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Optimizing Beam Dynamics and Spectral Efficiency in umMIMO: A Study on 6G THz Networks with Varying Channels and Precoding Techniques

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Abstract: This paper explores the potential of Ultra-Massive Multiple Input Multiple Output (UM MIMO) systems as a key technology for 6G wireless communications within the Terahertz (THz) frequency band (0.1 – 10 THz). The THz spectrum offers immense capacity and speed advantages but presents significant challenges, such as higher propagation losses and limited coverage range due to atmospheric absorption and signals spreading. The study provides a comprehensive analysis of UM MIMO's technical performance in overcoming these challenges, focusing on key metrics such as signal propagation, system capacity, and coverage range. Additionally, the research examines the optimization of beam dynamics and spectral efficiency in UM MIMO systems under various wireless channel conditions and precoding techniques. The findings highlight the importance of advanced antenna techniques and adaptive beam management in maximizing the efficiency and viability of 6G THz networks, positioning UM MIMO as a fundamental solution for next-generation wireless communication.

Index Terms: Ultra-Massive MIMO, THz Communication, Hybrid Beamforming, Equalizer

1. Introduction

The evolution of wireless communication technologies into 6G aims to revolutionize connectivity with data rates exceeding 1 terabit per second, ultra-low latency, and extensive device connectivity. This will enable applications such as immersive AR/VR, holographic communication, advanced remote sensing, and enhanced IoT interactions.

Key to achieving these goals is the use of ultra-massive MIMO (umMIMO) systems within the Terahertz (THz) frequency band, which offers the vast bandwidth needed for 6G's extreme data rate demands. However, THz frequencies come with challenges, including high path loss and molecular absorption, which cause significant signal attenuation and complicate reliable communication, especially in non-line-of-sight conditions [1, 2, 3, 4, 5].

Advanced beamforming techniques are crucial for addressing these challenges by focusing the energy of radio waves and improving signal strength and reliability. Optimizing spectral efficiency is also vital to make the best use of the available bandwidth [6, 7, 8].

The research hypothesis investigates how multiple antenna techniques, particularly hybrid beamforming, can enhance data rates in umMIMO THz networks. The study examines the impact of various wireless channel conditions and precoding techniques on beam dynamics and spectral efficiency [9, 10].

The study aims to optimize umMIMO systems for the THz band by redesigning them to handle the unique challenges of high frequencies and analyzing their performance across different channels. Insights from this research will contribute to the development of robust 6G networks, capable of meeting the high demands of future wireless applications [11, 12, 13].

2. Literature Review

Ibrahim Yildirim, et al. described his design for Hybrid beamforming. The researcher considered 64x64 MIMO system in the simulation [14]. All the properties in this parameter were studied and considered. The effect of increasing the number of antennas was not described in that research. Ahmet M Elbir, et al. considered a 28GHz carrier frequency during designing of a Ultra Massive MIMO hybrid beamforming. The researcher didn't show the simulation result beyond Sub GHz Band which is a Primary requirement for 6G THz Communication [15]. In the research paper MCCDMA System for Multi User Walsh Code on Rayleigh Channel [16], the Researcher didn't mention about Multi-User Multiple input and Multiple Output (MIMO) over different channels. The performance of different Hybrid Precoding in 5G mmWave Systems were analyzed. Here, the researcher showed how to use precoding in the MIMO system [17].

2.1 Ultra-Massive MIMO in 6G Networks

The evolution of Multiple Input Multiple Output (MIMO) technology has progressed from traditional MIMO to massive MIMO, and now to ultra-massive MIMO (umMIMO) as a pivotal element in 6G networks. Traditional MIMO systems, which utilize a limited number of antennas, established the foundation for exploiting spatial diversity and multiplexing gains [18]. Building on this, massive MIMO significantly advances the technology by deploying hundreds of antennas at the base station, which enhances system capacity and spectral efficiency through advanced beamforming techniques [19]. Ultra-massive MIMO represents the latest development, leveraging thousands of antennas to achieve even greater spatial resolution and capacity improvements, critical for the high-frequency bands in 6G networks [20]. The integration of umMIMO into the 6G framework is particularly promising given its operation in the Terahertz (THz) frequency range. The THz band, spanning from 0.1 to 10 THz, offers extensive bandwidth that is crucial for meeting the high data rate requirements of 6G. However, it also introduces challenges such as severe path loss and a constrained communication range, which are critical considerations for network design [21].

