3.18 with the model calculated by Ding et al in [38].

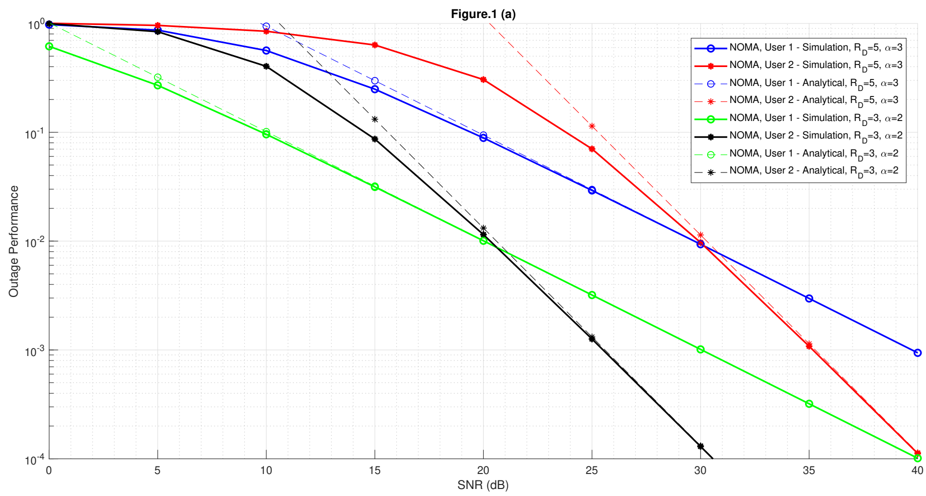


Figure 4.1. Outage probability of the NOMA in different situation

The simulation done in a setting shown in table 4.1:

| | $R_D$ | $\alpha$ | $\tilde{R}_1$ | $\tilde{R}_1$ |
|---|---|---|---|---|
| case 1 | 5 | 3 | 0.1 | 0.5 |
| case 2 | 3 | 2 | 0.1 | 0.5 |

and for the power allocation to users the in [38] they offered simple method to allocate appropriate amount of power to each user. In this simulation we continued to use their methods. Their algorithm can be summarised as:

**Algorithm 1:** Power Allocation Algorithm in NOMA

```
Result: Power allocation coefficient
initialization : Get the number of users;
if M = 2 then
    a_1 = 0.8;
    a_2 = 0.2;
else
    i = 0 ;
    u = 0 ;
    while i ≤ M do
        u = u + (M − m + 1);
        i + + ;
    end
    i = 0 ;
    while i ≤ M do
        a_i = (M−i+1)/u ;
        i + + ;
    end
end
```

| | $R_D$ | $\alpha$ | $\tilde{R}_1$ | $\tilde{R}_1$ |
|---|---|---|---|---|
| case 1 | 5 | 3 | 1 | 1 |
| case 2 | 5 | 3 | 3 | 3 |

From the simulation we can understand that outage performance of the NOMA in high SNR regions will reach its theoretical values. It is important to keep in mind that any inadequate choice of the power allocation, the outage will be certain or the performance will degrade significantly as shown in figure 4.2 as different values had been chosen for power allocation coefficient, further more also the incorrect choice of guaranteed serveries rate also cause the probability tank to one. In figure 4.3 this issue has been demonstrated with the selection of wrong $\tilde{R}_J$, the outage probability will be one.

