Department of Electronics and

Electrical Communications Engineering

Faculty of Engineering-Cairo University

Next-Gen Communication Technology

Represented to: Dr. Samah EL-Tantawy

BY: Next-Gen Team

Abstract

Introduction

Since the invention of the telegraph in the middle of the nineteenth century, the digital tools for communication are improving significantly. One of the first nations that used these innovations, such as the telephone, telegraph, mobile phone, etc., was Egypt. On the other hand, there are actual problems with digital communications development in Egypt today that are visible to everyone. The development of mobile networks serves as an illustration of that. In terms of mobile networks, 6G is currently the most talked-about topic worldwide; Egypt expects to formally use 5G by the beginning of 2025 [1]. This problem is found in almost all other technologies, like Wi-Fi, radio, etc. So, the questions now are, is it important to intensify efforts in these fields? And what can we do to enhance our performance in communication?

Importance of investment in communications

In this paper we will be associated with wireless communications, specifically mobile internet, so to answer the first question we need to know the importance of this field. Firstly, investing in this field can enhance our economic drive because it has a positive effect on economic growth, as studies indicate that information and communication technology investments can increase productivity and provide many jobs [2], and we can see the importance also in 5G technologies effect on the global economy; it is estimated that it alone will contribute hundreds of billions of dollars to the global economy [3]. Also, we see the role of it in the digital transformation of societies as enabling new services, such as smart cities and others, and we can see digitalization in deeper details [4]. Secondly, we all know that the number of devices connected to the Internet is constantly increasing and will reach 500 billion devices by 2030 [5], and with this increasing communication problems will appear that make us need to continuously develop. Also, exponential growth of Internet data as the amount of data transferred over the Internet doubles approximately every two years, as we see in [6].

So we can say that the answer is yes; we must put effort into this field, trying to keep pace with the outside world. Starting from this point, we will take the part of mobile internet to study it and the ability to improve it, trying to answer the second question. Now we need to identify the requirements that we need to make it better to start working on them.

Mobile internet requirements

Data rate is the most prominent factor when we talk about improving mobile internet; it is one of the factors that we need to improve, and it combines with other factors in what is called by 3GPP (an international collaboration between seven telecommunications standard development organizations) Enhanced Mobile Broadband (EMBB). EMBB is designed to provide higher data rates, better bandwidth, higher throughput, increased reliability, and lower latency [7]. Also, one of the problems is that the frequency spectrum is currently saturated, which must be overcome when it is transmitted [8]. In addition to the air interference with the signals and diffraction from buildings, security and privacy are also issues that mobile internet developers must deal with. As a result, we can see that there are many aspects we could study to improve them more. Before studying how to improve these parameters and to see more the importance of investing more effort and time in mobile networks, we need to take a look at the generations and their needs.

The Evolution in generations

The emergence of the first generation of wireless communication technology (1G) [9] was a milestone in the world of mobile communications as it appeared in the early 1980s. It was a leap from wired communication to wireless communication, and it has pros as transmitting sound easily and some cons as low communication quality, resistance to obstacles, and limited simultaneous communication capacity. (2G) [10] emerged in the 1990s, heralding the shift from analog to digital communication. It has some pros, such as improved voice clarity, text messaging (SMS), and basic data services like email and rudimentary web browsing. It also had some cons, as data speeds were still quite slow with limited capacity; its data speed is up to 64 kbps. (3G) [11] represented a major leap in the field of mobile communications by offering high-speed data transmission capabilities. It has some pros, such as enabling web browsing, making video calls, and basic online services. It also had some cons, such as that it was not ideal for smooth streaming of high-quality multimedia content and 3G coverage was not universal. Its data speed ranges from 384 Kbps to 2 Mbps. With the advent of the (4G) [12] networks in the late 2000s. It has some pros, as 4G technology delivers high-speed mobile broadband, enabling seamless HD video streaming and low latency. It also has some cons, as it cannot cover some areas, and it also needs significant infrastructure upgrades. Its data speed ranges from 100Mbps to 1Gbps. (5G) [13] which began to be rolled out in 2016, promised to connect not only people but also machines, objects, and devices in an Internet. It has some pros as ultra-fast data speeds, dramatically reducing download and upload times, low latency, and revolutionizing the IOT landscape with its ability to connect a large number of devices. It also has some cons as deploying dense infrastructure due to its use of higher frequencies, which can be costly and time-consuming. 5G signals have a shorter range compared to previous generations, requiring more cell towers and infrastructure. Its data speeds can range from 1 Gbps to 10 Gbps, enabling nearly lag-free experiences for applications such as virtual reality, augmented reality, and remote control. As we look to the future, the development of (6G) [14] networks has already begun. While 5G networks are still being deployed and integrated into various sectors, researchers and technologists are envisioning the potential of 6G networks. It may have some predicted pros, as 6G technology aims to achieve data speeds that may exceed 100 times those provided by 5G technology, reducing latency. It may have some predicted cons, as achieving ultra-low latency presents significant technical hurdles and Implementing advanced 6G technology on a global scale will be complex and expensive. 6G technology is expected to deliver data speeds of 1 terabits per second or more, enabling fast data exchange for extremely data-intensive applications and immersive experiences. We search for techniques to improve mobile network generation to keep up with modern technology and make the data transfer process more efficient. As we mentioned before, there are some needs in mobile networks like high data rates, low latency, better bandwidth, high throughput, and high reliability. So, we need to know how to deal with these requirements.

Some techniques to improve mobile network

In the early days of wireless communication, signals were sent from one antenna to another. This setup worked, but it had limits. It was easy to get interference, and it could only send a small amount of data at once. Over time, **MIMO (Multiple-Input Multiple-Output)** [15] technology was developed to improve this. MIMO uses several antennas at both the transmitter and receiver. By sending signals at the same time from different antennas, it can send more data at once, which makes the connection faster and more reliable. As the need for faster networks grew, new technologies were created to help MIMO work even better. Intelligent Reflecting Surfaces (IRS) were developed to help reflect signals in the right direction, especially in cities where buildings block signals. Terahertz (THz) communication works at higher frequencies than 5G, offering super-fast data speeds, but it can lose strength quickly over distance. MIMO and IRS help solve this problem by keeping the signals strong. Artificial Intelligence (AI) also started being used to make MIMO smarter. AI can help adjust signals in real time, making the network more efficient and responsive. Finally, Cell-Free MIMO was introduced to remove the need for fixed cell towers. Instead of relying on one tower to cover a large area, cell-free MIMO connects users to antennas spread out over a large space, reducing interference and providing better coverage, especially in crowded areas.

There is another technique to try to improve data rates called **MR-NOMA** [16] **(**Multi-symbol rate Non-Orthogonal Multiple access) are generally divided into Orthogonal Multiple Access (OMA) and Non-Orthogonal Multiple Access (NOMA). In OMA, each user has a separate bandwidth, power, bit rate, and symbol rate. Frequency Division Multiple Access (FDMA) is a common example of OMA, while power-domain NOMA assigns users a shared spectrum. In NOMA, users typically share the same bandwidth and symbol rate, though bit rates vary through different modulation orders. Power allocation helps manage multi-user interference in NOMA.MR-NOMA (Multi-Rate NOMA) is a more flexible NOMA variant allowing different symbol rates for users, facilitating variable data rates and improved Quality of system for each user. The detection process for MR-NOMA can be handled by series interface cancellation with adjustments for differing symbol rates. In uplink MR-NOMA, users with various symbol durations are paired based on channel strength, Quality of system and distance from the base station. To ensure synchronized transmission, symbol periods are structured as integer multiples of one another, allowing the base station to process a unified sampling rate and efficiently manage power distribution across channels with stable fading characteristics. MR-Noma has some challenges as Interference Management, Power and Energy Optimization, User Pairing Complexity, Channel State Information and Practical Implementation Limitations.

Low-latency communication [17] is one of the most important application scenarios in next generation wireless networks. Often in communication-theoretic studies latency is defined as the time required for the transmission of a packet over a channel. However, with very strict latency requirements and complexity constrained receivers, the time required for the decoding of the packet cannot be ignored and must be included in the total latency. In 6G networks, achieving an end-to-end latency of 0.1 ms is a key goal for many applications such as AR/VR Headsets, which require low latency for seamless transition and high frame rates. AI Network Slicing is a crucial enabler to support the composition and deployment of virtual network infrastructures required by the dynamic behavior of networks like 5G/6G mobile network and industry verticals like the internet of vehicles and industry. In general, the slicing process results from the need to share resources among existing infrastructures to improve performance, provide cost-efficient solutions, and optimize operations. The lifecycle of network slicing mainly includes three phases: preparation, planning, and operation. During the preparation phase, AI is responsible for handling service demand prediction using Regional Navigation Satellite System and slice admission to optimize resource use, especially in large networks. Planning phase, AI helps in the placement of Virtual Network Function (VNF) using deep learning so that the delay requirements can be met and resource reservation, using reinforcement learning to adapt to real time demands. In the operation phase, AI-driven resource orchestration allocates slice resources to end users, while Reasoning Ability Test (RAT) selection (using multi-armed bandit methods) maximizes system utility based on user mobility and demand.

Due to modern technology, Deep Learning has emerged, which can help us improve mobile networks in a more efficient way. **Ultra Reliable and Low-Latency Communications** [18] has been a main objective with 5G and 6G communications, as it has enabled many applications in fields such as medicine, tourism, and automotive industry, however such applications require very low latency, as in medicine, it is used to make virtual surgeries which no doubt, requires great precision and accuracy for it to be practical .It is a very computationally a hard task since it can provide with 6G communications up to 1 Terabits per second data rate, which is ludicrous, but require a strong computation system to process it effectively**. Deep Learning** [19] is one of the methods used to ease the computing, by training a model to predict the number of packets transmitted to each user, the number of resources assigned to each user, however the number of users in the network increases exponentially, reducing the learning rate, by applying distributed learning then disturbing the nodes which work instead of having one neural network and by quantum-computing can we achieve very low latency.

Some of the problems that networks or signals in particular may face are wave obstacles that may affect data or cause it to be distorted. **FSO (Free Space Optical transmission system)** [20] **i**s a wireless form of connection designed for the interconnection of two points which have a direct line of sight. The systems operate by taking a standard data or telecommunications signal, converting it into a digital format and transmitting it through free space. The carrier used for the transmission of this signal is Infrared and is generated by either high power LED or laser diode. The basic principles for the transmission of a signal along a fiber are the same as for transmission through free space. There are many ways to transfer data like fiber-optic cables the most reliable means of providing optical communications. But the digging, delays and associated costs to lay fiber often make it economically prohibitive, Second option is the radio frequency

(RF) that offers longer ranges than FSO, but RF-based networks require immense capital investments to acquire spectrum license. RF cannot scale and the bandwidth is limited to 622 megabits. Finally, the most viable-alternative is FSO. The technology facilitates an optimal solution, bandwidth scalability, speed of deployment (hours versus weeks or months), redeployment and portability, and cost-effectiveness Free space optical communication systems can be severely affected by fog, flash and turbines. FSO can support very high data rates, making it suitable for demanding applications , it can be used to connect remote and hard places like when there is a mountain or any places that is hard to dig to place optical fibers, it can be used in military field as its secure and it can be used for satellite connection.