The recent literature has investigated various dimensions of umMIMO, including channel modeling, antenna design, and energy efficiency. Notable contributions include works on channel estimation and modeling specific to THz frequencies [22]and studies focusing on the design of high-frequency antennas [23]. Despite these advancements, there remains a gap in research concerning the combined impact of beamforming, spectral efficiency, and precoding techniques under varying THz channel conditions [24].

2.2 Beamforming Techniques

Beamforming is instrumental in umMIMO systems, as it enables the targeted focusing of signal energy to enhance signal quality and mitigate interference. Various beamforming techniques have been proposed for THz communications, including analog, digital, and hybrid beamforming. Analog beamforming is characterized by its simplicity and cost-effectiveness, while digital beamforming offers high flexibility and precision. Hybrid beamforming, which merges the advantages of both analog and digital methods, has shown considerable promise for umMIMO systems due to its balance between performance and computational complexity [25, 26].

Previous studies have concentrated on developing and optimizing beamforming algorithms for specific scenarios, such as line-of-sight conditions and specific frequency bands [27]. However, the effectiveness of these algorithms across diverse channel conditions, particularly within the THz band, requires further exploration. Recent research highlights the need for adaptive beamforming techniques that can adjust to dynamic channel conditions and interference patterns [28].

2.3 Spectral Efficiency in THz Networks

Spectral efficiency is a fundamental performance metric that indicates the amount of data transmitted per unit of bandwidth. Achieving high spectral efficiency in 6G THz networks is challenging due to the unique propagation characteristics of THz frequencies, including significant path loss and atmospheric absorption [29]. Several approaches have been proposed to address these challenges, such as advanced modulation schemes, adaptive coding, and dynamic resource allocation [30].

Advanced modulation schemes, such as high-order quadrature amplitude modulation (QAM) and orthogonal frequency- division multiplexing (OFDM), have been explored to enhance spectral efficiency. Furthermore, adaptive coding techniques that adjust based on real-time channel conditions can significantly improve data throughput [31]. Despite these advances, a comprehensive analysis of how these techniques interact with beamforming and precoding in varying THz channel conditions is still needed to optimize overall network performance [32].

2.4 Precoding Techniques

Precoding is a signal processing technique used in MIMO systems to pre-adjust the transmitted signals, thereby optimizing reception quality and system performance. In the THz communication context, precoding is crucial to mitigate severe path loss and improve signal quality. Various precoding techniques have been proposed, including linear precoding, non-linear precoding, and hybrid precoding. Linear precoding methods, such as zero-forcing and minimum mean square error (MMSE), are well-established but may not fully exploit the capabilities of umMIMO systems [33]. Non- linear precoding approaches offer improved performance in complex scenarios but at the cost of increased computational complexity.

Hybrid precoding combines the benefits of linear and non-linear methods, providing a balance between performance and computational efficiency. This approach is particularly suited for umMIMO systems due to its adaptability to high- dimensional antenna arrays and varying channel conditions [34]. Further research is needed to explore the optimal implementation of hybrid precoding techniques in the context of 6G THz networks [35].