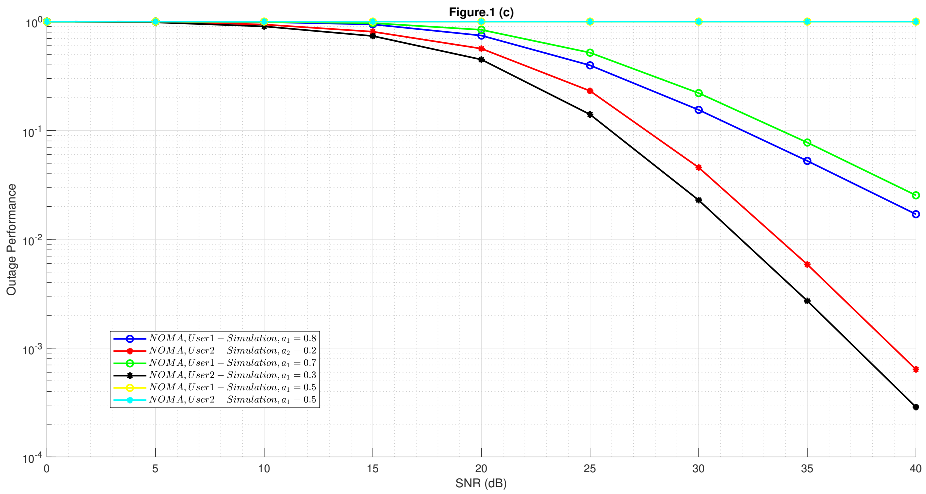


Figure 4.2. Outage probability when the inadequate power allocation coefficient selected.

Therefore more sophisticated approaches power allocation and rate distribution are studied for instance in [45], optimal power allocation model of NOMA for 2 users, under various scenarios has been studied. The power allocation of multi user NOMA is more difficult although the used criterion are same. Some of those criterion are Max/Min fairness (MMF), weighted sum rate Maximization and QoS constraint sum rate maximization.

## 4.2 Simulation Part 2:

Along with last section, the performance of NOMA also analysed by simulating the Ergodic sum-rate of in various scenarios. In the first scenario we analyse the performance of the approximation made by [38] to the equation 3.22 in different states, then we continue with the analysing with respect to number of users to verify its functionality with increase number of users. In the first case, we analysed two cases with respect to the SNR to see the accuracy of our model.

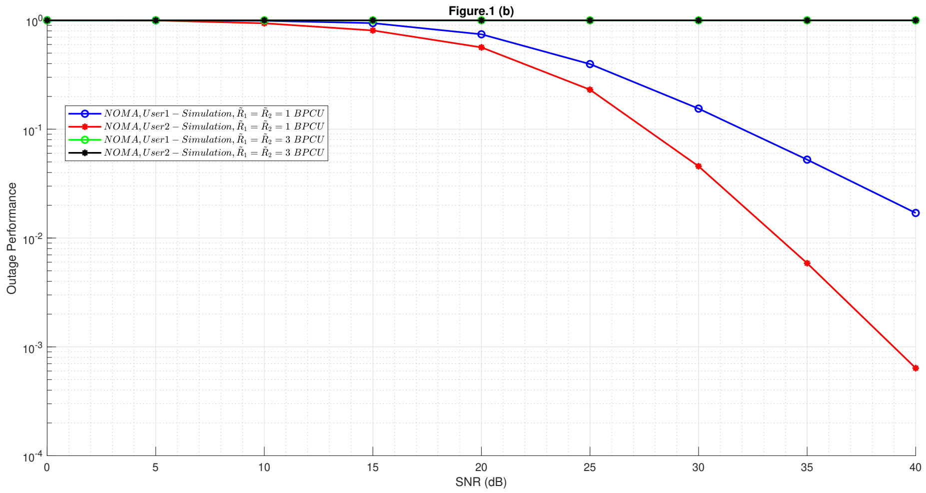


Figure 4.3. Outage probability when inadequate rate allocation coefficient selected.

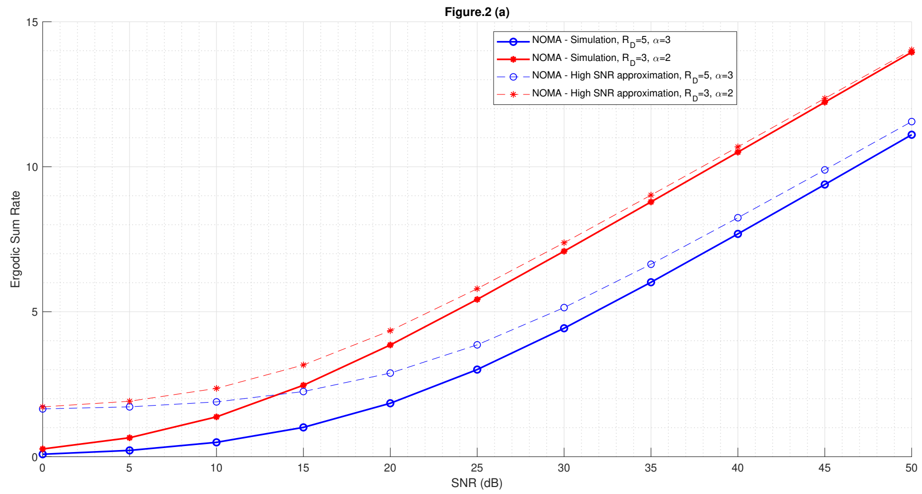


Figure 4.4. Ergodic Sum-rate of NOMA .

