Performance Analysis of Multi-User Massive MIMO Precoding Techniques at Millimeter Wave Frequency Bands

Wesene Derbe Negeri

A Thesis Submitted to

Department of Electronics and Communication Engineering

School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Master of Science Degree in Electronics and Communication Engineering

Office of Graduate Studies

Adama Science and Technology University

June, 2023

Adama, Ethiopia

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Major Advisor: Dr. Demissie Jobir

Co-advisor: Dr. Shanko Chura

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APPROVAL PAGE OF M.SC. THESIS

We, the advisors of the thesis entitled **"Performance Analysis of Multi-User Massive MIMO Precoding Techniques at Millimeter Wave Frequency Bands"** and developed by Wesene Derbe, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Major Advisor	Signature	Date
Co-advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by Wesene Derbe have read and evaluated the thesis entitled **"Performance Analysis of Multi-User Massive MIMO Precoding Techniques at Millimeter Wave Frequency Bands"** and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Electronics and Communication Engineering.

Chairperson	Signature	Date
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Finally, approval and acceptance of the thesis are contingent upon the submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

Department Head	Signature	Date
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DECLARATION

I hereby declare that this Master Thesis entitled **"Performance Analysis of Multi-User Massive MIMO Precoding Techniques at Millimeter Wave Frequency Bands"** is my original work. That is, it has not been submitted for the award of any academic degree, diploma, or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

____________________	____________________	____________________
Name of the student	Signature	Date

RECOMMENDATION

We, the advisors of this thesis, hereby certify that we have read the revised version of the thesis entitled **“Performance Analysis of Multi-User Massive MIMO Precoding Techniques at Millimeter Wave Frequency Bands”** prepared under my/our guidance by Wesene Derbe submitted in partial fulfillment of the requirements for the degree of Master of Science in Electronics and Communication Engineering. Therefore, we recommend the submission of the revised version of the thesis to the department following the applicable procedures.

Dr. Demissie Jobir

___________________ ________________ _________________

Major Advisor name Signature Date

Dr. Shanko Chura

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Co-Advisor name Signature Date

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LIST OF ACRONYMS

5G	Fifth Generation
BS	Base Station
CSI	Channel State Information
EE	Energy Efficiency
DPC	Dirty Paper Coding
GoB	Grid of Beam
LDPC	Low-density Parity Check
LTPE	Lower Truncated Polynomial Expansion
LTPE-DPC	Lower Truncated Polynomial Expansion-Dirt Paper Coding
MIMO	Multiple-Input Multiple-Output
MMSE	Minimum Mean Square Error
mm-wave	Millimeter Wave
MRT	Maximum Transmission Ratio
MU	Multi-user
OFDM	Orthogonal Frequency Division Multiplexing
RLS	Regularized Least Square
RZF	Regularized Zero Forcing
SE	Spectral Efficiency
SINR	Signal plus Interference and Noise Ratio
SNR	Signal-to-Noise Ratio
TPE	Truncated Polynomial Expansion
UT	User Terminal
ZF	Zero Forcing

LIST OF SYMBOLS

$\|.\|2$	2- norm
$\|.\|$	Frobenius
α	Covariance/correlation between antennas
β	Normalized power factor
σ^2	Noise Variance
n	Thermal noise
C	Set of all complex numbers
M	Number of base station antennas
K	Number of user terminals
H	Channel matrix
S	Data vectors
N	Noise
H^H	Conjugate transpose
$(H)^{-1}$	Inverse channel matrix
γ	Channel state information quality
φ	Covariance matrix
$\widehat{H}$	Estimated channel matrix
X	Transmit vector
X^-	Mean
Tr (.)	Matrix trace function
I_M	$M \times M$ identity matrix
I_K	$K \times K$ identity matrix
J	TPE order

