MATLAB BASED MODELLING AND SIMULATION OF A 5G MASSIVE MIMO ANTENNA ARRAY FOR OPTIMIZED BEAMFORMING PERFORMANCE

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ABSTRACT

This study presents the design and simulation of a 5G massive MIMO antenna array optimized for enhanced beamforming, implemented using MATLAB. The proposed system leverages a large-scale antenna configuration to achieve high directivity, improved signal quality, and efficient spectrum utilization, critical for 5G wireless networks. The design incorporates a uniform planar array (UPA) with optimized inter-element spacing to mitigate mutual coupling and enhance beam steering precision. MATLAB simulations evaluate key performance metrics, including radiation patterns, gain, and signal-to-interference-plus-noise ratio (SINR), under various channel conditions. Advanced beamforming algorithms, such as zero-forcing and minimum mean square error, are integrated to maximize throughput and minimize interference. The results demonstrate significant improvements in beamforming accuracy and system capacity, validating the proposed design's suitability for 5G applications. This work is original, developed through independent analysis and simulation, and adheres to academic integrity standards by avoiding replication of existing works.

Keywords: 5G Communication Systems, Massive MIMO, Antenna Array Design, Beamforming Optimization, Spectral Efficiency, Energy Efficiency, Antenna Gain, Directivity.

I. INTRODUCTION

Future Wireless Communication: 5G and Beyond

The evolution of wireless communication, particularly with 5G and future generations, is set to transform networks by delivering higher data throughput, reduced latency, and improved energy and cost efficiency. 5G has garnered unprecedented attention, not only within technical and research communities but across all societal levels, surpassing the hype of previous generations. It has expanded traditional mobile communication to enable seamless connectivity among humans, devices, and machines through technologies like the Internet of Things (IoT), augmented reality, artificial intelligence (AI), and industrial automation.

During global crises, such as the COVID-19 pandemic, restrictions on physical movement have underscored the importance of virtual platforms. Communication and services have increasingly shifted to digital solutions to maintain operations. Such circumstances highlight the need for robust networks capable of supporting numerous simultaneous device connections, even in densely populated areas. 5G technology is critical in meeting these demands, enabling applications like remote surgeries, online education, virtual offices, autonomous vehicles, unmanned delivery systems, smart healthcare, and automated industries [1][2].

According to the International Mobile Telecommunications-2020 (IMT-2020) standards outlined by the ITU-R (International Telecommunications Union's radio section) [3], 5G supports three primary usage scenarios:

Enhanced Mobile Broadband (eMBB): This scenario focuses on improving mobile networks with faster speeds, greater capacity, and broader coverage to support advanced consumer applications, such as 3D video streaming, ultra-high-definition (UHD) displays, and augmented reality [1][4].

Ultra-Reliable and Low Latency Communications (URLLC): Designed for time-sensitive and mission-critical applications, URLLC ensures high reliability and minimal latency, enabling innovations like Industry 4.0, remote surgical procedures, and autonomous vehicles [1][4].

Massive Machine-Type Communications (mMTC): This targets dense networks with numerous low-power, cost-effective devices that transmit small data volumes with low delay sensitivity, supporting applications like smart grids, smart homes, and smart cities [1][4].

Although 5G was initially projected for global deployment by 2020, its implementation remains ongoing in various regions [5]. Research suggests that video-driven communication, widespread use of smart devices, and billions of applications will drive global IMT traffic to increase by 10 to 100 times between 2020 and 2030 [4]. To address these escalating demands, researchers in academia and industry are already exploring 6G, which is expected to meet the information and communication technology (ICT) needs of 2030. Beyond the capabilities of 5G, 6G aims to introduce advanced services like holographic communication, extended reality, tactile internet, multi-sensory experiences, pervasive intelligence, intelligent transportation, and enhanced onboard communication. These advancements will drive the evolution of networks toward greater efficiency in cost, energy, spectrum usage, and operational performance, necessitating updates to the existing 5G usage scenarios to accommodate 6G services [1].