As shown in Figure 4.4 we could notice at the low SNR our model has much more error rate margin, but with increase of SNR the our tends to be more accurate. Thus it is recommended it this model only to be used where the user can achieve high SNR. More detail of the simulation parameters are displayed in table 4.2 .

| | $R_D$ | $\alpha$ |
|---|---|---|
| case 1 | 3 | 2 |
| case 2 | 5 | 3 |

In the figure 4.5, the performance of NOMA has been analysed with different number of users to show the feasibility of the algorithm in larger number users. One of the main issues which still remained in the approximation is the huge amount of computational power is required to compute the Whitaker function which in essence makes the feasibility of system when there are many users are available to be served. Simpler algorithms are suggested as mentioned in previous chapter. Returning to the simulation results, the results are very promising even if the number users increased by large margin although there are still some drawbacks in low SNR region, in which it is possible to use better SIC techniques at the receivers to partially mitigate the issue. But it is important to find better solutions to resolve the issues. One of the techniques can be use of orthogonal multiple access methods in other bands to maintain connectivity of user. Other methods can be use of beamforming for achieving higher SNR at the receiver.

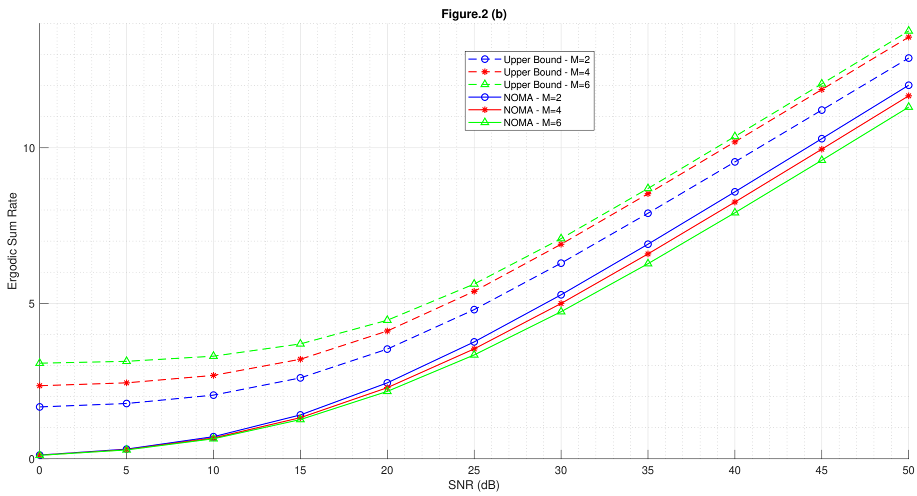


Figure 4.5. Ergodic Sum-rate of NOMA with respect to the number of users.

## 4.3 Simulation Part 3:

In the last section of the simulation we have analysed the outage performance of NOMA in more realistic scenarios. The simulation variables are described in the table 4.3:

| | $R_D$ | $\alpha$ | $\tilde{R}_1$ | $\tilde{R}_1$ |
|---|---|---|---|---|
| case 1 | 80 | 3 | 0.1 | 0.5 |
| case 2 | 80 | 3 | 0.2 | 0.6 |
| case 3 | 100 | 3 | 0.1 | 0.5 |
| case 4 | 100 | 3 | 0.2 | 0.6 |

and for all case the transmitting power and noise are respectively 10 Watt and -40 dBm.
As shown in the table 4.3 NOMA still performs well in the realistic condition. Even in range larger distance than 80 meter we get acceptable performance. As written in previous chapters and section the NOMA is relatively short studied subject and many improvement can be augmented over its algorithms, although the base theory goes back to the 1970s. For instance in [46] the authors has achieved the to more robust model meanwhile their modeling system seems to be less resource exhaustively compared to used model in this thesis, which will an important element in the next generation of telecommunication system due to widespread use of small base station to offer mm-Wave bands to users.