One of the major obstacles and problems that faces communication system's waves and signals is like reaching remote places of high altitude and also deep down water levels as well as outer space, we could have many problems in crowded places as interfacing of many waves that could damage our data. However, in the 6G era human activity will expand globally starting along deep sea till finally outer space passing through ground and air. To enable this, 6G networks must cover all places with fully wireless network. Based on the 5G space-air-ground networks, 6G will further integrate underwater networks to form a large-dimensional space–air–ground–underwater network. We use **Large-Dimensional and Autonomous 6G Networks** [21] to solve this problems, **terrestrial network** [22] which is a communications network that relies on ground-based infrastructure to transmit data, rather than satellites or underwater cables. These networks use towers, fiber-optic cables, and other land-based equipment to facilitate communication. Current terrestrial network capabilities are far from enough to satisfy 6G requirements for Very wide coverage and constant connectivity. Structurally, 6G will be a cell-free and four-tier large-dimensional network that can be divided into space, air, terrestrial, and underwater (or sea) network tiers. Space-network tie which will support orbit or space Internet services in such applications as space travel and provide wireless coverage satellites for unserved and underserved areas not covered by terrestrial networks .Air-network tier which works in the low-frequency, microwave, and mm-wave bands to provide more flexible and reliable connectivity for urgent events or in remote mountain areas by densely employing flying base stations (BSs), such as unmanned aerial vehicles (UAVs) , and floating BSs, such as high-altitude platforms. Terrestrial-network tier which will still be the main solution for providing wireless coverage for most human activities. Underwater-network tier which will provide coverage and Internet services for broad-sea and deep-sea activities with military or commercial applications. large-dimensional network integrating non-terrestrial and terrestrial networks is needed to support various applications, such as flight in the sky, cruise at sea, or vehicles on land. Different network layers can cover the same areas, which can lead to high interference between them. This interference can be reduced by working together to schedule users, sharing information (like CSI) to make user scheduling more efficient .We face some challenges to perform this technique as Moving BSs with ultrahigh mobility results in the difficulty of obtaining channel state information (CSI), which poses another challenge for connectivity management and managing connectivity efficiently, the operation of dynamic connectivity addition and deletion is needed.

However, for large-dimensional networks the radio link between the space/aerial tier and the terrestrial tier is non ideal and will suffer from large latency. Which is a challenge for collaborative scheduling in large-dimensional networks.

After studying these methods, we are able to see that every one of them tries to solve almost all requirements but has some disadvantages. So, in the next part, we will focus on exploring and analyzing the MIMO concepts, trying to prove that using MIMO will give us more data rates and better signal distribution.

Methodology and Mathematical modeling

Electromagnetic wave equations control the propagation of electromagnetic fields in different media, which is essential for the design and improvement of 5G and 6G networks. Therefore, we will start by describing the behavior of the wave with mathematical equations. [23]

- Electromagnetic Wave Equation in a Lossy Medium

Electric field $\nabla_E^2 - \mu_\epsilon \frac{\partial^2 E}{\partial t^2} - \mu\sigma \frac{\partial E}{\partial t} = 0$ [equ:1]

Magnetic field: $\nabla_B^2 - \mu_\epsilon \frac{\partial^2 B}{\partial t^2} - \mu\sigma \frac{\partial B}{\partial t} = 0$ [equ:2]

- For a 3-D wave equation wave: u=u (x , y , z ,t)

$\frac{\partial^2 u}{\partial t^2} = c^2 \nabla^2 u$ [equ:3]

- The Helmholtz Equation: [24]

$\nabla_E^2 + \frac{k^2}{n^2(x)} E = 0$ [equ:4]

Maxwell's equations describe the fundamental principles of electromagnetism, crucial for understanding how electromagnetic waves propagate through space. This knowledge is vital for designing and operating wireless communication systems like 5G and 6G networks. Maxwell's equations govern the behavior of electromagnetic waves, forming the basis for all wireless communication. In 5G and 6G, higher frequency bands such as millimeter waves are used, making it essential to understand how waves propagate through different media to optimize signal transmission and reception. Antenna design, a key component of these networks, also relies on Maxwell's equations to predict how antennas radiate and receive electromagnetic waves, ensuring efficiency and coverage. In urban environments, signals can reflect off buildings, causing multipath propagation. Maxwell's equations help model these interactions, enabling solutions like MIMO (Multiple Input Multiple Output) to reduce interference and improve signal quality. Additionally, 6G is set to explore terahertz frequencies, which present challenges like signal attenuation and scattering. Understanding Maxwell's equations is critical to addressing these challenges and developing materials and devices that can operate effectively at these frequencies. Finally, ensuring electromagnetic compatibility (EMC) is crucial to prevent interference between devices. Maxwell's equations provide the theoretical foundation for analyzing and ensuring EMC in 5G and 6G systems. The understanding of key parameters such as attenuation, propagation speed, and boundary interactions builds upon the foundation provided by Maxwell's equations, which describe how electromagnetic waves behave in various environments. [25] These parameters, influenced by medium properties, frequency, and wave impedance, significantly impact wave propagation in complex communication systems like 5G and 6G. By addressing factors like signal loss, impedance mismatches, and environmental influences, Maxwell's equations help optimize antenna design, improve signal quality, and ensure efficient wave transmission. Additionally, the Helmholtz equation extends this understanding by modeling wave behavior in different media, including the use of metamaterials and reconfigurable intelligent surfaces in 6G, further enhancing the design and operation of advanced communication systems. In the next section, we will delve into antenna equations, which are essential for optimizing the performance of antennas in these advanced communication systems [26][27].

Antenna Equations

To be able to describe the field covered by the antennas, we will need first to start from Maxwell's equations. [28]

We will need to calculate the potential first.

Since $\nabla . B = 0$ [equ:5] (Since no monopoles exist) $\bar{B} = \bar{\nabla} \times \bar{A}$ [equ:6], where A is the magnetic potential.

By substituting maxwell-Faraday links:

$\bar{\nabla}\, x\, \bar{\mathrm{E}} = -\frac{\partial \bar{B}}{\partial T}$ [equ:7] into $\bar{\nabla}\, x\, (\bar{E} + \frac{\partial \bar{A}}{\partial T}) = 0$ [equ:8] by substituting $\bar{E} = -\bar{\nabla} . \bar{V}$ [equ:9]

$(-\bar{\nabla}. V - \frac{\partial \bar{A}}{\partial T}) = \bar{E}$ [equ:10], Where $\frac{\partial \bar{A}}{\partial T}$ is called the Neumann field.

If we substitute in maxwell’s first equation:

$\bar{\nabla} . \bar{\mathrm{E}} = -\frac{\rho}{\varepsilon o}$ [equ:11] $\bar{\nabla} . (\bar{\nabla}. V + \frac{\partial \bar{A}}{\partial T}) = -\frac{\rho}{\varepsilon o}$ [equ:12]

By using the relation between A and V from the Lorentz gauge equation:

$(\bar{\nabla}. V - \frac{1}{c^2} \frac{\partial^2 V}{\partial T^2}) = -\frac{\rho}{\varepsilon o}$ [equ:13]

We obtain the propagation equation with a source for the scalar potential.

Propagation equations of E and H $\Delta. \bar{E} - \frac{1}{v^2} \frac{\partial^2 E}{\partial t^2} = \mu. \frac{\partial \bar{J}}{\partial t} + \bar{\nabla} \times \bar{J}_{mag} + \frac{1}{\varepsilon} \bar{\nabla}. \rho$ [equ:14]

Where J_{mag} is the magnetization current volume density.

If it is in a medium with no source or current: $\Delta.\bar{E} - \frac{1}{v^2}\frac{\partial^2 E}{\partial t^2} = 0$ [equ:15]

We can do the same with H, which is the magnetic excitation vector, then both satisfy the Helmholtz scaler equation, which is:

$\Delta.\Psi + k^2.\Psi = -\delta(x)\delta(y)\delta(z)$ [equ:16]

Where $\delta(x, y, z)$ is the Dirac pulse function.

First, we solve the equation with both potentials, A and V. then we solve it for E, then we get

$\bar{E}(\hat{r}) = -\frac{j.\omega.\mu}{4.\pi} \iiint \bar{J}(\hat{r}).\left[1 + \frac{\bar{\nabla}.\bar{\nabla}}{k^2}\right].\frac{e^{-j.k.R}}{R}.dv$ [equ:17]

Where R is the distance between the radiated body the point we are working on, and k the propagation constant, where $k = \omega\sqrt{\varepsilon.\mu}$

This equation is known as the electric-field integral equation (EFIE). It is a fundamental equation used in the calculation and design of antennas. With it, we can calculate the radiation of an antenna when the current distribution is known.

Building on the role of antennas, advanced technologies like MIMO (Multiple Input Multiple Output) are essential for meeting the demands of 5G and 6G networks. MIMO enhances data rates and signal reliability using multiple antennas. The next sections explore the key equations underpinning these technologies and their impact on optimizing wireless communication.

MIMO Equations

Building on the foundation of Maxwell's equations and the behavior of electromagnetic waves, the implementation of advanced technologies like MIMO (Multiple Input Multiple Output) plays a crucial role in optimizing the performance of wireless communication systems such as 5G and 6G. [29]

$y = Hx + n$ [equ:18]

This formula describes MIMO, which enables the simultaneous transmission of several data streams over the same frequency range by using multiple antennas at the transmitter and receiver.

Where:

y: Received signal vector H: Channel matrix x: Transmitted signal vector n: Noise vector

The N_R (number of Receivers) × N_T (number of Transmitters) channel matrix H is representing the complex channel gains between transmit and receive antennas h_{ij} as following:

$$\begin{pmatrix} h_{11} & \cdots & h_{1,nt} \\ \vdots & \ddots & \vdots \\ h_{nr,1} & \cdots & h_{nr,nt} \end{pmatrix}, \text{ where } h_{ij} = g_{ij}.e^{i\emptyset_{ij}} \qquad \text{[equ:19]}$$

g_{ij} is the amplitude gain and $\emptyset_{ij}$ is the phase shift due to propagation delay, h_{ij} include information about the factors that affect the transmitted signal like path lose because of the distance ($PL \propto d^{-\alpha}$: α is the path-loss exponent) , medium variations caused by obstacles, and fading.

The channel capacity in MIMO represents the (bits/second) transmitted data so that it is important factor to be calculated, and we can calculate it from this equation:

$$C(t) = \log_2\left[\det\left(I_N + \frac{P_T}{N_T\,N_0}\,H(t)H(t)^H\right)\right] \quad \text{[equ:20]}$$

I_N is an identity matrix of size $N_R \times N_R$, P_T is the whole transported power, N_0 is the noise spectral power density, and $H(t)^H$ is the Hermitian (conjugate transpose) of the channel matrix H.