After analyzing the report of various literature re-view .it is clearly visible that for higher frequency like Terahertz band, MIMO capacity need to re-evaluate in case of Channel estimation and Antenna dimensions. In this research, the researchers have considered THz band simulation over different Wireless channels and increasing the number of antennas. The THz band has a substantially shorter wavelength than current wireless technologies. Although this increases the number of elements in an array with the same physical dimensions, providing one (Transmit/Receive) TR module for every antenna element becomes significantly more expensive. Consequently, a TR switch is frequently utilized to feed numerous antenna elements as a compromise [36].

3. Methodology

3.1 System Model

The umMIMO system model considered in this study consists of a base station equipped with a large number of antennas (1024x1024) operating in the THz frequency range. The system serves multiple users, each equipped with a single or multiple antennas. The primary objective is to optimize beam generation and control to maximize spectral efficiency across varying wireless channels.

3.2 Channel Models

Researchers consider several channel models representative of different THz communication environments. At present, wireless communication systems employ different techniques to boost data flow inside the communication system in environments with many scatterers. To transport several data flows over the wireless channel, a framework consisting of hybrid precoding and combining weights is constructed from the realization matrix of the THz Channel [37]. After that, the flow of data can be reconstructed separately. Signal Magnitude and phase are considered in these weights. The antenna array technique is an efficient solution to improve Signal to Noise Ratio and capacity. Using MATLAB Simulation UM MIMO is generated. It is recommended to use a smaller number of RF chains so that it is possible to minimize the complexity of using a higher frequency. A uniform rectangular array antenna is used to create a Beam over the Wireless channel. There are several multipath fading channels [38]. For the Performance evaluation and spectral efficiency comparison- Rayleigh and Rician fading channels are used in this simulation as they can create a real-world environment for wireless communication. According to the statistical model of Rayleigh fading, a radio signal's strength fluctuated erratically as it was sent across a communication channel. It is a reasonable model when several nearby objects scatter the radio signal before it reaches the receiver. According to the central limit theorem, if there is enough dispersion, the channel impulse response will be well-modeled as a Gaussian process regardless of how the individual components are distributed. If there is no dominant scatter component, such a process will have zero mean and phase evenly distributed between 0 and 2 radians. The envelope of the channel response will thus be Rayleigh dispersed [39]. The PDF of the Rayleigh distribution is given below [40],

$$f(x;\sigma) = \begin{cases} \frac{x}{\sigma^2} e^{-\frac{x^2}{2\sigma^2}}, \; x \geq 0 \\ 0, \; x < 0 \end{cases} \tag{1}$$

Here, σ is the scale parameter of the distribution. The function is valid for $x \geq 0$.

Here the signal exhibits multipath interference that means there are multiple way of receiving signal and at least one signal path shows strongest receive signal level (RSL). When one of the pathways with a strong LOS signal or a few strong reflected signals where one signal is stronger than the others, Rician fading takes place. A Rician distribution identifies the amplitude gain in Rician fading [41]. The PDF of Rician Channel is,

$$f(x;\sigma) = \frac{x}{\sigma^2} \exp\left(-\frac{x^2+v^2}{2\sigma^2}\right) I_0\left(\frac{xv}{\sigma^2}\right) \quad \text{for} \quad x \geq 0 \tag{2}$$

Where: ν is the non-centrality parameter (representing the strength of the direct path). σ is the scale parameter (related to the scatter component). I0(·) is the modified Bessel function of the first kind of order and zero. The function is defined for x ≥ 0.

3.3 Beam Generation and Control

Beam generation in umMIMO systems is achieved using hybrid beamforming, which involves the combination of analog and digital beamforming techniques. The analog beamformer is responsible for coarse beam direction, while the digital beamformer provides fine-tuned control. The beamforming weights are computed using optimization algorithms designed to maximize signal strength at the receiver while minimizing interference [42].