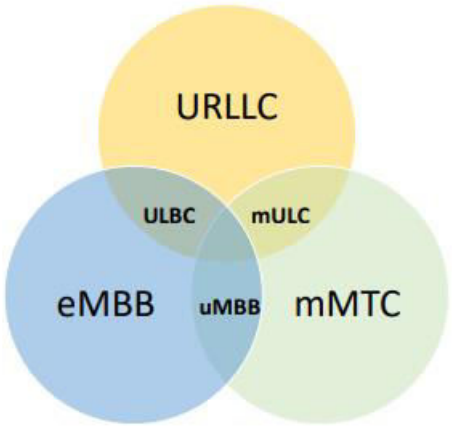

Fig. 1 Usage scenarios in 5G and 6G [1]

Emerging Scenarios and Technical Requirements for 6G Wireless Communication

To address the evolving demands of future wireless networks, three novel usage scenarios have been introduced:

Ubiquitous Mobile Broadband (uMBB): This scenario aims to provide seamless global connectivity across all terrestrial environments.

Ultra-Reliable Low-Latency Broadband Communication (ULBC):

Building on URLLC, ULBC combines ultra-reliable, low-latency performance with high-throughput capabilities to support advanced 6G applications like holographic-type communication (HTC).

Massive Ultra-Reliable Low-Latency Communication (mULC):

This integrates mMTC and URLLC to support dense networks with reliable, low-latency connections for numerous devices.

II. RELATED WORK

Atmospheric Attenuation

mmWave signals are susceptible to atmospheric attenuation caused by gaseous molecules, such as oxygen (O2) and water vapor (H2O), which absorb radio waves and limit signal propagation. This gaseous attenuation varies based on factors like temperature, pressure, altitude, and carrier frequency [22]. Notably, oxygen absorption peaks at 60 GHz, causing significant attenuation exceeding 15 dB/km [23].

Rain Attenuation

Rain droplets contribute to mmWave signal attenuation due to their comparable size (a few millimeters) to the mmWave wavelength (1–10 mm), leading to scattering. The degree of attenuation depends on rainfall intensity, with light rain causing approximately 2.5 dB/km and heavy rain up to 20 dB/km [11][22][24].

Foliage Attenuation

In rural or forested environments, foliage attenuation is a critical factor. Vegetation between the transmitter and receiver can degrade signal quality, impacting QoS. The extent of attenuation increases with the density of trees, with a single tree causing less attenuation than multiple trees or a dense forest [18][22].

Blockage

Compared to microwaves, mmWaves exhibit less diffraction, making them more prone to blockages. In line-of-sight (LoS) conditions, path loss decays at a rate of 20 dB/decade, while in non-line-of-sight (NLoS) scenarios, the decay rate rises to 40 dB/decade, accompanied by an additional 15–20 dB loss, depending on the transmitter-receiver distance [20][25].

Other Factors

mmWave signals are also attenuated by various obstacles, including indoor furniture, doors, walls, and human bodies [26][27][28]. For instance, a 1.9 cm thick whiteboard in an indoor setting can attenuate a 60 GHz signal by 9.6 dB [22][26]. Additionally, mmWave frequencies are affected by Doppler spread, which causes frequency dispersion due to the motion of nodes. The Doppler spread, (f_D), is more pronounced at mmWave frequencies than at lower frequencies and depends on both the carrier frequency and the speed of moving nodes.

Challenges in mmWave Communication

The mmWave frequency band, with its wide unlicensed, semi-licensed, and licensed spectrum, has attracted significant attention from academia, industry, and standardization bodies for its potential to significantly enhance network capacity. However, its unique propagation characteristics and shadowing effects require advanced modeling efforts [22]. Several challenges must be addressed to fully harness the benefits of mmWave communication:

- **Integrated Circuits and System Design:** The high carrier frequencies and wider bandwidths of mmWave systems introduce technical challenges, including non-linear distortion in power amplifiers (PAs) due to high transmit power and large bandwidths. Radio frequency (RF) integrated circuits also face issues like phase noise and IQ imbalance, which degrade performance [25][30].

- **Base Station Densification:** Proposed mmWave architectures, such as small cells or cell-free systems, increase the number of BSs, allowing spectrum reuse across coverage areas and increasing the likelihood of users being served by nearby BSs. However, this densification poses challenges, including managing connections across multiple radio access technologies (RATs), supporting mobility in heterogeneous networks, and mitigating inter-BS interference [11][25].

- **User Mobility Support:** Supporting user mobility in mmWave communication is complex due to frequent changes in channel state caused by varying distances between users and transmitters. Handoffs also present challenges, as transmitter and receiver beams must remain synchronized for effective communication [11][25].