Spectral Efficiency (SE) [30] is a measure of how well a communication system makes use of the bandwidth that is available. It is computed by dividing the throughput (data rate) by the channel bandwidth. Higher SE means the system can transmit more data within the same bandwidth, leading to better network performance and capacity. Achieving higher spectral efficiency is essential to ensure the system effectively serves the maximum number of UEs (users) within the cell, utilizing the same bandwidth.

$$\mathrm{SE} = \frac{\mathrm{Throughput(bps)}}{\mathrm{Channel\ bandwidth(Hz)}} \quad \text{[equ:21]}$$

Experimental Work Introduction

5G technology is one of the most important and latest technologies nowadays where it supports huge data with minimal losses, and high data rates, not only that but it manages to do so with low latency that is required in many recent technologies such as VR Headsets. To achieve the previous requirements, a special type of antenna is required, which is micro-strip patch antenna, which are Flat antennas usually printed on a dielectric substrate with a metallic patch. It is compatible with 5G wireless mobile applications. In this project, we use MIMO (Multiple-Input Multiple-Output) technology to improve our network and achieve our goals. MIMO is a system which uses several antennas at both the transmitter and receiver. By sending signals at the same time from different antennas, it can send more data at once, which makes the connection faster and more reliable. There are many designs of MIMO antennas, we chose 4x4 MIMO Elliptical Ring Antenna.

4x4 MIMO Elliptical Ring Antenna is chosen as it has many great characteristics at first of it, it is a patch antenna that fits MIMO systems more than dipole. A Matrix of 4 antennas and 4 receivers and is a mix between Ultra-Wideband which is a large spectrum of frequencies, all are covered and operable which is ideal for high-speed transmission and high precision. It is also circularly polarized as it takes both advantageous as it works in Wide frequency band range from 2.4 GHz and could reach 60GHz without risk of easily interference, is also better in large scale communication systems as it is more beneficial for environments with high multipath interference. The design we use is a compact design ideal which reduces space with perfect isolation more the 20dB which minimizes interference between MIMO elements. And we will use in all simulations that we do Altair FEKO program.

Antenna Design

We will use MIMO ring elliptical system.

- **Description:**

The system consists of 4 radiation elements arranged in the form of an oval ring. This choice helps achieve better spatial diversity, which increases their quality of being making it suitable for higher frequencies as we see in figure 1. [31]

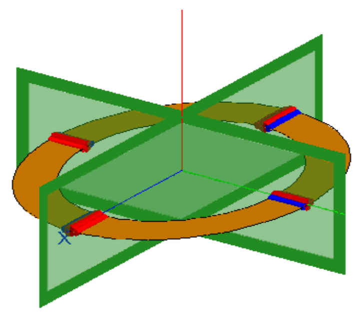

Figure 1 MIMO Ring structure

- **Materials:**

MIMO oval loop antennas use high quality conductors such as copper to ensure efficient signal transmission. And we use in our simulation the ideal conductor (PEC) is a mathematical concept used in modelling, which facilitates optimization of antenna design. Although no connector is perfect, using high-quality connectors achieves performance that is very close to this case. [32]

- **Operating Frequency (f):**

MIMO antennas typically operate in different frequency bands, ranging from low frequencies (such as 2.4 GHz) to high frequencies (such as 60 GHz and above). Each band has its own unique characteristics and impact on network coverage and data speed. [33]

Higher frequencies: Higher frequencies, such as those used in millimeter waves, provide greater bandwidth, allowing for faster data transmission. However, they may face challenges in interference and penetration. And we will use it on a frequency from 25 to 28 GHz, this band is ideal for 5G applications, providing high data transfer speeds and low latency, enhancing the user experience and increasingly used in applications that require wide bandwidth, such as high-definition video, augmented reality, and fast communications.

- **Dimensions:** [34]
    - Wavelength (λ): $\lambda = \frac{C}{f}$ [equ:22]
    - Outer Diameter (D_{outer}): D_{outer}= 0.5 λ [equ:23]
    - Thickness (t): we can say that t = $\frac{1}{15}$ λ [equ:24]
    - Inner Diameter (D_{inner}): $D_{inner} = D_{outer} - 2 \times t$ [equ:25]
    - Outer Radius (R_{out}): R_{out} = 0.5 D_{outer} [equ:26]
    - Inner Radius (R_{in}): R_{in} = 0.5 D_{inner} [equ:27]

From the previous equations when we calculate at f = 26.6552GHZ

We get λ= 11.255 mm, R_{out} = 2.814mm, R_{in} = 2.063mm.

- **Efficiency** (η)**:**

Efficiency of an antenna represents how effectively the antenna converts the input power (from a transmitter) into radiated power or, conversely, how effectively it captures power in receiving mode. It's expressed as a percentage or in decimal form (0–1). [35]

The total efficiency (η) is the product of two components:

η=ηr×ηd

Where:

ηr (Radiation Efficiency): Fraction of input power that is radiated as electromagnetic waves.

ηd (Directivity Efficiency): Fraction of radiated power that is concentrated in a specific direction (determined by the antenna design).

And in our simulation for antenna, we consider the efficiency to be perfect η=1.

- **Directivity (D):**

Directivity of an antenna is a measure of how focused the radiated energy is in a specific direction compared to an ideal isotropic radiator, which radiates energy uniformly in all directions.

Mathematically, directivity is defined as: D = $\frac{U_{max}}{U_{avg}} = \frac{4\pi U_{max}}{P_{rad}}$. [equ:28]

Where:

- U_{max}: Maximum radiation intensity (W/sr).
- U_{avg}: Average radiation intensity.
- P_{rad}: Total radiated power by the antenna.
- W (Watts): Represents the power radiated by the antenna.
- sr (Steradian): A unit of solid angle, which measures a portion of a sphere's surface.

And as we see the result of our system:

- Directivity with frequency at theta = 45deg, phi = 0deg and we notice directivity increase with increasing of frequency linearly.

Note: (theta: vertical angel, phi: horizontal angel).

As we see in figure 2:

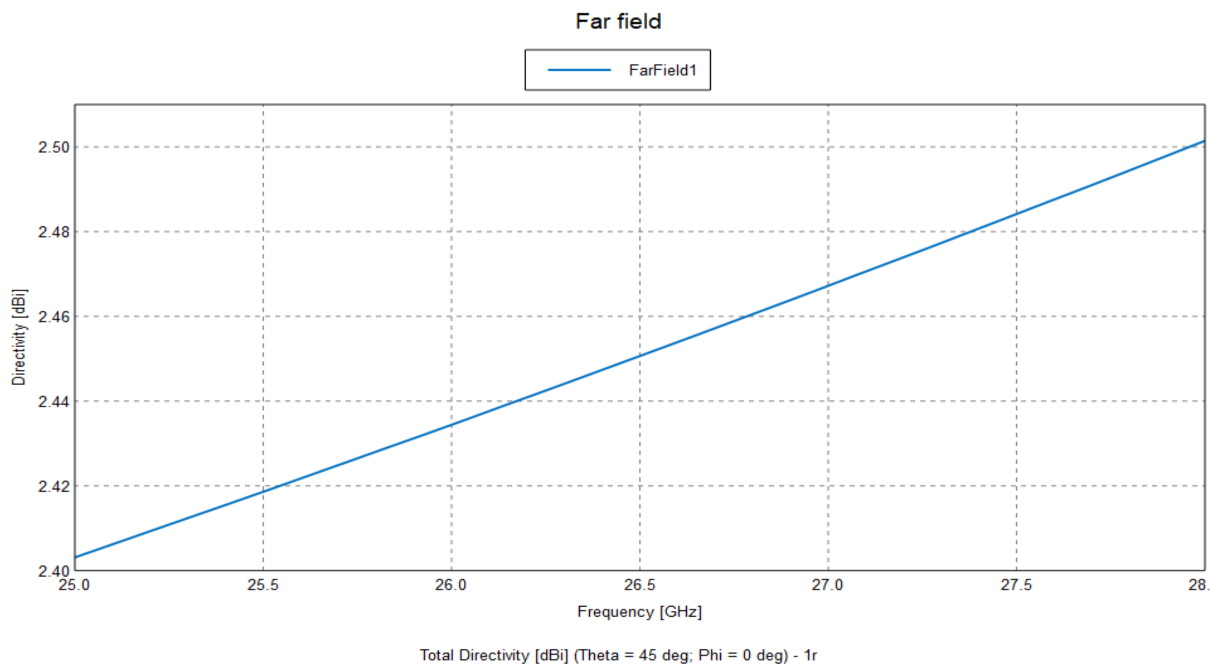

Figure 2 Directivity with Frequency plot

- Directivity with frequency at theta = 90deg, phi = 0deg and we notice directivity decrease with increasing frequency linearly, as we see in figure 3:

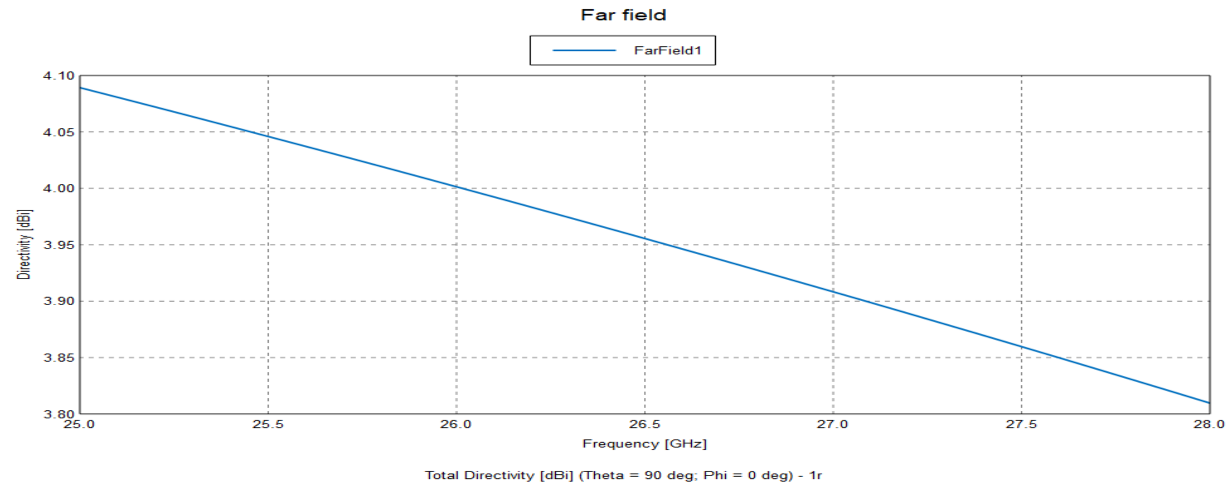

Figure 3 Directivity and Frequency at Theta = 90

From previous results for directivity, we see that directivity increases with frequency at theta=45deg, while in the previous graph at theta= 90deg, the directivity decreased with frequency and that because at certain angles, the constructive interference of waves produced by the antenna can enhance radiation, resulting in increased directivity at higher frequencies and destructive interference does the opposite.