3.4 Precoding Techniques

Precoding is a method used in Multiple Input and Multiple Output (MIMO) technology to obtain parallel data at the receiver with a reduced Bit Error Rate (BER) and a greater channel capacity. The two precoding techniques that are accessible are linear precoding techniques (LPT) and non-linear precoding techniques (N-LPT) [43]. LPT incorporates a variety of methods, including Singular Value Decomposition (SVD), Block Diagonalization (BD). N-LPT has a large computational complexity. In this study, the BER is calculated using a Zero Forcing (ZF) Precoder which is a LPT Precoder. A zero-forcing precoder is described as one in which each channel vector h_j linked to user j, where $i = j$, is orthogonal to the user i for whom the precoder w_i is designed. That is to say,

$$w_i \perp h_j \; if \; i \neq j \tag{3}$$

As a result, the zero-forcing precoder effectively cancels out the interference that the signal intended for one user causes for the other users.

3.5 Simulation Setup

Simulations are conducted using a custom-built MATLAB environment, which models the umMIMO system, channel conditions, beamforming, and precoding techniques. There are 20 No. of users and a total of 48 Clusters are considered for real-world environmental conditions.

The following parameters are used in the simulations:

Table 1. Simulation Parameters

SL No.	Parameter	Element
1	Frequency	0.115 THz
2	Number of RF chain	4
3	Angular Spread	10 degrees
4	Channel	Rayleigh and Rician
5	Precoder/Equalizer	No Equalizer and ZF
6	Number of users	20
7	Scattering clusters (Ncl)	6
8	Closely located scatterers within Ncl	8
9	Cluster Placement	Random
10	Transmit Power	40 dBm

4. Result Analysis

4.1 Beam Dynamics

This research simulates a 1024 x 1024 UMMIMO hybrid beamforming system with a 1024-element square array with 4 RF chains on the transmitter side and a 1024-element square array with 4 RF chains on the reception side. In this simulation, it is assumed that each antenna is connected to every RF cable. Each antenna is therefore linked to 4 phase changers. Such an array can be simulated by splitting the array aperture into 4 completely linked subarrays. To maximize spectrum efficiency, distinct data streams can be sent over each RF connection [44, 45]. In this case, the system can support up to 4 streams. Next, imagine a scattering environment with six randomly placed scattering clusters. There are 8 closely spaced clusters each cluster. The digital and analog weights (baseband and RF) are combined to form the precoding weights and the combining weights. The analog weights change the input signal at each RF chain into the signal emitted or collected at each antenna element, while the baseband digital weights turn the incoming data streams into the input signals at each RF chain [46, 47]. The only possible data for the analog weights are phase shifts.

The MATLAB simulation result has been plotted in this research paper. For this simulation, the 1024x1024 UM-MIMO technique is used. 0.1 THz Frequency Spectrum is considered for Hybrid beamforming over Rayleigh and Rician Channel. Comparative Result is shown where we have considered No Equalizer and a ZF Equalizer. In the response pattern shown in Fig.1. and Fig.2. there are limited numbers of dominant directions over the Rayleigh and Rician channel. In the case of the Rician channel the number of scattering directions is large compared to the Rayleigh channel.