ABSTRACT

Millimeter wave (mm-wave) and Massive Multiple Input Multiple Outputs (MIMO) systems are the two key enabling technology of 5G and beyond . These technologies use large antennas system within short-range wavelength and high-frequency bands. The mm-wave frequency bands are easily susceptible to path loss and inter-user interference. In this thesis, the performance of large downlink multiple input multiple output systems using precoding techniques such as Maximum Ratio Transmission (MRT), Zero-Forcing (ZF), Regularized Zero-Forcing (RZF), Dirty Paper Coding (DPC), Lower order Truncated Polynomial Expansion (LTPE) and Lower order Truncated Polynomial Expansion-Dirty Paper Coding (LTPE-DPC) are evaluated and compared. The main objectives of linear precoding are to cancel interference between user terminals and mitigate noise amplification, improve spectral efficiency and energy efficiency, and also optimize the transmission of signals from the base station to the user terminals. In this thesis work we evaluated the spectral efficiency , sum rate , and energy efficiency of proposed LTPE-DPC. As the simulation results show the proposed LTPE-DPC precoder has bettr performance than the exsiting precoder ZF, RZF, LTPE, AND DPC and LTPE-DPC, has been evaluated sum rate at SNR levels of -5dB, 5dB, 10dB, and 15dB respectively .

Keywords: Millimeter wave , Massive Multiple Input Multiple Outputs, Lower Truncated Polynomial Expansion, Lower Truncated Polynomial Expansion- Dirty Paper Coding Precoding Techniques.

CHAPTER ONE

1 INTRODUCTION

1.1 Background of the Study

This work focused on reducing complexity in the massive MIMO downlink system, which was completely defined in a single-cell massive MIMO scenario that was carried out under a suitable situation. As a result, new technologies were incorporated into multiple-input multiple-output (MIMO) schemes in the context of fifth-generation (5G) and beyond fifth-generation (B5G) communication systems (Albreem et al., 2021). To elaborate further, Wireless technology made it easier and more common to convey information. Massive MIMO (Ma-MIMO) was a technology that enables multiple users to simultaneously transmit and receive data using multiple input and multiple outputs (MIMO) systems that were capable of providing wireless terminals equivalent and even better services in areas with significant mobility. Considering that 5G offered sub-6 GHz wireless access technologies, it was essential to carry out more research in this field. The demand for very high data rates on wireless channels with limited bandwidth and power had risen as a result of recent breakthroughs in mobile technology. The increasing data flow results in a higher ISI and greater complexity. Due to the user-friendliness of communication and the advancement of feature-rich mobile devices over time, higher data rates in a communication system are becoming increasingly crucial. A large quantity of antennas used for transmission and reception is required for millimeter-wave (30-300 GHz) communication to achieve significant beamforming gains and reduce the high path loss. Because so many antenna arrays are needed for digital precoding/combining, the hardware is complex, and analog precoding/combining has a low-performance rate. As a result, as the number of users grows, hybrid precoding is a compromise between analog and digital precoding/combining.(Singh & Shukla, 2022).

Another technology to achieve 5G aspirations is millimeter wave communication to achieve a high data rate and serves a large number of users at a time. Globally, the number of people who have access to mobile communication ser vices has increased dramatically during the past ten years (Gao et al., 2017). The demand for seamless high-speed data rates is increasing along with Utilizing smartphones and similar intelligent devices that use cellular data (Gautam, 2023).

The traditional 6 GHz frequency spectrum is exhausted because of the rise in users and demand for high data speeds. The mm-wave spectrum spans Operating within the frequency spectrum of 30 to 300 GHz, corresponding to wavelengths ranging from approximately 10 to 1 mm.

Massive MIMO systems have received attention recently as upgraded technologies for future wireless communication systems known as 5G and beyond communication systems. It will act as a catalyst for the fifth-generation wireless system since it may satisfy those needs by suggesting the usage of a substantial quantity of antennas deployed at the base station or BS. The system can also become more reliable and efficient while obtaining remarkable spectrum density, quality of service (QoS), and objectivity(Jit Singh et al., 2023). Point-to-point communication systems with multiple antennas on both transmitters and receivers are classified as MIMO devices. The employment of multiple antennas on both ends of the communication link provides superior performance compared to systems where either the transmitter or receiver has multiple antennas. (Jui, 2020). Spectral efficiency, communication reliability, energy efficiency, low-complexity signal processing, advantageous propagation conditions, and channel hardening are all key benefits of large MIMO systems. A general representation of massive MIMO is shown in Figure 1.1. (Borges et al., 2021).