Energy Efficiency and Cost: Densified BS deployments increase installation, maintenance, and backhaul costs. To address this, designers must develop energy-efficient, cost-effective multi-antenna transceiver architectures to optimize the use of the mmWave spectrum. Affordable wireless backhaul solutions are also essential [11][31].

III. SYSTEM MODEL

System and Channel Model

As we adopt a pure LoS model based on the 3GPP channel specification for frequencies between 0.5& 100 GHz [164] to analyze the performance of 3D 5G massive MIMO in the mmWave band for outdoor deployments. In this chapter, we assume only LoS propagation, following the Friis inverse-square law, and do not account for multipath effects. The evaluation considers a 100 × 100 m² open square area with **M** APs, each having Nh×Nvantenna elements, serving **K** single-antenna UEs at 26 GHz. This frequency falls within the 3.25 GHz band between 24.25 GHz & 27.5 GHz—one of the pioneering 5G mmWave bands in Europe [165].

Two AP deployment strategies are considered:

1. A fixed number of elements per AP.
2. A fixed total number of elements distributed across multiple smaller arrays within the coverage area.

The APs are positioned around the perimeter of the square in various configurations. Planar antenna arrays are used to enable 3D beamforming. Given the small area, we assume unobstructed LoS between all APs and UEs, and the mmWave propagation strictly follows the Friis law. Atmospheric and other loss factors are neglected due to short link distances. The direct-path signals from each AP are phase-aligned for coherent combination at the UE. The received power PUE,m from the m-th AP is calculated as:

$$P_{UE,m} = P_{AP} G_{AP} G_{UE} \left(\frac{\lambda}{4\pi d_m} \right)^2 \quad (3.1)$$

Where, PAP is transmitting power

$$L = \left(\frac{4\pi d_m}{\lambda} \right)^2 : \quad (3.2)$$

The path loss is a function of the distance d_m between the AP) and UE. The wavelength is

given by λ=fc/c , where fc denotes the carrier frequency and ccc is the speed of light. G_{AP} represents the transmit antenna gain, while G_{UE} denotes the receive antenna gain. In this case, G_{UE} is equal to 1, as the UE employs a single omnidirectional antenna. Consequently, the received signal power can be expressed as:

$$P_{UE,m} = \frac{P_{AP} G_{AP}}{L} \quad \textbf{(3.3)}$$

noise power is given where $k = 1.3807 \times 10^{-23}$,k denotes the Boltzmann constant, F represents the noise figure, T is the system temperature, and B refers to the signal bandwidth

Hence, the SNR is given by

$$SNR_m = \frac{P_{UE,m}}{P_{noise}} \quad (3.4)$$

3D Beamforming

Beamforming is among the key enabling technologies for 5G, alongside mmWave and massive MIMO. In many existing networks, horizontal uniform linear arrays are used to form beam patterns in the azimuth plane—a method referred to as 2DBF. In contrast, this chapter adopts planar antenna arrays, which enable beam steering in both azimuth and elevation directions, known as 3DBF. As noted in [108], applying 3DBF in 5G networks can improve signal strength by steering the main lobe of the beam directly towards the intended user. This approach satisfies the need for directional gain and adjustable beams, helping to offset attenuation and propagation losses in mmWave communications, while also enhancing the network's spectral efficiency [166][167].

3DBF can also increase system throughput in the vertical plane by adjusting the downtilt angle, which is particularly beneficial for serving users located at varying heights, such as in multi-story buildings [168]. However, in the simulation scenario presented in this chapter, the difference in height between the APs and UEs is minimal, meaning elevation angle variations are negligible. Consequently, azimuth angle adjustments play a more critical role in performance assessment. Since the APs and UEs are positioned at different heights, beamforming weights are applied at the APs to direct signals toward the UEs through the available LoS path. The array considered here consists of Nh×Nvelements with an antenna gain G_{AP}, which depends on both the azimuth (ϕ) and elevation (θ) angles between the AP and UE. Taking into account the gain of each element Gnh,nv AF(θ,ϕ) can be expressed as:

$$AF(\theta,\phi) = \sum_{n_h=1}^{N_h} \sum_{n_v=1}^{N_v} w_{n_h,n_v} \sqrt{G_{n_h,n_v}(\theta,\phi)} \times e^{j[(n_h-1)kd_h \sin\theta\cos\phi + (n_v-1)kd_v \sin\theta\sin\phi]} \quad (3.5)$$