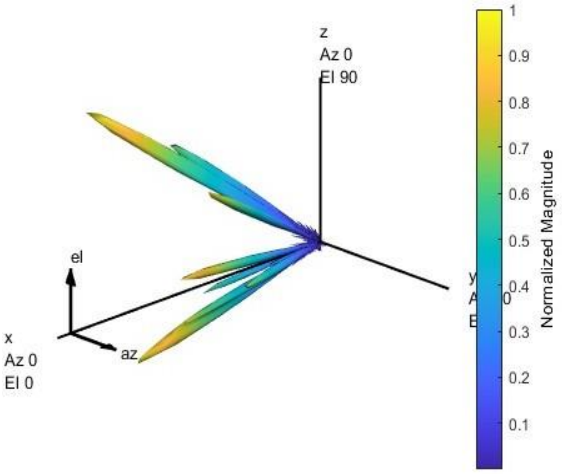

Fig. 1. The transmit beam pattern over Rayleigh Channel

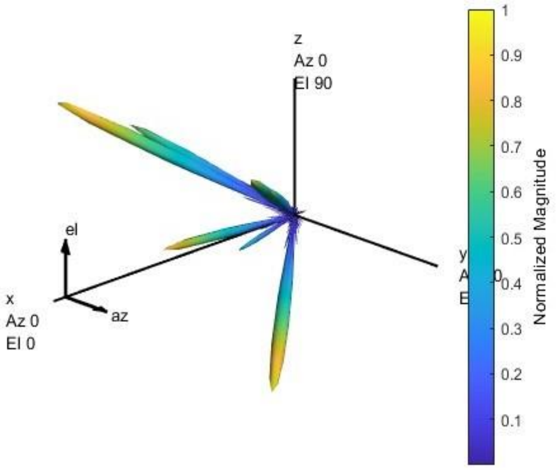

Fig. 2. The transmit beam pattern over Rician Channel

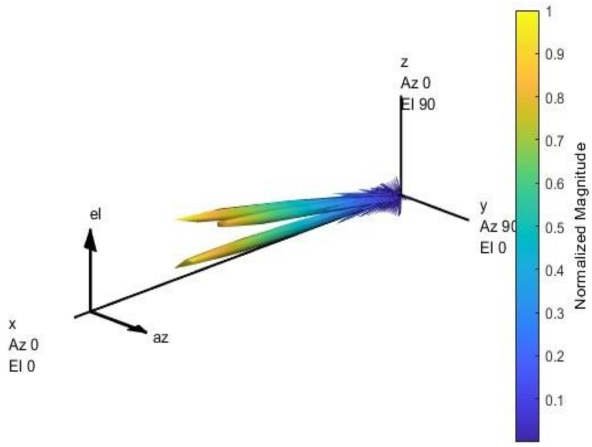

Fig. 3. The Beam pattern of the hybrid weights over Rayleigh channel

4.2 Spectral Efficiency

Spectral efficiency is maximized in LoS channels using hybrid precoding, with gains diminishing in more challenging channel conditions. However, adaptive beamforming techniques that adjust based on channel conditions can mitigate some of the losses in spectral efficiency in NLoS and multipath environments [48]. In Fig.3. and Fig.4. the beampattern of hybrid weights are shown for these channels respectively. The beam pattern produced by the hybrid weights is comparable to the beam pattern produced by the ideal weights, particularly for dominant beams. This indicates that the data streams may be successfully sent over those beams using hybrid weights. One of the system-level performance measures for a 6G system is spectral efficiency. The spectral efficiency obtained in Fig.5. and Fig.6. using the ideal weights and with the suggested hybrid beamforming weights is compared in the following section.