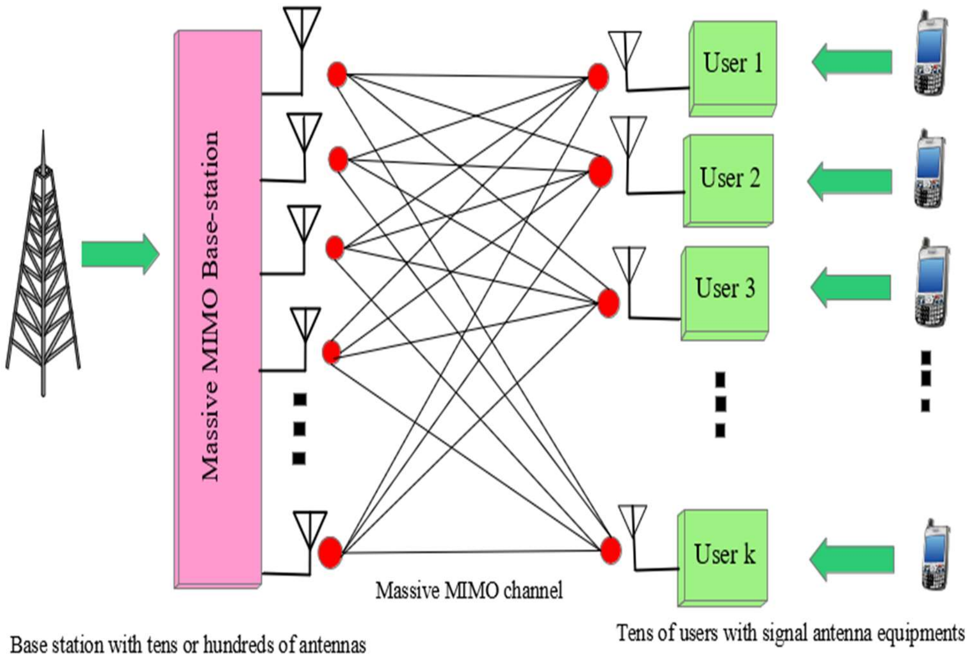

Figure 1. 1: Massive MIMO architecture (Jui, 2020).

Massive MIMO challenges and mitigation methods the implementation of large MIMO systems requires overcomingvarious problems and obstacles, extending beyond the scope of traditional MIMO technology. Figure 1.2 depicts the primary challenges associated with large MIMO systems.

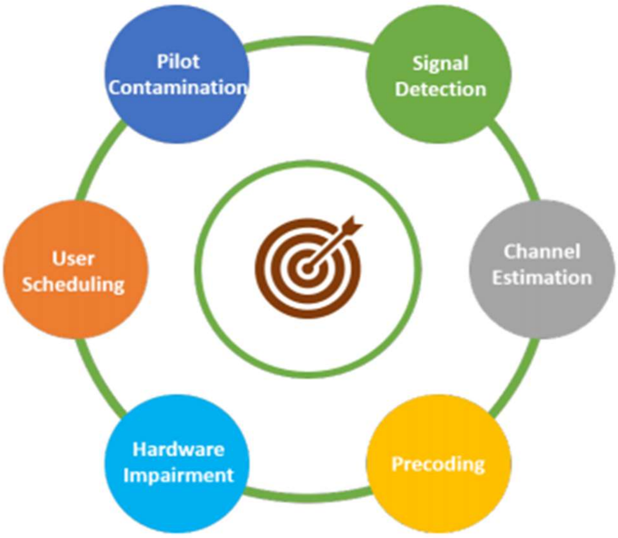

Figure 1. 2: Massive MIMO system deployment problems (Schumacher et al., 2020).

Pilot Contamination: Massive MIMO technology implementation is slowed down by pilot contamination, which is a serious obstacle. (Dutta, 2022). In a massive MIMO system, the base station makes use of a lot of antennas to simultaneously serve multiple users. The base station sends pilots, which are recognized signals, to the users to make this possible. The channels between the users and the base station that are required for data transmission and reception are then estimated by the users using these pilots.

Channel state information (CSI) plays a vital role in massive MIMO systems as it enables signal detection and decoding by providing insights into the communication link's characteristics, such as fading and scattering. Precoding, on the other hand, is an essential technique used in massive MIMO to maximize throughput while minimizing the impact of path loss and interference.