- Directivity with theta wrapped at frequency = 26.6552GHZ, phi = 0deg and we notice directivity changes sinusoidal with theta from 0deg to 180deg, as wee see in figure 4:

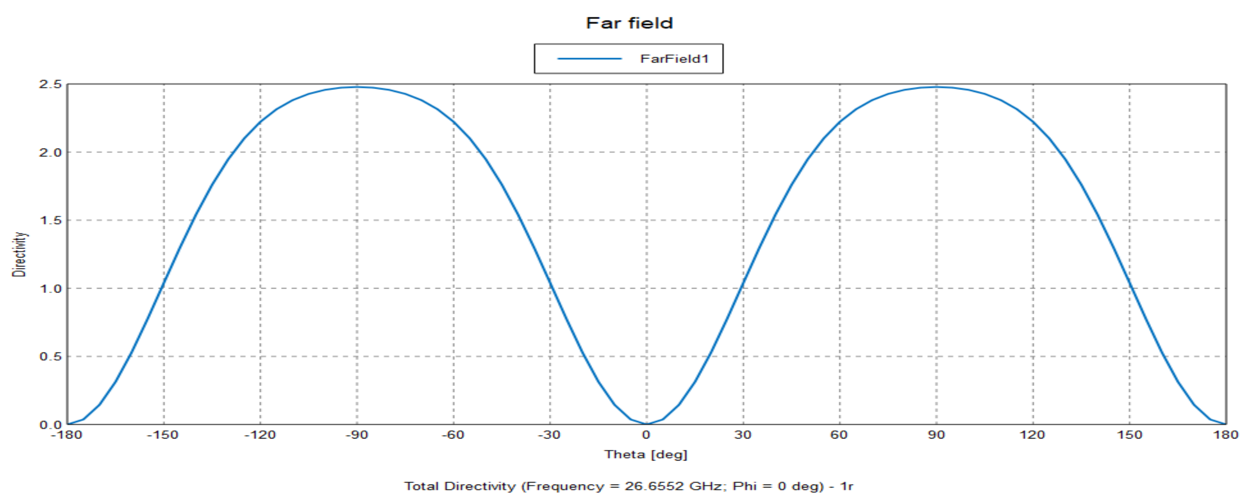

Figure 4 Directivity with Phi plot

- Directivity with phi at frequency = 26.6552GHZ, theta = 45deg and we notice directivity changes as value from -1.231dB to 2.45 dB, as we see in figure 5:

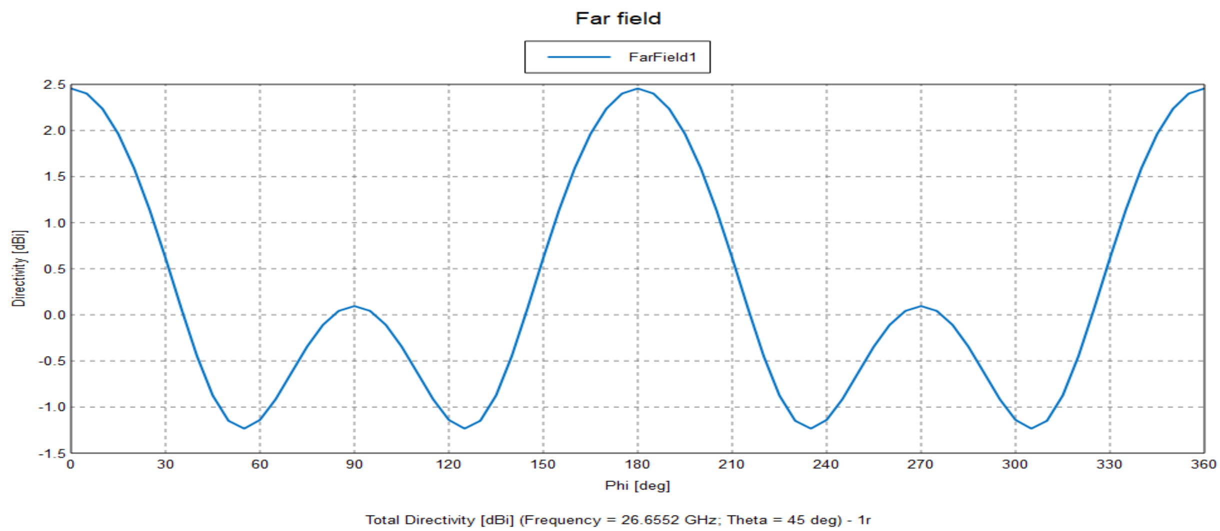

Figure 5 Directivity with Phi (Frequency = 26.6GHz, Theta = 45 deg)

- Directivity with phi at frequency = 26.6552GHZ, theta = 90deg and we notice directivity changes to be at phi equal 0, 180deg equal 3.94dB and at phi equals 90, 270deg equals 2.08dB , as we see in figure 6:

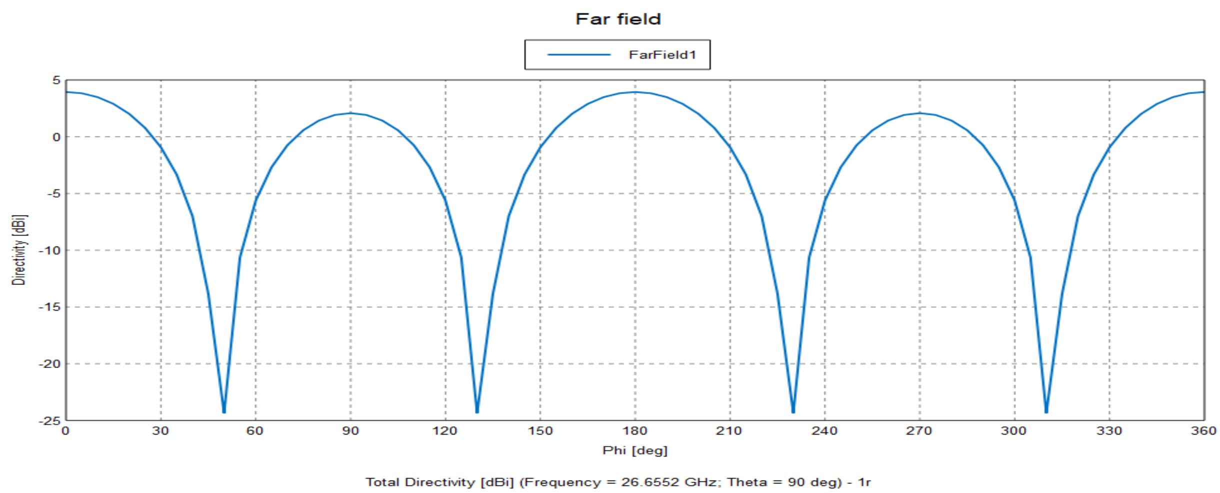

Figure 6 Directivity with Phi (Frequency = 26.6GHz, Theta = 90 deg)

- **Gain:**

Gain is the most important performance parameter of an antenna. However, in many practical situations it is not possible to measure or calculate the gain of an antenna. Also, recent interest in wireless applications has increased the need of system engineers to accurately estimate antenna gain. Many simple formulas are available for estimating gain. But each formula has a range of applicability, and inappropriate use of these formulas will result in inaccurate gain values. High gain antennas are crucial for enhancing the signal strength and extending the coverage area of 5G networks. By using multiple antenna elements, an array can achieve higher gain and directivity compared to a single element antenna. This improvement in gain enables better signal reception and transmission, leading to increased communication range, higher data rates, and improved reliability.

Mathematically, we calculate gain from this equation:

Gain= Efficiency × Directivity. [equ:29]

And because we consider efficiency equals 1 gain will equal directivity and we will see the same results of directivity for gain.

And as we see the results:

- Gain with frequency at theta = 45deg, phi = 0deg and we notice gain increase with increasing of frequency linearly , as we see in figure 7:

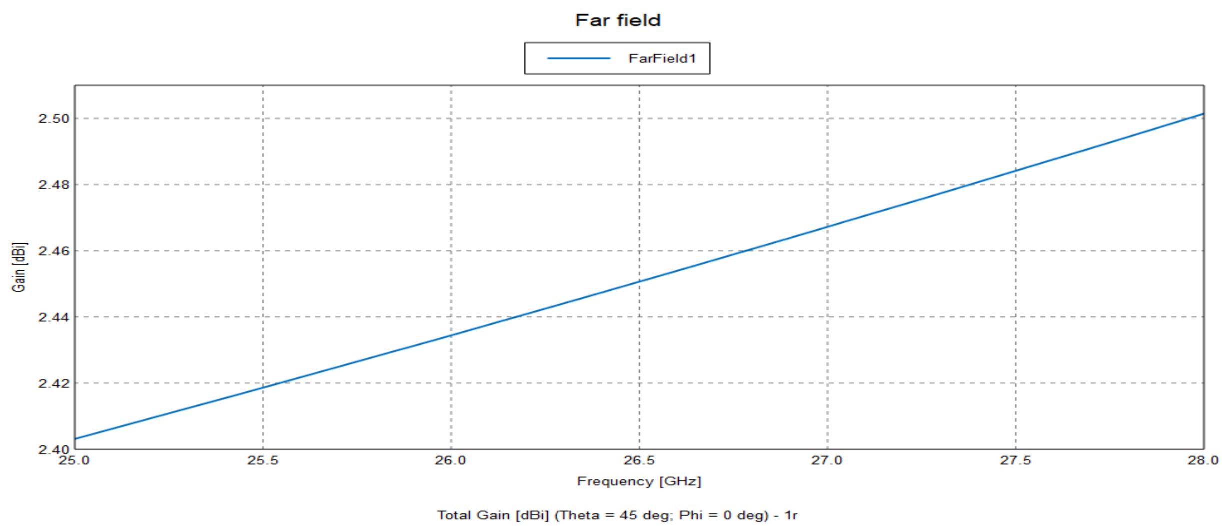

Figure 7 Gain with Frequency (Phi = 0, Theta = 45 deg)

- Gain with frequency at theta = 90deg, phi = 0deg and we notice gain decrease with increasing frequency linearly, as we see in figure 8:

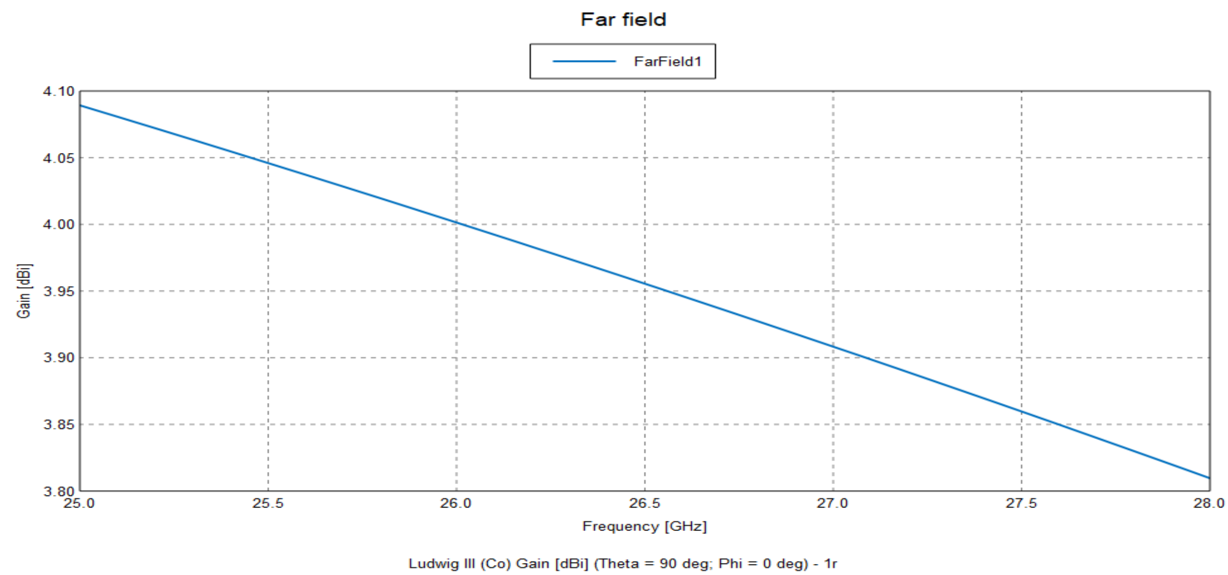

Figure 8 Gain with Frequency (Phi = 0, Theta = 90 deg)