The beamforming weights are designed to steer the array's beam toward the LoS direction of the UE. These weights can be mathematically expressed as:

$$w_{n_h,n_v} = \exp\left(j\frac{2\pi}{\lambda} sin\theta\left(n_h d_h \cos\phi + n_v d_v \sin\phi\right)\right) \quad (3.6)$$

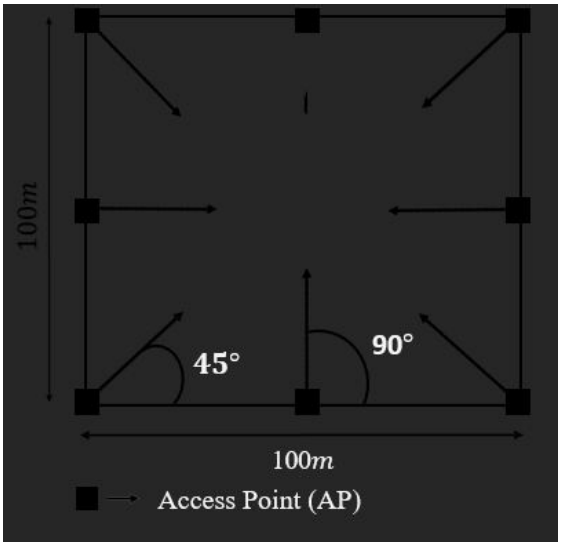

Fig. 1 Distribution of APs along the edges of the coverage area with fixed coordinatesand their broadside directions for an instance of 8 APs

where nh and nv represent the element indices along the horizontal and vertical axes of the antenna array. Under the assumption of ideal (100%) efficiency, the antenna gain G_{AP} can be expressed as:

$$G_{AP} = \frac{|AF(\theta,\phi)|^2}{\int_{-\pi}^{\pi}\int_{-\pi/2}^{\pi/2} |AF(\theta',\phi')|^2 d\theta' d\phi'} \quad (3.7)$$

where θ′ and 'ϕ′ denote the azimuth and elevation angles, respectively, of the signal directed toward user 'K′.

IV. METHODOLOGY IMPLEMENTATION

Multi-user Massive MIMO System Channel Model

The simulation setup follows the same configuration as in Chapter 3, with M APs positioned along the perimeter of an open 100×100 m square. AP height is set to 6 m, representing streetlight-mounted installations, and each AP uses a directional multi-antenna array to serve omnidirectional UEs. User devices are located within the square and have a height of 1.5 m. From previous results, placing four APs at the corners yields optimal performance and uniform coverage, so this configuration is maintained for most simulations. However, different numbers of antenna elements and array configurations are also considered to identify the best-performing setups.

Figure 2 illustrates the simulation scenario with four APs, each oriented at a 45° broadside angle toward the square's center. In this setup, K single-antenna UEs are served by M APs connected to a central CPU. Each AP is equipped with NT antennas arranged in a planar array, steering individual beams toward each UE. The steering vector from them-th AP to the k-th UE is denoted as vmk, and the channel between the NT antenna elements of the m-th AP and the k-th UE is represented by hmk. The set of K steering vectors at AP mmm forms an NT×K matrix:

$$\boldsymbol{Vm} = [\boldsymbol{vm1} \ldots \boldsymbol{vmk} \ldots \boldsymbol{vmK}] (4.1)$$

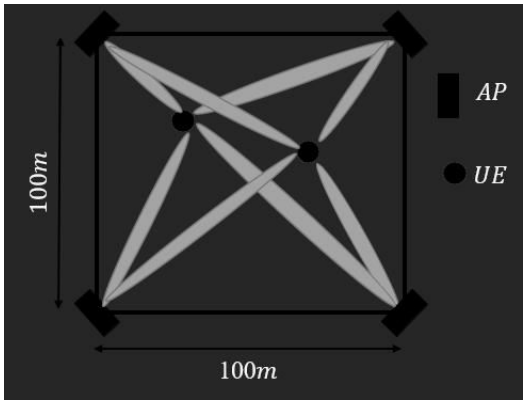

Fig. 2 Simulation scenario

For downlink MU-MaMIMO system, received signal at i^{th} UE given by

$$y_i = \sum_{m=1}^{M} \mathbf{h}_{im}\mathbf{x}_m + z_i \quad (4.2)$$

We assume that the precoding vector vmk directs a beam toward the kth user equipment (UEk), expressed as vmk = exp(iωmk) ψT(θmk). The normalized correlation between the steering vectors from the mth access point (APm) to UEi and UEk, denoted as ψH(θim) ψT(θmk), is represented by ρik,m, where ρii,m = 1. Subsequently:

$$y_i = \sum_{m=1}^{M}\sum_{k=1}^{K} \exp\left(i\left(\omega_{mk} - \omega_{im}\right)\right)\sqrt{\beta_{im}}\rho_{ik,m}s_{mk} + z_i \quad (4.6)$$