User scheduling is a crucial aspect in massive MIMO systems, where a base station equipped with a large number of antennas can communicate with multiple users concurrently. However, simultaneous communication with multiple users introduces multi-user interference, which can negatively impact the system's throughput performance.

Despite the benefits of precoding techniques in mitigating interference, they face two significant limitations. Firstly, they have a limited capability to spatially multiplex a restricted number of users within a given resource slot. Secondly, their performance tends to degrade when serving users with spatial correlation. Hardware Impairments: Massive MIMO system depends upon a large number of antennas to reduce the effect of noise, fading, and interference. A large number of antennas in massive MIMO increases the system complexity and increases the hardware cost.

Energy Efficiency Energy: The increasing number of antennas does always increase the spectral efficiency because the power consumption also increases along with the number of antennas and more users.

Signal Detection: In massive MIMO systems, due to a large number of antennas, the uplink signal detection becomes computationally complex and reduces the achievable throughput.

Millimeter-wave massive MIMO: millimeter radio waves have garnered significant interest in academic and industrial research due to their extensive application in military and limited space communication systems. These waves are valued for their unique frequency spectrum characteristics, which offer enhanced transmission capacity reaching several gigabits per second. Specifically, at a frequency of 60 GHz, this technology enables transmission speeds of up to 1 Gbps. This capability is facilitated by the wave's high transmission steering, effectively mitigating interference between connections. (Osama et al., 2022).

A focus of interest across the whole world is Multiple-input multiple-output (MIMO) communication is a technology that allows for high-speed and high-quality wireless transmission without the need for physical line connections. (Mir et al., 2019). Reasons for utilizing mmWave for 5G: Wide bandwidth: mmWave bands offer a large bandwidth, enabling peak data rates of approximately 10 Gbps or even higher with full duplex capability. This surpasses the 1 Gbps limit achievable at lower microwave frequencies. Short wavelength advantages: The small wavelength of mmWave bands allows for the integration of compact components, enabling the inclusion of more antennas within smaller devices. This facilitates the miniaturization of circuits, modules, and equipment for 5G mmWave applications. Shorter wavelengths also result in higher antenna gains, as per electromagnetic and antenna theories. Narrow beams: In mmWave antenna arrays, it is possible to create highly directional and steerable narrow beams. This capability enables precise power transmission toward intended users in specific directions. Enhanced security and interference immunity: The use of highly directional beams and increased resolution in mmWave signals makes them difficult and expensive to jam, as they are restricted to a relatively confined area. Moreover, the narrow beams make mmWave transmission highly resistant to interference and noise at the receiver's end, thanks to the ability to concentrate the transmit power of the signal. (McHangama et al., 2020).

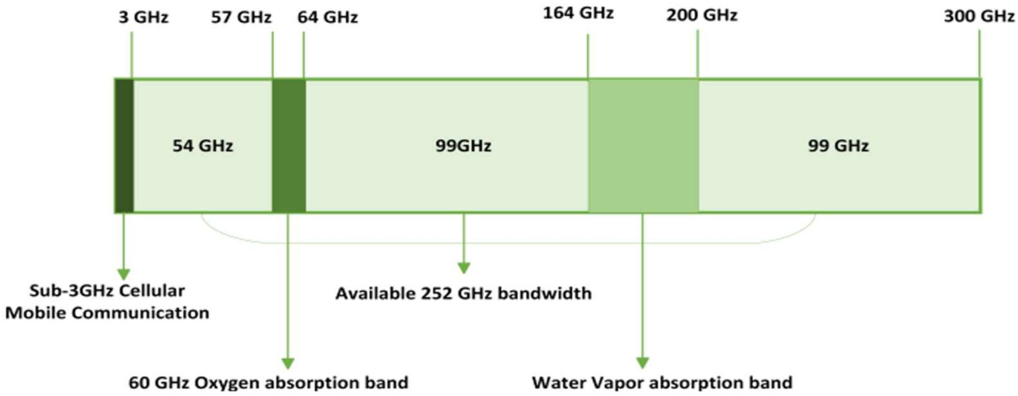

Figure 1. 3: The mm-wave region of the electromagnetic spectrum (Xiao et al., 2022).