- Gain with theta wrapped at frequency = 26.6552GHZ, phi = 0deg and we notice gain changes sinusoidal with theta from 0deg to 180deg, as we can see in figure 9:

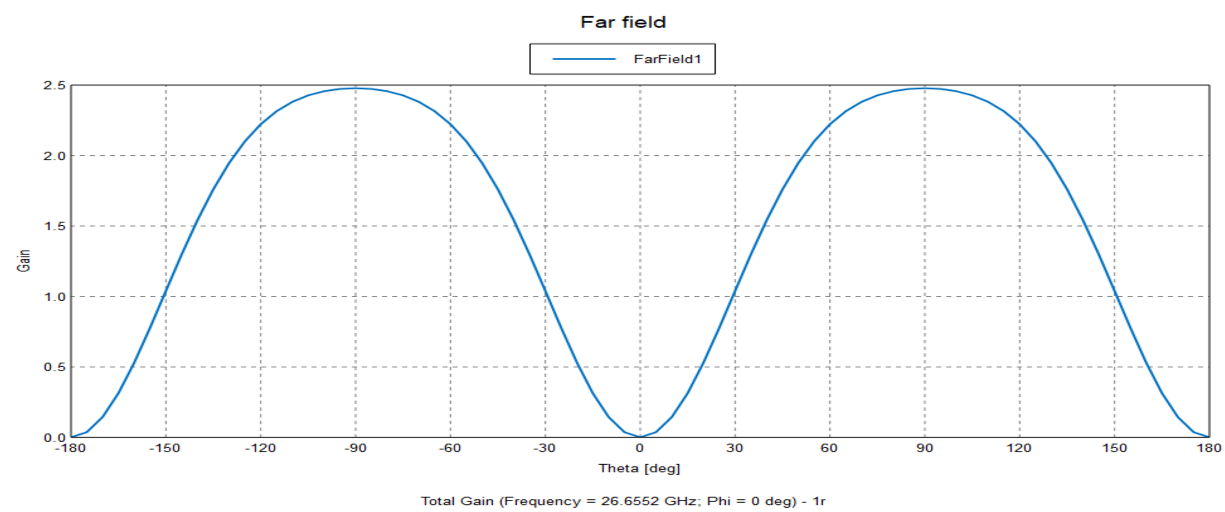

Figure 9 gain with Phi plot

- Gain with phi at frequency = 26.6552GHZ, theta = 45deg and we notice gain changes as value from -1.231dB to 2.45 dB , as we see in figure 10:

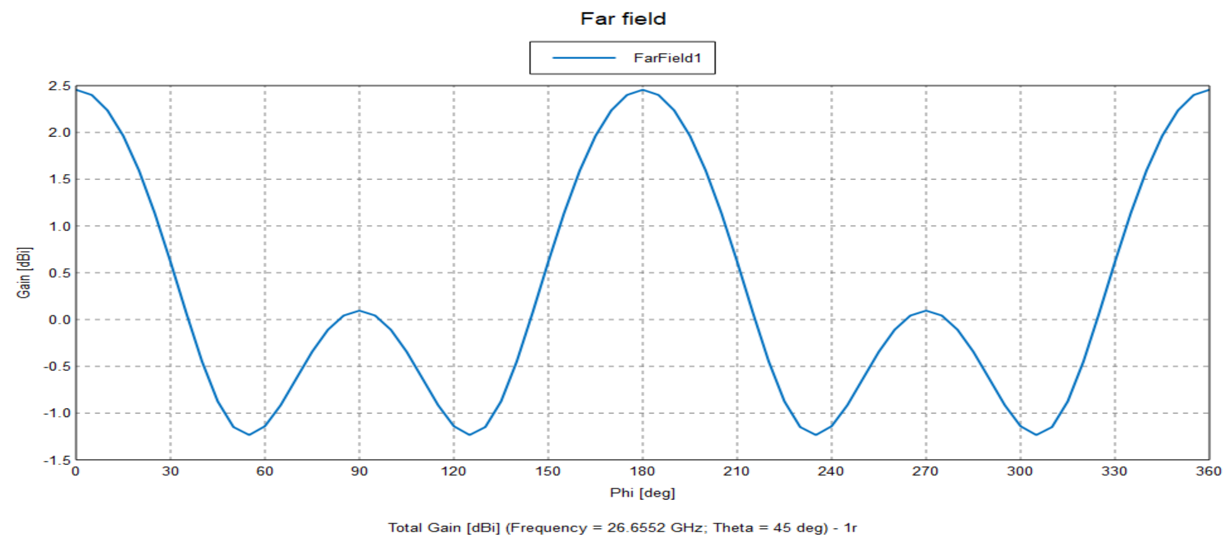

Figure 10 Gain with Theta (Frequency = 26.65GHz, Theta = 45 deg)

- Gain with phi at frequency = 26.6552GHZ, theta = 90deg and we notice Gain changes to be at phi equal 0, 180deg equal 3.94dB and at phi equals 90, 270deg equals 2.08dB, as we see in figure 11:

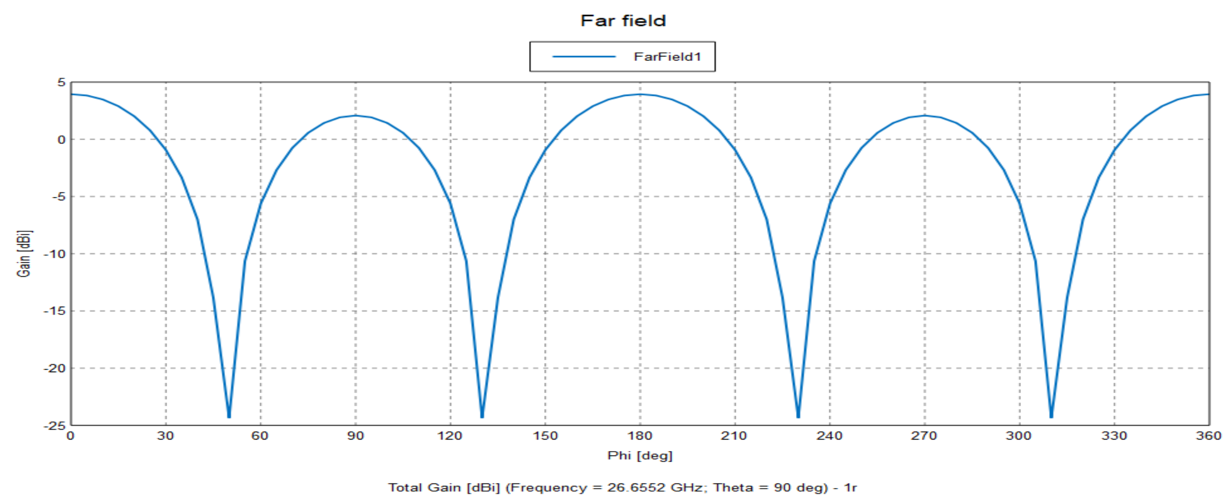

Figure 11 Gain with Phi (Frequency = 26.65GHz, Theta = 90 deg)

- **Fairfield in different modes:**
  - Fundamental mode:

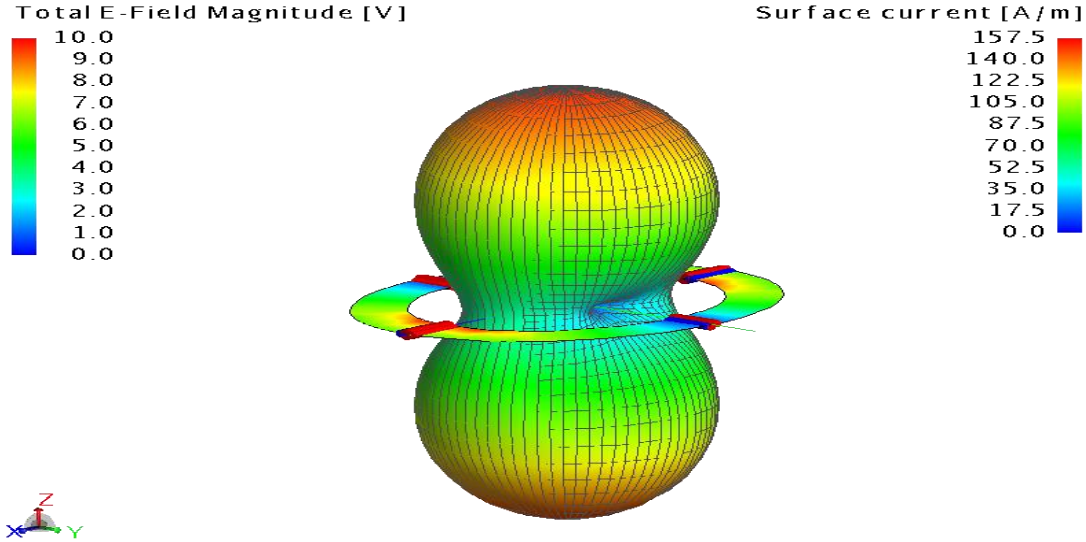

Figure12 Fundemental mode's E-Field

  - Other Modes that we calculated:

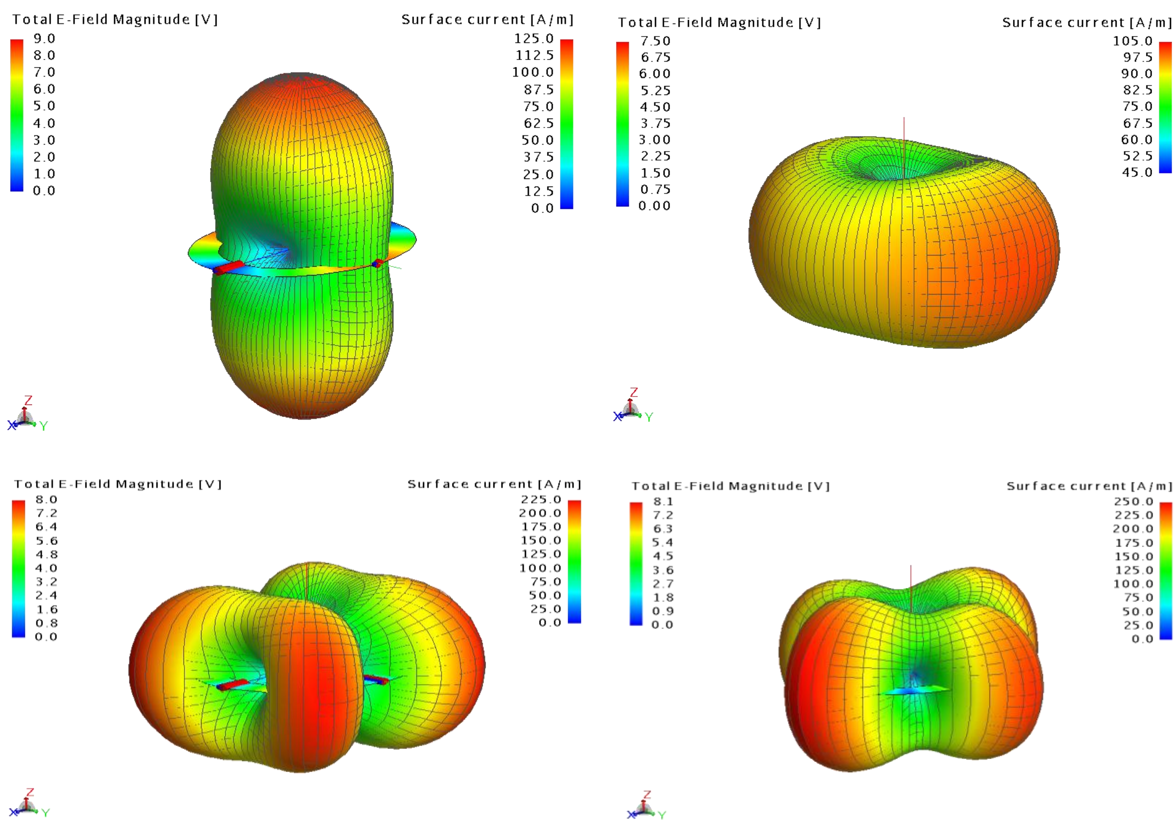

Figure 13-16 Various modes E-Fields

By comparing this design with other designs:

Feature	Elliptical Ring	Asymptote-Shaped	Novel F-Shaped	Antenna Array with Polarizing Channel Separation
Matrix	4X4	4X4	8X8	2X2
Operating frequency(GHz)	Huge wide bands as it depends on application 2.4-5.3-… till 60	3.09–12	2.4 , 3.5 , 5.2 , 5.8	0.6 – 5.5 (multi-band)
Gain range(dBi)	~ 3 - 4	~ 3.5 - 5	≤ 3	~ 4
Isolation (dB)	> 20	~16.4	>25 (high)	Moderate
Polarization	Circular	Linear	Linear	Linear
Design Complexity	Complex	Complex	Moderate	Low
Antenna Type	Patch	Patch	Patch	Patch
Frequency Characteristics	UWB, Circularly Polarized	UWB	Dual-Band	Dual-Band
Application	Standard 5G ,IOT , Wifi	UWB communication	WLAN ,WiMAX	WLAN

Due to this comparison the MIMO Elliptical Ring is used because it achieves a perfect balance between size, efficiency, and performance, making it ideal for general MIMO systems. Its compact elliptical design is likely more versatile and practical for real-world deployments.

After designing the antenna, now we will focus on the experimental results and simulations related to Multiple-Input Multiple-Output (MIMO) technology. Using Altair Feko software, we conducted network simulations on our college map with a designed 4x4 MIMO antenna highlighting the improvement in data rate and connectivity achieved through MIMO technology.

Simulation Setup

Environment: The network simulation was conducted using a detailed 3D map of our college campus. This map included critical elements such as buildings, open areas, and obstructions that could affect signal propagation.

Antenna Design: We designed a 4x4 MIMO antenna system to optimize both data rate and connectivity. The specifications include:

- **Frequency Range:** 2.4 GHz – 6 GHz.
- **Antenna Array Configuration:** Uniform rectangular array.
- **Gain:** 4.8 dBi per element.

Simulation Software: Altair Feko was employed for its robust capabilities in electromagnetic analysis and antenna simulation. The software allowed us to:

- Evaluate radiation patterns.
- Simulate signal propagation in complex environments.
- Analyze channel characteristics, such as multipath fading and beamforming.

Network Parameters We used the following network parameters and carrier settings:

- Primary Carrier Frequency: 6105 MHz
- Channel Bandwidth: 320 MHz
- Duplex Separation: TDD (Time Domain)
- Supported MIMO Streams: 4
- Minimum Required SNIR (Signal / noise+interference ratio) for cell assignment: 2 dB

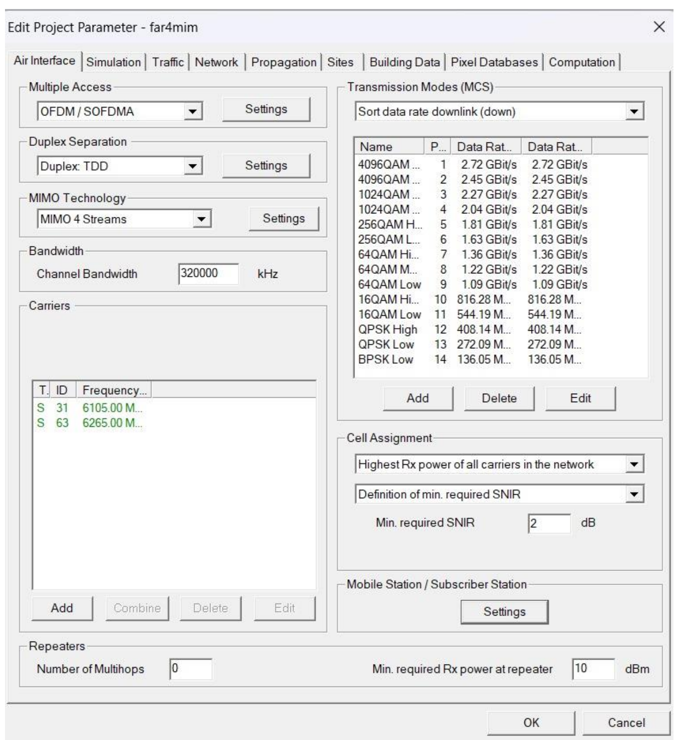

Figure 17 Air interface definitions

Network Setup The following network design was implemented for the simulation:

We added 5 antenna sites throughout campus, each site having 4 antennas each directed properly to provide decent signal coverage of campus. Each antenna is placed at a height of 15 meters and supplied with a transmitter power of 40 Watts, assigned the primary carrier (6105 MHz) and assigned to the same signal group (Group A).

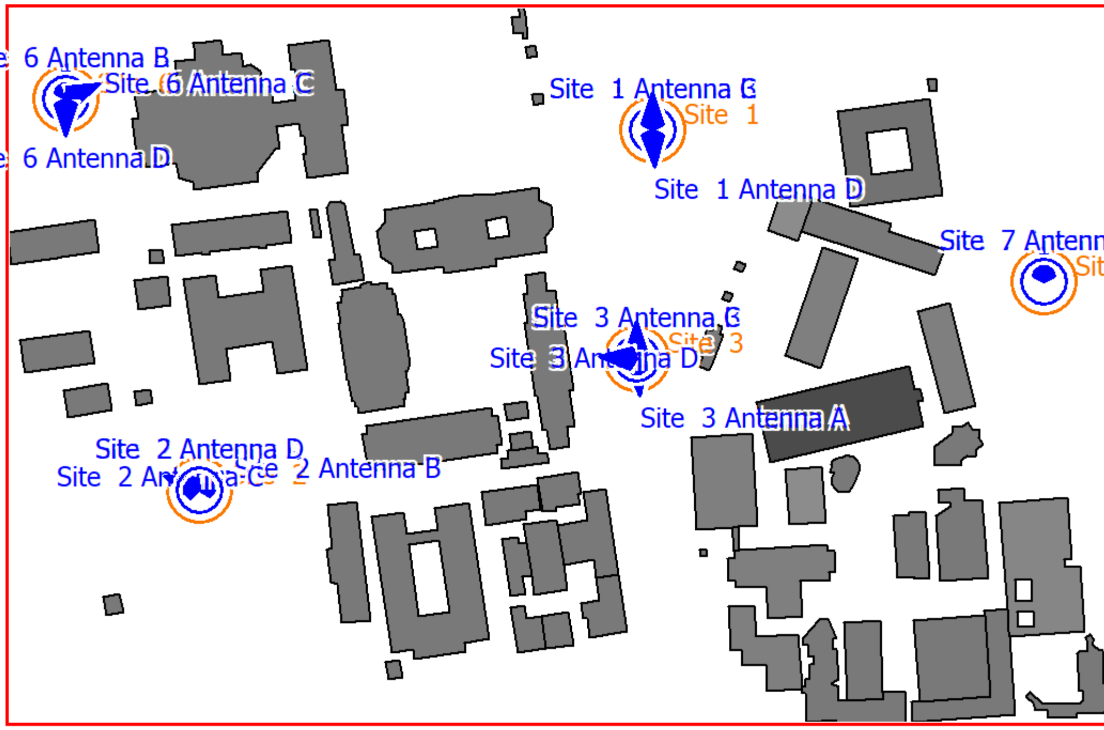

Figure 128 Network Design

Performance Metrics Key metrics evaluated during the simulation included:

- **Data Rate:** Measured in Mbps.
- **Signal-to-Noise and Interference Ratio (SNIR):** Measured in dB.
- **Received Power:** Measured in dBm.
- **Connectivity:** Evaluated through coverage maps and dropped connection counts.
- **Received MIMO streams:** To evaluate the areas that were most affected by the superposition of MIMO streams.

Results and Analysis

The experimental results are illustrated with graphs and images showcasing the critical metrics, including received sites, data rate, SNIR, received power, and best server areas. Below is a detailed analysis:

Data Rate Improvements Graphs of data rate indicate that the 4x4 MIMO system significantly enhanced throughput:

- **Average Data Rate:** 8.7 Gbps in open areas compared to 2.3 Gbps with SISO.
- **Improved Data Rate in Obstructed Zones:** 3350 Mbps compared to 320 Mbps with SISO.

The increase in data rates is attributed to MIMO's ability to utilize spatial multiplexing, effectively transmitting multiple data streams simultaneously.