| $\times 10^{-4}$ | case 1 | case 2 | case 3 | case 4 |
|---|---|---|---|---|
| User 1 -simulation | 3.7803 | 7.9862 | 7.3817 | 16.00 |
| User 1 -analytical | 3.7812 | 7.990 | 7.3852 | 16.00 |
| User 2 -simulation | 0.1824 | 0.2824 | 0.6917 | 1.0689 |
| User 2 -analytical | 0.1837 | 0.2847 | 0.7007 | 1.0863 |

Table 4.1. Outage performance of NOMA in realistic conditions

# Chapter 5

# Future developments

In this chapter briefly the foreseeable future development of Non-orthogonal Multiple Access (NOMA) is surveyed.

## 5.1 NOMA-MIMO

One the main point of focus in current and next generation of telecommunication systems is the extensive use of MIMO for improving the achievable throughput of the users in the network. MIMO has been extensively studied in the conventional OMA like TDMA. There are some studies done by scholars to survey feasibility and performance analyses of the NOMA-MIMO system. In most researches the system considered as a set of clusters where in each cluster there are several users and for serving these users simultaneously NOMA has been proposed and studied. For example in [47] Ding et al. studied application of MIMO in NOMA have shown that with correct choice of power distribution coefficient with right allocation of available bit rate the NOMA-MIMO can outperform the orthogonal multiple access techniques. In [48] the writers, worked over a method for a fair resource allocation for users within a newly defined criteria which expressed as "relative fairness" which accumulate the network wide fairness with maximisation of the allocated rate to the user. Later on in their work, a algorithm is proposed to calculate such a definition in reasonable amount of computation resource.

## 5.2 NOMA-Beamforming

Similar to clustered NOMA-MIMO, the base station creates several beams to serve many users. But unlike clustered version of NOMA-MIMO, in Beamformaing NOMA-MIMO each user exclusively gets access to each beam therefore limiting the required SIC operations to decode the message.

## 5.3 NOMA- mm-wave radio

One of the main advancement of 5G will be use of mm-wave bands to coupe ever increasing demands in data transmission rate. One of the main issues of mm-wave is design of antenna to put in the cellular mobile equipment. The limited space and high frequency diversity of 5G makes it difficult to design a single unitary antenna to operate at all frequencies. The situation get worth if the MIMO and massive MIMO also included because of large antenna array they are required to use, to operate properly. This issues are almost non existent in the PD-NOMA because of usage all band to transmit data to the users.Using together with MIMO-NOMA which increase spatial diversity of network and thereof performance of the system makes NOMA ever more interesting. Unfortunately the mm-wave NOMA is not well studied in the literature but for starting point, in the [49] Zhu et. al surveyed a sub-optimal solution to maximization of sum-rate of the NOMA based mm-wave system for two users system. One of the issues that they faced was the increase of the complexity of power allocation techniques used in NOMA with increase number of users. In a follow up work Zhu et. al, suggested another approach for power allocation in NOMA by defining the metric as the User fairness and showed that although their result approaximated the ideal situation but the method per se was suboptimal.[50]

# Conclusion

The fifth generation of mobile networks is a very promising meanwhile complex system. One of the main aspects of every modern mobile network is to provide service to multiple users, simultaneously. To achieve this goal, we have first, briefly analysed the Orthogonal multiple access techniques used in the previous generation of mobile networks. Then we have shown that in any broadcast channel the non-orthogonal multiple access will perform better than OMA counterpart.
From various NOMA techniques, we first model the Power Domain NOMA. Then using MATLAB program, we demonstrated that the NOMA can keep up the performance in the high SNR regions as the mathematical model which per se are Superior to OMA. The performance of NOMA was analysed in a more realistic scenario and the results looked very promising.
Future works in PD-NOMA can focus toward more robust and efficient Power allocation systems. Design of specialized version Interference Cancellation techniques are also very promising and their usage is not limited to only NOMA.

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