1.2 Statement of the problem

In the realm of performance analysis for precoding techniques in massive MIMO mm-wave systems, various methods have been explored. However, these methods present certain limitations, such as matrix inversion issues in the case of RZF, high complexity coupled with high performance for DPC, and low performance alongside low complexity for LTPE.
In light of these limitations, this study aims to propose a technique, LTPE-DPC to overcome the aforementioned challenges. The objective is to reduce complexity while simultaneously enhancing system performance. By integrating the advantageous aspects of both LTPE and DPC, this approach seeks to address the limitations of existing techniques and give the way for improved precoding solutions in massive MIMO at mm-wave frequency bands.

1.3 Objectives

1.3.1 General objective

The objective of this thesis is to analyze the performance of multiuser massive MIMO precoding techniques at millimeter wave frequency bands.

1.3.2 Specific objective

- To compute the sum rate of linear and non-linear precoders.
- To evaluate the energy efficiency of base station antennas in a massive MIMO system.
- To analyze the spectral efficiency of mmwave wave frequency bands.
- To compare the performance metrics of ZF, RZF, DPC, LTPE, and LTPE-DPC precoding techniques.

1.4 Scope of the study

The scope of this thesis is to conduct a comprehensive analysis and evaluation of linear precoding techniques specifically designed for multi-user massive MIMO systems operating at mmWave frequency bands. The focus of the thesis is to compare and assess the performance of prominent precoding techniques, namely Maximum Ratio Transmission (MRT), Zero Forcing (ZF), Regularized Zero Forcing (RZF), Lower order Truncated Polynomial Expansion (LTPE), Dirty Paper Coding (DPC) and LTPE-DPC. The evaluation will be based on key performance metrics such as sum rate ,energy efficiency and energy efficiency, aiming to identify the strengths and limitations of each technique. Additionally, the study aims to explore methods for reducing the complexity of the massive MIMO system, to improve overall efficiency and practical implementation of the precoding techniques. Different scenarios will be considered, involving varying base station antenna configurations and user terminal settings, to provide a comprehensive understanding of the performance and suitability of the studied precoding techniques. The thesis aims to provide valuable insights and recommendations that can contribute to the advancement of multi-user massive MIMO system linear precoding at mmWave frequency bands, ensuring a focused and in-depth investigation within the defined boundaries.

1.5 Significance of the study

Nowadays, MIMO is a new technology, and conventional MIMO employs two or more antennas, with the use of many or massive antennas that are large in number rather than size being the exception. The benefit of pursuing this notion is that it will allow researchers to look into a good idea for a large MIMO system that reduces complexity under the stated linear pre-coding MRT, ZF, RZF, DPC, LTPE, and LTPE-DPC in a more effective manner.

1.6 Limitation

Both linear and non-linear precoding techniques have limitations in scenarios characterized by high channel correlation or non-linearity. These scenarios can lead to incomplete removal of interference between users, resulting in degraded system performance. Moreover, the computational complexity of advanced linear precoding techniques like High order Truncated Polynomial Expansion (HTPE) can be demanding, making real-time implementation challenging in resource-constrained systems.

1.7 Thesis contributions

- Improved Spectral Efficiency: Precoding can enhance the overall system capacity by mitigating interference and optimizing the allocation of resources among users.

- Interference Mitigation: Precoding techniques can reduce inter-user interference, allowing multiple users to simultaneously transmit and receive data without significant performance degradation.
- Robustness to Channel Conditions: Precoding algorithms can be designed to adapt to varying channel conditions, such as channel fading or mobility, to maintain reliable communication links.
- Energy Efficiency: By optimizing the spatial transmission, precoding techniques can improve energy efficiency by minimizing transmit power or maximizing data rate per unit power.
- User Fairness: Precoding algorithms can also be designed to ensure fairness among users, allocating resources and optimizing performance for all users in the system.
- To maintain the system's efficiency, it is vital to consider both the computational complexity and performance factors when designing and optimizing multi-user wireless communication systems.

1.8 Thesis organization

This thesis is structured into five chapters, each serving a specific purpose.

Chapter 1: Provides the necessary background information on mm-wave massive MIMO systems and precoding techniques. It outlines the research problem, objectives, significance, scope of the study, and the underlying motivation behind the research.