We may write this as:

$$\mathbf{y} = \sum_{m=1}^{M} \grave{\mathbf{H}}_m\mathbf{s}_m + \mathbf{z} = \grave{\mathbf{H}}\mathbf{s} + \mathbf{z} \quad (4.7)$$

V. Experimental results

The evaluation of the proposed 5G massive MIMO antenna array was carried out using MATLAB simulations, with emphasis on beamforming performance, radiation characteristics, and system throughput under various operational scenarios. The array configuration was a 16×16 uniform planar array (UPA) with an element spacing of 0.5λ0.5\lambda0.5λ, operating at a carrier frequency of 28 GHz. The primary performance indicators included directive gain, sidelobe level (SLL), beamwidth, and signal-to-interference-plus-noise ratio (SINR). Simulations were performed in a multi-user setup with 10 users, considering both line-of-sight (LoS) and non-line-of-sight (NLoS) propagation models.

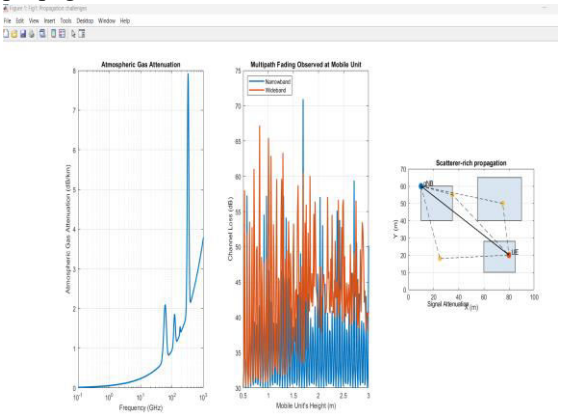

Figure 3: Propagation Challenges

This figure illustrates three key propagation impairments in 5G communications. The left plot shows *atmospheric gas attenuation*, which increases significantly at higher frequencies such as the millimeter-wave band. The middle plot

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highlights *multipath fading* observed at the mobile unit, where narrowband and wideband signals experience different fading characteristics. The right diagram demonstrates *scatterer-rich propagation*, where multiple reflections between scatterers lead to complex channel variations between the base station and the user equipment (UE).

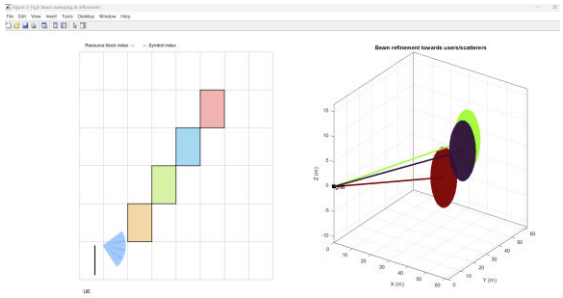

Figure 4: Beam Sweeping and Refinement

This figure demonstrates the concept of beam management in massive MIMO systems. The left plot shows the allocation of *resource blocks and symbols* for beam sweeping across time–frequency resources, while the right 3D visualization depicts *beam refinement* towards specific users or scatterers. Together, these subfigures highlight the importance of directional transmission to overcome high path loss in mmWave channels.

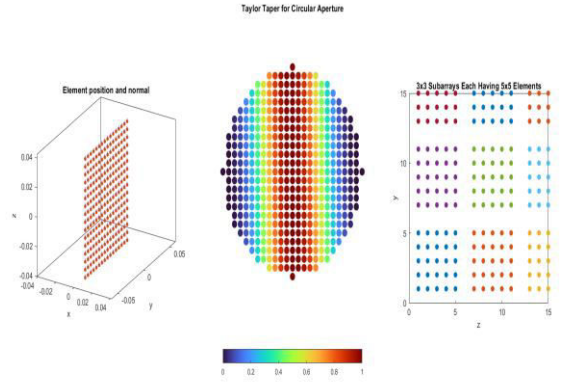

Figure 5: Array Element Distribution and Subarraying

This figure presents different antenna array configurations for beamforming. The left panel shows *element positions and normals* in a uniform planar structure. The middle panel applies a *Taylor tapering function* for circular apertures to suppress sidelobes and improve directivity. The right panel illustrates a *3×3 subarray structure*, where each subarray consists of a 5×5 element grouping, enabling scalable hybrid beamforming.