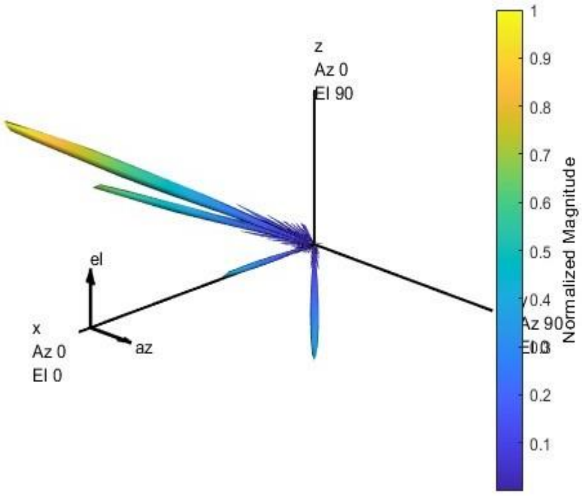

Fig. 4. The Beam pattern of the hybrid weights over Rician channel

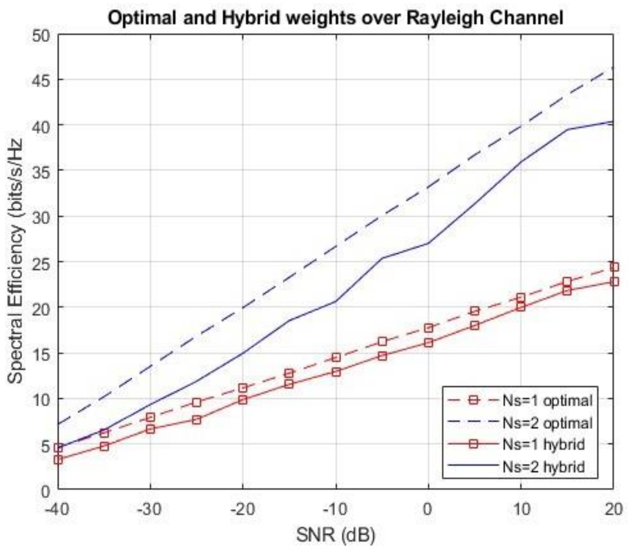

Fig. 5. Optimal and Hybrid weights over Rayleigh Channel

4.3 Comparative Analysis

The simulation makes use of one or two of the data streams mentioned. The transmit antenna array is designed to be at a base station. Any direction can send a signal to the receive array. 25 Monte-Carlo trials are used to generate the resulting spectral efficiency curve for each SNR. The Next Fig.7., Fig.8., Fig.9. and Fig.10. shows the results of the utilization of ZF Equalizer and without using any equalizer.