Chapter 2: Conducts an extensive literature review, which holds greater importance compared to other chapters. It offers a comprehensive overview of the subject matter, discussing previous research conducted by others that is relevant to the present study.

Chapter 3: Details the materials and methods employed in this research thesis, outlining the approach and techniques used to address the research problem.

Chapter 4: Presents the proposed results obtained from the research and facilitates discussions around them.

Chapter 5: Concludes the thesis by summarizing the findings and providing recommendations for future research directions in the field.

CHAPTER TWO

2 LITERATURE REVIEW

2.1 Overview

Chapter 2 of the thesis is dedicated to a comprehensive review of the existing literature on mm-wave massive MIMO systems and precoding techniques. This section is a critical component of the thesis as it provides context and background information relevant to the research topic. Through an extensive analysis of previously conducted studies by other researchers, this chapter aims to identify gaps, limitations, and areas that require further investigation. The literature review serves as the foundation for the current research, demonstrating its significance in the context of the existing body of knowledge, and providing valuable insights to guide subsequent chapters.

2.2 Precoding techniques for mmwave massive MIMO systems

Massive MIMO is considered a highly promising technology for 5G and future wireless communication systems. It represents a significant advancement over existing MIMO systems by incorporating a large number of antennas, ranging from hundreds to thousands, at the base station. This enables the system to support simultaneous connections for a considerably higher number of users, potentially reaching tens of thousands. The implementation of massive MIMO has the potential to revolutionize wireless networks, offering enhanced capacity, improved spectral efficiency, and increased overall system performance. (Jit Singh et al., 2023).

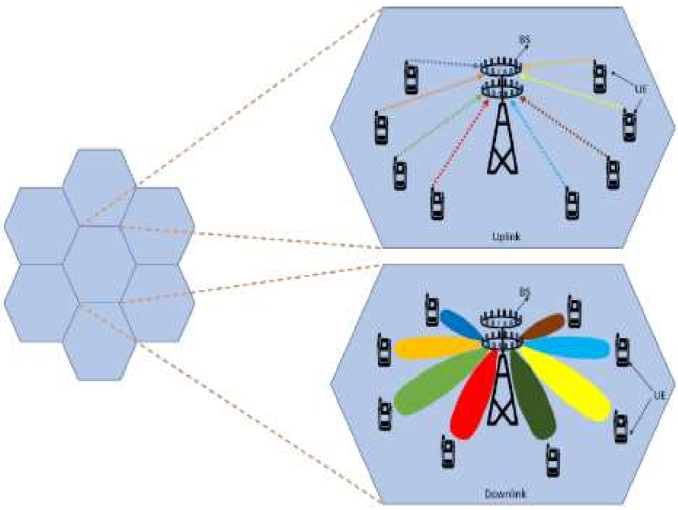

Figure 2. 1: The uplink and downlink of mmWave massive MIMO (Chataut & Akl, 2020).

- Increased Spectral Efficiency: By employing a large number of antennas at the transmitter and receiver, multiple users can be spatially multiplexed, leading to improved spectral efficiency. Consequently, mmWave systems can support a larger number of users and achieve higher data rates compared to conventional systems.
- Enhanced Reliability: Through the utilization of spatial diversity, massive MIMO technology mitigates the effects of fading and interference, thereby enhancing the dependability of mmWave communication. The use of large antenna arrays enables the creation of focused and directional beams, effectively addressing the challenges of severe path loss and interference at mmWave frequencies.
- Support for Low-Latency Communication: Real-time applications like autonomous vehicles, industrial automation, and virtual reality rely on low-latency communication, and massive MIMO technology is capable of supporting such requirements. Spatial multiplexing and the utilization of directional beams help reduce propagation delays and improve synchronization between transmitters and receivers.
- Energy Efficiency: By optimizing the allocation of available resources such as transmission power and antenna resources, massive MIMO technology enhances energy efficiency. This optimization leads to reduced power consumption and extended battery life for mobile and IoT devices, which is crucial in these domains.
- Scalability: Massive MIMO technology exhibits high scalability as it can accommodate a large number of antennas and users. This makes it suitable for various applications, ranging from small-scale wireless networks to large-scale cellular networks. (Kabaou, 2022).