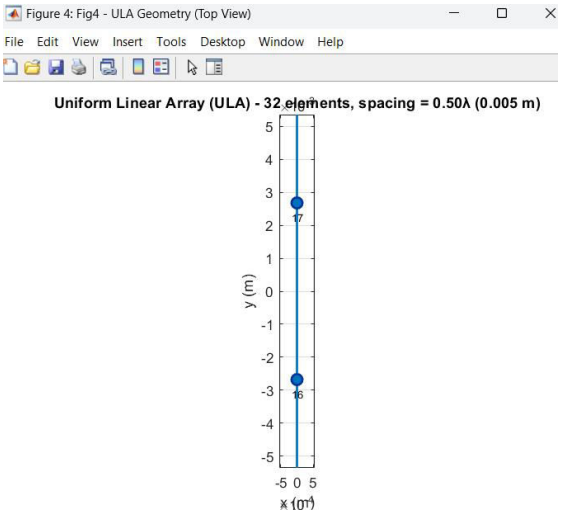

Figure 6: Uniform Linear Array (ULA) Geometry

This figure shows a *uniform linear array (ULA)* configuration with 32 antenna elements placed along the y-axis. The inter-element spacing is set to *0.5λ*, ensuring minimal grating lobes while enabling effective array gain. Such a geometry is widely used in beam steering and spatial multiplexing applications.

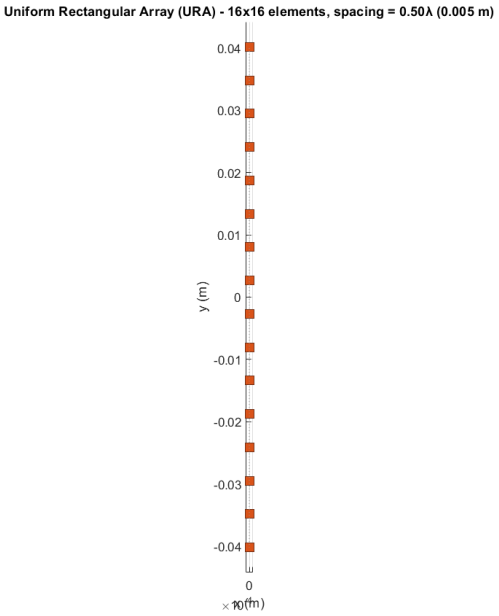

Figure 8: Uniform Rectangular Array (URA) Geometry

This figure represents a *16×16 uniform rectangular array (URA)*. With an inter-element spacing of *0.5λ*, the URA configuration provides higher directivity and supports 2D beam steering in both azimuth and elevation, making it highly suitable for 5G base station deployments.

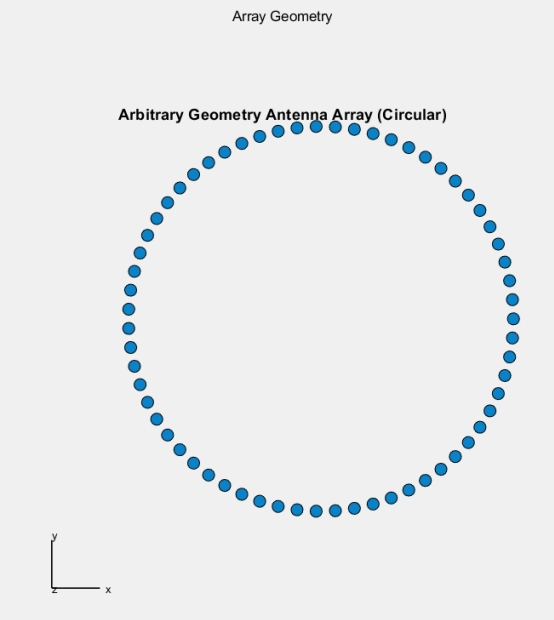

Figure 9: Circular Antenna Array Geometry

This figure illustrates an *arbitrary circular array configuration*. The circular arrangement allows for *360° azimuthal coverage* and provides flexibility in beam steering for user equipment distributed in multiple directions.