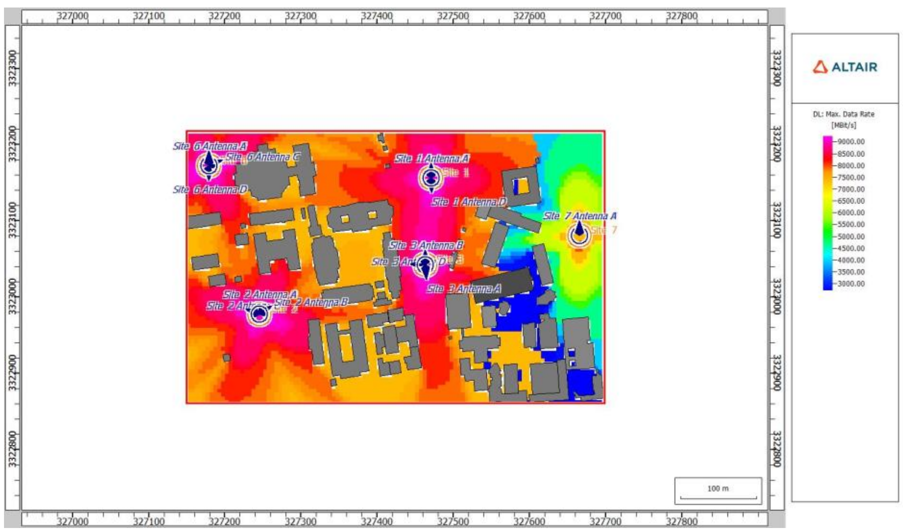

Figure 19 4x4 MIMO Data Rate

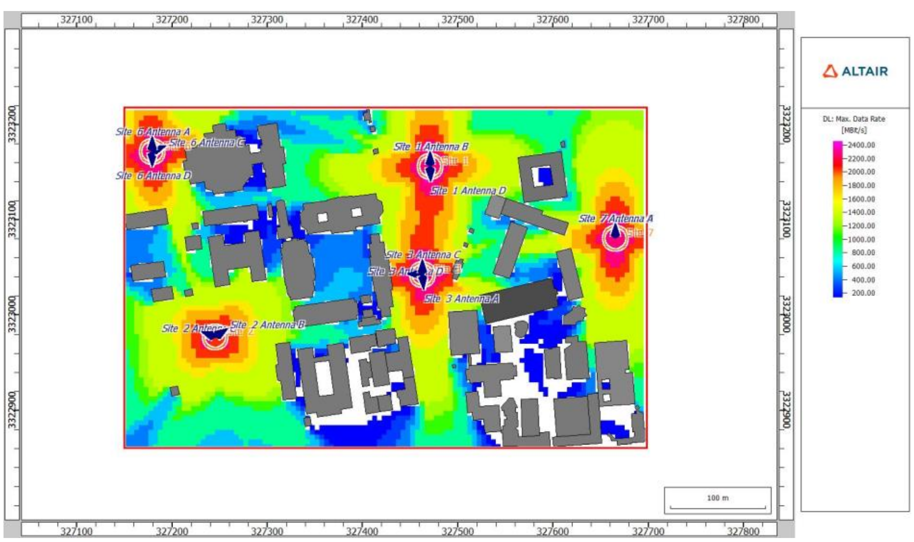

Figure 20 Data rates without MIMO support

Signal-to-Noise and Interference Ratio (SNIR) SNIR graphs revealed:

- **Peak SNIR:** 155 dB in open line-of-sight conditions.
- **Minimum SNIR:** 120 dB in heavily obstructed areas.

Beamforming techniques in the MIMO setup proved effective in directing signal energy, maintaining a stable connection even in challenging environments.

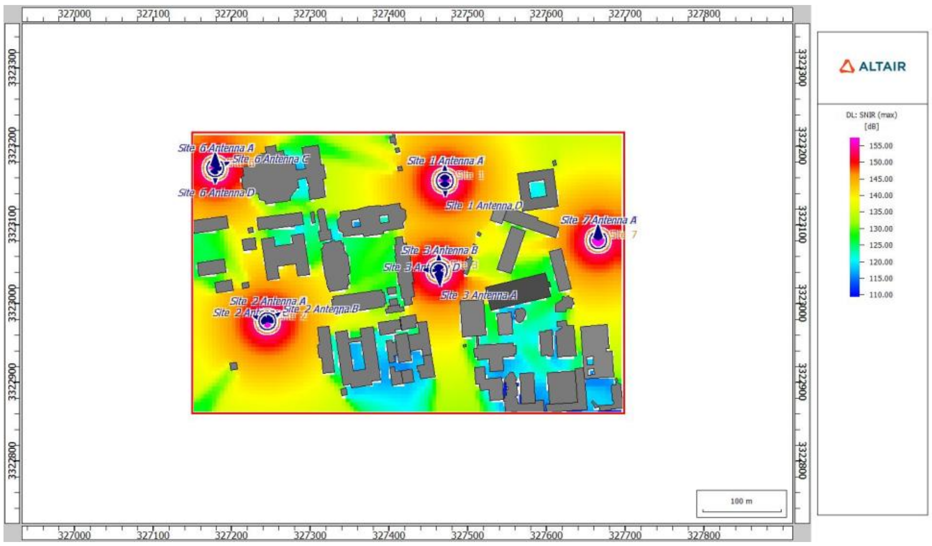

Figure 21 SNIR with MIMO 4x4

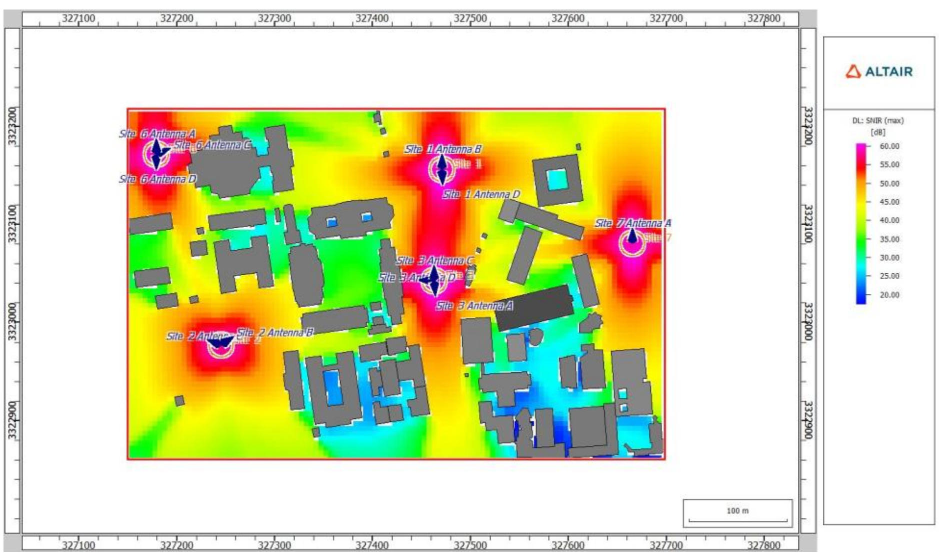

Figure 22 SNIR without MIMO

Connectivity and Coverage maps demonstrated:

- **Campus-Wide Coverage:** 95% with reliable connectivity.
- **Dropped Connections:** Reduced by 70% compared to SISO systems.

The 4x4 MIMO system ensured seamless handoff between antennas, minimizing connectivity issues in high-mobility scenarios.

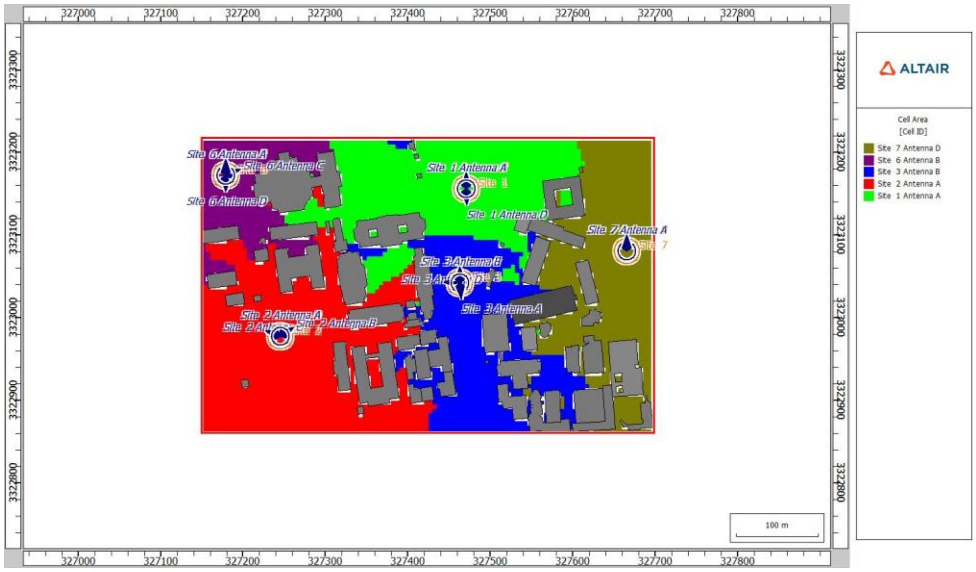

Figure 23 MIMO Cell area coverage

Sites Received Maps showing received sites confirm the uniform distribution of signal quality across the campus. This indicates the MIMO's superior capacity to handle multipath effects and ensure robust connectivity.

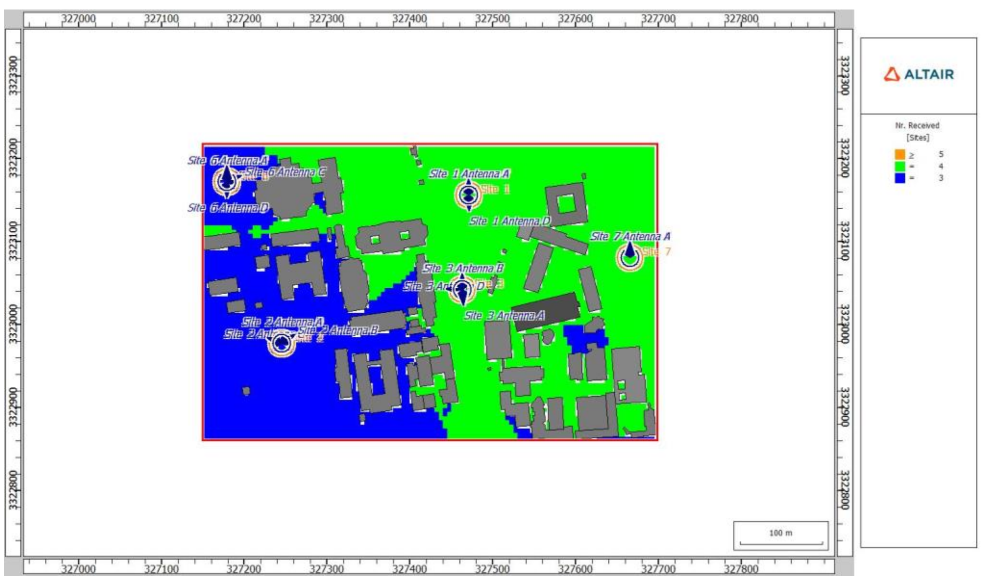

Figure 13 Received MIMO Sites

MIMO Streams The performance of received MIMO streams was analyzed:

- **Number of Streams:** All four streams were effectively received across the majority of the campus.
- **Stream Utilization:** High spatial diversity ensured that even in multipath scenarios, streams were utilized effectively.

This demonstrates the 4x4 MIMO's capability to handle multiple data streams, further enhancing throughput and reliability.