2.2.1 Linear precoding techniques

Linear precoding techniques, such as zero-forcing (ZF) and regularized zero-forcing (RZF), are widely used in massive MIMO systems.

Linear precoding performs precoding operations by using linear combinations of the transmit antennas' signals.ZF precoding aims to completely eliminate inter-user interference by nullifying the interference from other users at the receiver side. RZF precoding is a regularized version of ZF that balances the trade-off between interference cancellation and noise amplification. Linear precoding techniques are computationally efficient and easier to implement compared to nonlinear precoding. However, linear precoding may not fully exploit the available spatial degrees of freedom, leading to suboptimal performance in certain scenarios.

2.2.2 Nonlinear precoding techniques

such as dirty paper coding (DPC) and Tomlinson-Harashima precoding (THP), are more advanced approaches. Nonlinear precoding exploits the nonlinear characteristics of the transmit signal processing to achieve improved performance. DPC is a nonlinear precoding technique that achieves optimal performance by pre-canceling the interference at the transmitter side using information about the users' channel state information (CSI).THP is another nonlinear precoding technique that introduces memory in the precoder to effectively cancel the inter-symbol interference (ISI) caused by the nonlinear transmit processing. Linear precoders that have a lower computational cost and can perform close to optimally than nonlinear precoders (Albreem et al., 2021).

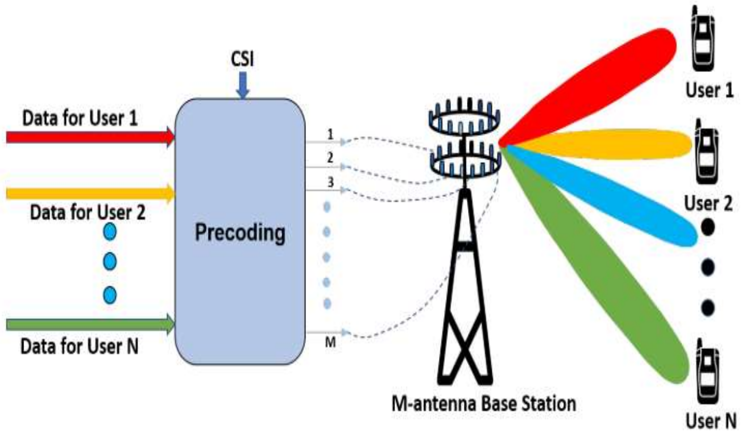

Figure 2. 2: Precoding Techniques (Bobrov et al., 2021).

2.3 Types of beamforming used in 5G

With the help of highly directed broadcasts, new networking at FR2 frequencies mm-wave would heavily rely on analog or hybrid beamforming to get around the route loss penalty and improve spatial selectivity (Ali et al., 2017).

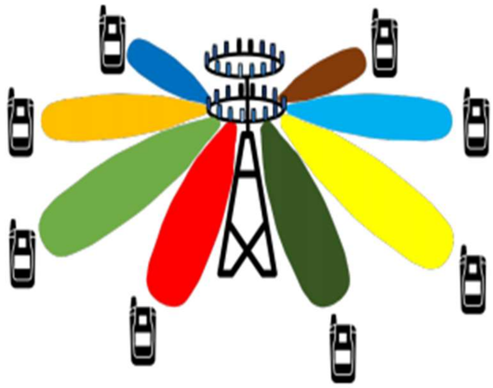

Figure 2. 3: Massive Multiple Output–Multiple Output (MIMO) beamforming (Dilli, 2022).

2.3.1 Analog beamforming

The system transmits an identical signal to each antenna and employs analog phase shifters to direct the beams, resulting in the transmission of the same signal from multiple antennas with varying phases. (Lu et al., 2021). Consequently, it is inexpensive but only supports single-stream transmission. The fact that only one beam is generated at a time due to this approach's inability to apply different beamforming weights for different users means that beamforming and MIMO will lose the benefits of spatial multiplexing (Gautam & Zhang, 2022).

2.3.2 Digital beamforming

Digital beamforming is particularly advantageous in spatial multiplexing scenarios within the digital baseband. By generating individual signals for each antenna, it becomes possible to transmit a combination of signals, each with its distinct directionality. This capability enhances the effectiveness of spatial multiplexing, enabling the transmission of signal superposition with separate directivities. (Du et al., 2021).