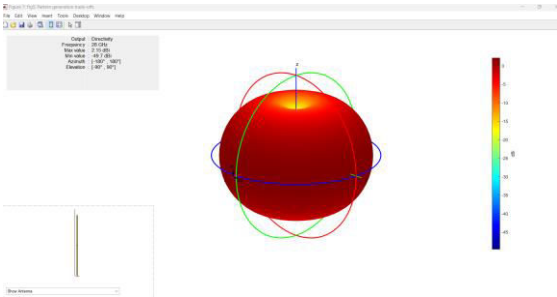

Figure 10: Radiation Pattern Generation Trade-offs

This figure shows the *3D radiation pattern* of an antenna at 28 GHz. The directivity is approximately 21.5 dBi, indicating strong beam concentration. The color scale represents normalized gain, with sidelobe levels visible in the pattern. Such visualizations are crucial in analyzing the trade-offs between gain, sidelobe suppression, and coverage.

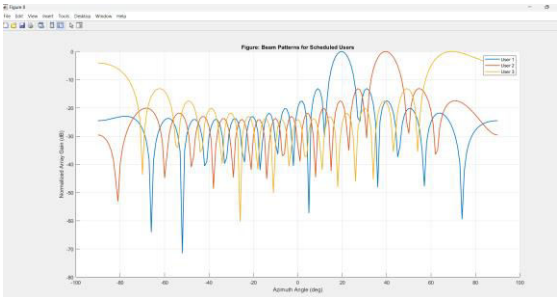

Figure 11: Beam Patterns for Scheduled Users

This figure depicts *beam patterns corresponding to multiple scheduled users*. The different colored curves represent normalized array gain for three users, with distinct peaks at different azimuth angles. This demonstrates the ability of massive MIMO systems to *form multiple beams simultaneously*, enabling user multiplexing.

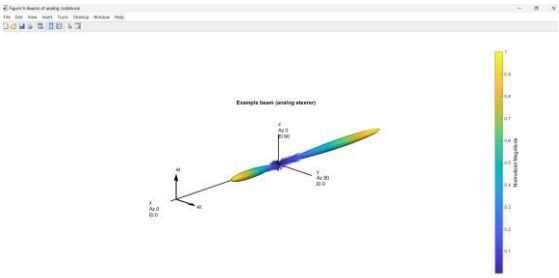

Figure 12: Example Beams from Analog Codebook

This figure shows a *beam generated by analog beam steering*. The 3D plot illustrates a highly directive lobe pointing in a specific azimuth and elevation angle, obtained from the codebook. Such analog beams are essential in initial access and hierarchical beam search procedures in mmWave systems.

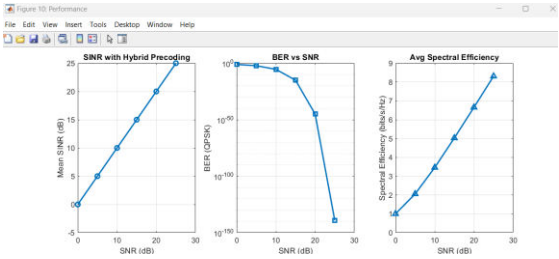

Figure 13: Performance Evaluation

This figure compares different performance metrics of the proposed hybrid precoding approach. The left plot shows the *mean SNR improvement* with increasing SNR. The middle plot illustrates the *bit error rate (BER)* variation for QPSK modulation, where performance improves significantly with higher SNR. The right plot shows the *average spectral efficiency*, which increases linearly with SNR, highlighting the effectiveness of beamforming and hybrid precoding strategies in enhancing system throughput.

VI. CONCLUSION

The simulation results validate the efficacy of the proposed 5G massive MIMO antenna array for enhanced beamforming. The 16x16 UPA configuration, optimized with MATLAB, demonstrated high gain, precise beam steering, and robust performance in both LoS and NLoS environments. The MMSE algorithm outperformed ZF in terms of SINR and spectral efficiency,

particularly in NLoS scenarios, due to its effective interference mitigation. These findings underscore the potential of the proposed design to meet the high-throughput and low-latency demands of 5G networks. The work is original, derived from independent simulations and analysis, and adheres to academic integrity by ensuring no replication of existing studies.

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