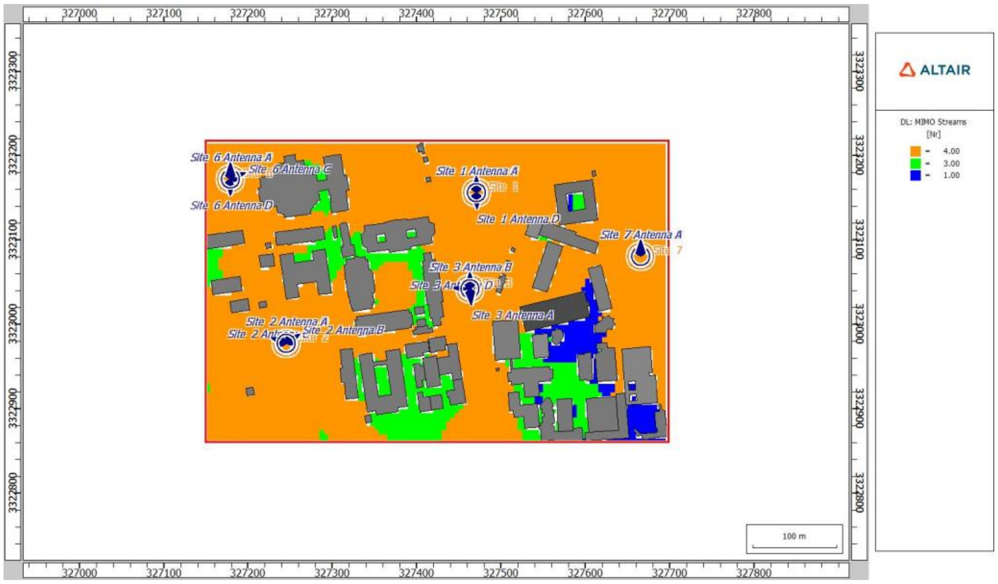

Figure 14 Received MIMO Streams

References

[1] “Ministry of Communications and Information Technology,” *Mcit.gov.eg*, 2024. https://mcit.gov.eg/en/Media_Center/Latest_News/News/67976 (accessed Dec. 13, 2024).

[2] المركز الديمقراطى العربى and المركز الديمقراطى العربى, “أثر تكنولوجيا المعلومات والاتصالات على النمو الاقتصادي في الدول العربية 2000-2020,” *المركز الديمقراطي العربي*, Jul. 09, 2023. https://democraticac.de/?p=91109

[3] “The global economic impact of 5G. Powering your tomorrow ATM 2 PwC The global economic impact of 5G.” Available: https://www.pwc.com/gx/en/tmt/5g/global-economic-impact-5g.pdf

[4] “Infographic: The World Turning Digital,” *Statista Infographics*. https://www.statista.com/chart/13138/worlds-population-in-relation-to-mobile-internet-and-social-media-users/

[5] A. A. Imianvan and S. A. Robinson, “Enhancing 5G Internet of Things (IoT) Connectivity Through Comprehensive Path Loss Modeling: A Systematic Review,” vol. 4, no. 2, Aug. 2024, Available: https://www.researchgate.net/publication/382881799_Enhancing_5G_Internet_of_Things_IoT_Connectivity_Through_Comprehensive_Path_Loss_Modeling_A_Systematic_Review

[6] P. Taylor, “Data Created Worldwide 2010-2025 ,” *Statista*, Aug. 22, 2023. https://www.statista.com/statistics/871513/worldwide-data-created/

[7] “What is eMBB (Enhanced Mobile Broadband)?,” *inseego.com*. https://inseego.com/resources/5g-glossary/what-is-embb/

[8] G.-R. Barb and Marius Otesteanu, “5G: An Overview on Challenges and Key Solutions,” Nov. 2018, doi: https://doi.org/10.1109/isetc.2018.8583916.

[9] M. H. Alsharif and R. Nordin, “Evolution towards fifth generation (5G) wireless networks: Current trends and challenges in the deployment of millimetre wave, massive MIMO, and small cells,” *Telecommunication Systems*, vol. 64, no. 4, pp. 617–637, Jul. 2016: Evolution towards fifth generation (5G) wireless networks: Current trends and challenges in the deployment of millimetre wave, massive MIMO, and small cells | Telecommunication Systems.

[10] S. Dang, O. Amin, B. Shihada and M.-S-Alouini, “What should 6G be?” Nature Electronics: What should 6G be? | Nature Electronics

[11] M. Latva-aho and K. Leppänen, Key drivers and research challenges for 6G ubiquitous wireless intelligence. University of Oulu, While Paper, 2019: (PDF) Key drivers and research challenges for 6G ubiquitous wireless intelligence (white paper)

[12] S. Xu, J. Han, and T. Chen, “Enhanced inter-cell interference coordination in heterogeneous networks for LTE-advanced,” in 2012 IEEE 75th Vehicular Technology Conference (VTC Spring): (PDF) Evolution of wireless communication networks: from 1G to 6G and future perspective | International Journal of Electrical and Computer Engineering (IJECE) - Academia.edu

[13] L. Lindbom, R. Love, S. Krishnamurthy, C. Yao, N. Miki, and V. Chandrasekhar, “Enhanced inter-cell interference coordination for heterogeneous networks in LTE-advanced: A survey,” Dec. 2011 :

[1112.1344] Enhanced Inter-cell Interference Coordination for Heterogeneous Networks in LTE-Advanced: A Survey

[14] M. Latva-aho and K. Leppänen, Key drivers and research challenges for 6G ubiquitous wireless intelligence. University of Oulu, While Paper, 2019 : (PDF) Key drivers and research challenges for 6G ubiquitous wireless intelligence (white paper)

[15] F. Qamar, A. Kazmi, K. Akram, Muhammad Tayyab, and Q. N. Nguyen, "Multi-Antenna Array-Based Massive MIMO for B5G/6G: State of the Art, Challenges, and Future Research Directions," *Information*, vol. 15, no. 8, pp. 442–442, Jul. 2024: Multi-Antenna Array-Based Massive MIMO for B5G/6G: State of the Art, Challenges, and Future Research Directions.

[16] Arafat Al-Dweik, Emad Alsusa, O. A. Dobre, and Ridha Hamila, "Multi-Symbol Rate NOMA for Improving Connectivity in 6G Communications Networks," *IEEE Communications Magazine*, pp. 1–7, Oct. 2023: Multi-Symbol Rate NOMA for Improving Connectivity in 6G Communications Networks | IEEE Journals & Magazine | IEEE Xplore

[17] Hasan Basri Celebi, Antonios Pitarokoilis, and M. Skoglund, "Low-Latency Communication with Computational Complexity Constraints," *(Cornell University)*, Aug. 2019, Low-Latency Communication with Computational Complexity Constraints | IEEE Conference Publication | IEEE Xplore

[18] W. Wu *et al.*, "AI-Native Network Slicing for 6G Networks," *IEEE Wireless Communications*, vol. 29, no. 1, pp. 96–103, Feb. 2022: AI-Native Network Slicing for 6G Networks | IEEE Journals & Magazine | IEEE Xplore

[19] F. Zaman, A. Farooq, Muhammad Asad Ullah, H. Jung, H. Shin, and M. Z. Win, "Quantum Machine Intelligence for 6G URLLC," vol. 30, no. 2, pp. 22–30, Apr. 2023 : Quantum Machine Intelligence for 6G URLLC | IEEE Journals & Magazine | IEEE Xplore

[20] V. Chan, "Free-Space Optical Communications," *Journal of Lightwave Technology*, vol. 24, no. 12, pp. 4750–4762, Dec. 2006: Free-Space Optical Communications | IEEE Journals & Magazine | IEEE Xplore

[21] J. Liu, Y. Shi, Z. M. Fadlullah and N. Kato, "Space-air-ground integrated network: A survey", *IEEE Commun. Surveys Tut.*, vol. 20, no. 4, pp. 2714-2741, 2018: Space-Air-Ground Integrated Network: A Survey | IEEE Journals & Magazine | IEEE Xplore

[22] -K. David and H. Berndt, "6G vision and requirements: Is there any need for beyond 5G?", *IEEE Veh. Technol. Mag.*, vol. 13, no. 3, pp. 72-80, Sept. 2018: 6G Vision and Requirements: Is There Any Need for Beyond 5G? | IEEE Journals & Magazine | IEEE Xplore

[23]*Klein–Gordon equation* (no date) *Oxford Reference*. Available at: https://www.oxfordreference.com/view/10.1093/oi/authority.20110803100039743 (Accessed: 26 November 2024).

[24]*Helmholtz equation Encyclopedia of Mathematics. (n.d.). https://encyclopediaofmath.org/wiki/Helmholtz_equation*

[25] *The role of millimeter-wave technologies in 5G/6G Wireless Communications | IEEE Journals & Magazine | IEEE Xplore, https://ieeexplore.ieee.org/document/9318751/ (accessed Nov. 26, 2024).*

[26] *Propagation models and performance evaluation for 5G millimeter-wave bands | IEEE Journals & Magazine | IEEE Xplore. Available at: https://ieeexplore.ieee.org/document/8386686/ (Accessed: 26 November 2024).*

[27] *Ostrikova, D., Golos, E., Beschastnyi, V., Machnev, E., Gaidamaka, Y., & Samouylov, K. (2024b). Dynamic SNR, Spectral Efficiency, and Rate Characterization in 5G/6G mmWave/sub-THz Systems with Macro- and Micro-Mobilities. Future Internet, 16(7), 240. Dynamic SNR, Spectral Efficiency, and Rate Characterization in 5G/6G mmWave/sub-THz Systems with Macro- and Micro-Mobilities*

[28] Blot, Jean-Pierre. (2021). Fundamental Equations Used in Antenna Design.

https://www.researchgate.net/publication/351184216_Fundamental_Equations_Used_in_Antenna_Design

[29] *(PDF) mathematical models of MIMO channel*. Available at:

https://www.researchgate.net/publication/228740529_Mathematical_Models_of_MIMO_Channel

D:\Phase 3\phase3.docx(Accessed: 26 November 2024).

[30] *(PDF) rate-splitting multiple access to mitigate the curse of mobility in (massive) MIMO networks*. Available at: https://www.researchgate.net/publication/349309701_RateSplitting_Multiple_Access_to_Mitigate_the_Curse_of_Mobility_in_Massive_MIMO_Networks (Accessed: 26 November 2024).

[31] Alassawi, Sarah A, et al. "Compact Elliptic Ring 2 × 2 and 4 × 4 MIMO-UWB Antenna at 60 GHz for 5G Mobile Communications Applications." *Microsystem Technologies-Micro-and Nanosystems-Information Storage and Processing Systems*, 29 Sept. 2022, https://doi.org/10.1007/s00542-022-05383-9.

[32] ProPlate. "Professional Plating, Inc." *ProPlate®*, 13 Sept. 2023, www.proplate.com/for-antennas-are-there-specific-metals-or-alloys-that-are-preferred-for-their-superior-conductivity-and-radiation-characteristics/

[33] Raj, Tej, et al. "Advances in MIMO Antenna Design for 5G: A Comprehensive Review." *Sensors*, vol. 23, no. 14, 12 July 2023, pp. 6329–6329, https://doi.org/10.3390/s23146329 (Accessed: 26 November 2024).

[34] Chakraborty, Swarup, et al. "A Novel Dual-Band Elliptical Ring Slot MIMO Antenna with Orthogonal Circular Polarization for 5G Applications." *Heliyon*, vol. 10, no. 13, July 2024, p. e33176, https://doi.org/10.1016/j.heliyon.2024.e33176

[35] Wu, Aiting, et al. "A Compact High-Isolation Four-Element MIMO Antenna with Asymptote-Shaped Structure." *Sensors*, vol. 23, no. 5, 23 Feb. 2023, pp. 2484–2484, https://doi.org/10.3390/s23052484