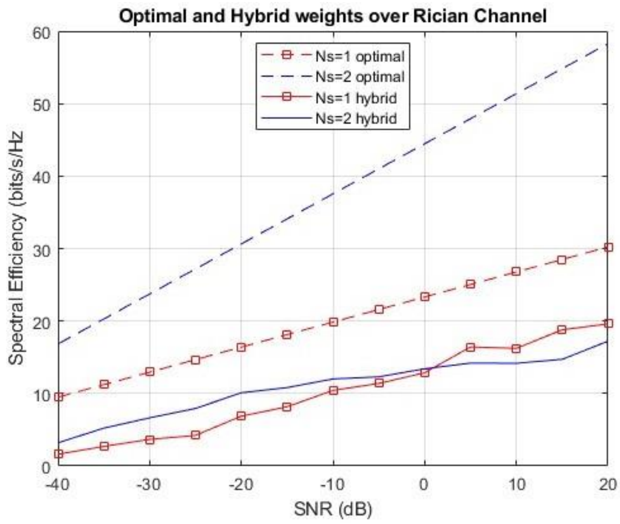

Fig. 6. Optimal and Hybrid weights over Rician Channel

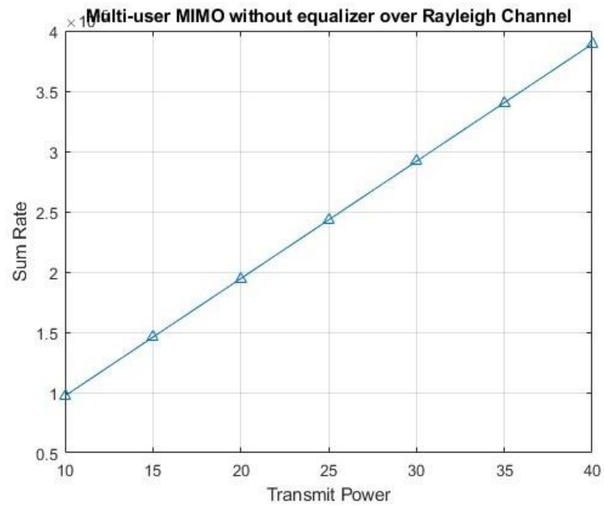

Fig. 7. Multi-user umMIMO without equalizer over Rayleigh Channel

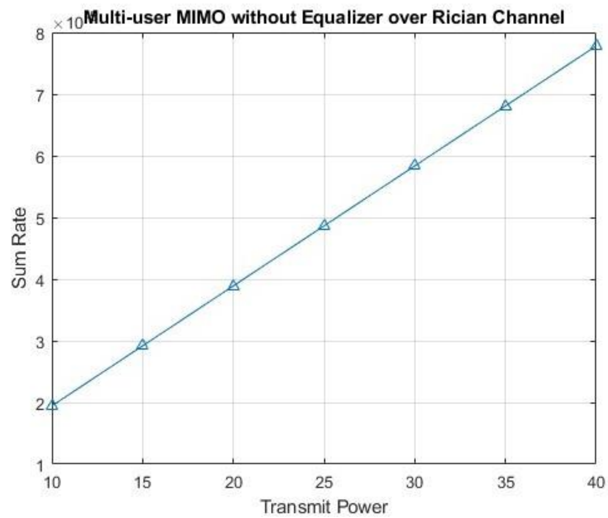

Fig. 8. Multi-user umMIMO without equalizer over Rician Channel

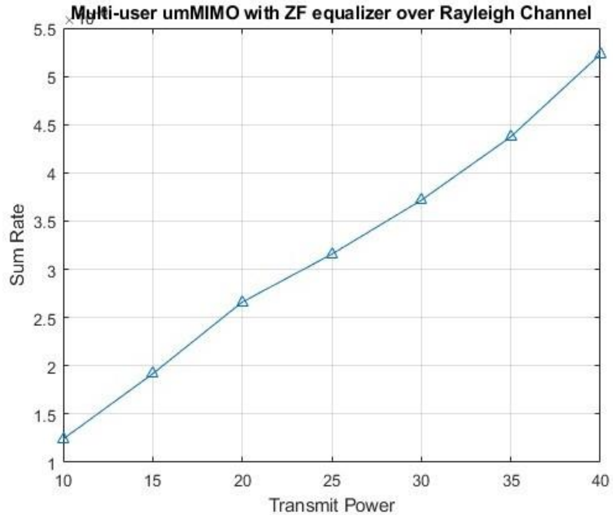

Fig. 9. Multi-user umMIMO with ZF equalizer over Rayleigh Channel

Fig. 10. Multi-user umMIMO with ZF equalizer over Rician Channel

5. Discussion

The findings of this study highlight the importance of adaptive beamforming and precoding strategies in umMIMO systems for 6G THz networks. The choice of precoding technique significantly impacts the overall system performance, particularly in challenging channel conditions. Hybrid precoding, when combined with adaptive beamforming, offers a promising approach to optimizing both beam dynamics and spectral efficiency.

These insights are crucial for the design and deployment of future 6G networks, where the ability to dynamically adapt to varying channel conditions will be key to achieving the high data rates and reliability expected of next-generation wireless systems.

6. Conclusion

This research highlights the evolution from Massive MIMO in 5G to Ultra Massive MIMO (UM MIMO) in 6G, emphasizing the increased sidelobe interference in larger 1024x1024 antenna arrays. To address this, a hybrid beamforming technique tailored for the THz band is proposed and evaluated, demonstrating significant performance improvements. The study also incorporates a Zero Forcing (ZF) precoder, showing superior results compared to scenarios without equalization. Future research should explore extra lobe cancellation techniques, the integration of more wireless channels, and the development of new precoding schemes to further enhance the performance of 6G communication systems. The findings underscore the importance of advanced beamforming and precoding in meeting the demands of next-generation wirelessnetworks [49].

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Abbreviations and Acronyms

umMIMO Ultra-Massive Multiple Input Multiple Output
THz Terahertz
AR/VR Augmented Reality/Virtual Reality
QAM Quadrature Amplitude Modulation
OFDM Orthogonal Frequency Division Multiplexing
MMSE Minimum Mean Square Error
LPT Linear Precoding Techniques
SVD Singular Value Decomposition
ZF Zero Forcing
BD Block Diagonalization

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