2.3.3 Hybrid beamforming

Massive MIMO antenna systems that use digital and analog beamforming together have improved performance and reduced the RF chain (Sun et al., 2020).

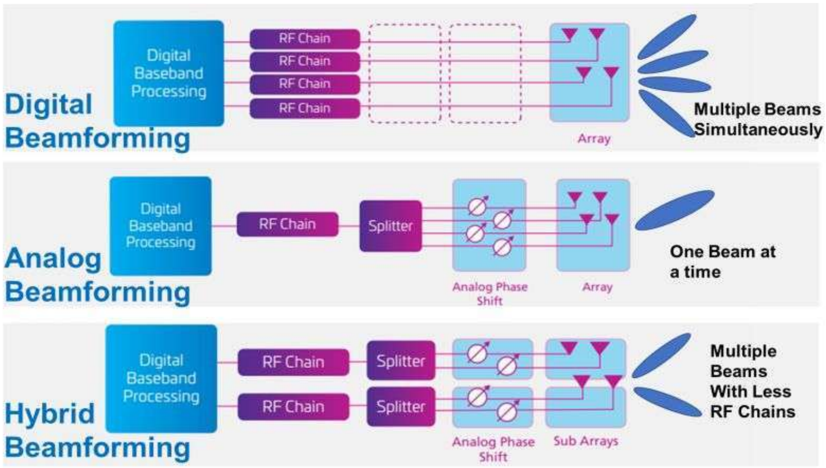

Figure 2. 4: Types of beamforming (Shahjehan et al., 2022).

2.4 Review of other related work

In (Rose & Zorzi, n.d.), conducted a study to evaluate the performance of multi-user MIMO (Multiple-Input Multiple-Output) systems using metrics such as Signal-to-Interference-plus-Noise Ratio (SINR) and capacity. They focused on downlink pre-coding techniques, specifically linear precoders such as zero-forcing and matched filtering, based on the optimization of a grid of beams (GOB). The study aimed to assess the effectiveness of precoding in practical mmWave (millimeter wave) conditions. The results of the study indicated that GOB optimization methods were successful in achieving improved performance when used with realistic channel models that had directionality. However, the study's effectiveness was limited by its reliance on accurate channel estimation.

In (Series & Science, 2021), this study focused on evaluating the performance of different linear precoding methods in the design of massive MIMO systems for 5G technology. The main areas of assessment include the bit error rate (BER) and practical sum rate. The study specifically investigated precoding techniques such as zero-forcing (ZF), minimum mean square error (MMSE), and conjugate gradient (CG)-based precoding. Various channel scenarios, including urban, suburban, and rural environments, are considered in the analysis.

The evaluation involved testing these methods in a MIMO-OFDM system with 52 subcarriers and a base station equipped with over 100 antennas capable of serving multiple simultaneous users. To simulate stochastic channels, Winner II is employed as the chosen channel model. The aim is to examine the effectiveness and suitability of the studied precoding techniques within the context of massive MIMO systems for 5G technology, taking into account different channel conditions and deployment scenarios.

In(Sacko et al., 2022), proposed the energy efficiency of two linear precoding methods, MRT and ZF, which were compared in large multi-user MIMO systems with imperfect channel state information at the base station. The objective was to exploit the potential advantages of 5G networks. The study considered circuit consumption during power transmission. According to the results, MRT precoding outperformed ZF precoding when the number of BS antennas was smaller than the number of users. This approach can provide high data rates when multiple user terminals are present simultaneously. In summary, large MIMO systems can achieve excellent energy efficiency using simple linear precoding methods.

In (Systems, 2021), in this paper presented, a novel energy-efficient precoding scheme for massive multiple-input multiple-output (MIMO) systems is introduced. This scheme surpasses the conventional zero-forcing (ZF) precoder in terms of power consumption and achievable transmission rate by incorporating a complex-valued regularization parameter. By introducing this parameter, the energy efficiency of the system is enhanced. The proposed energy-efficient complex regularized zero-forcing precoder is subjected to analytical evaluation, simulation verification, and a comparison with the ZF precoder. Through the obtained results, it is demonstrated that the proposed precoder exhibits robustness in massive MIMO systems, validating its improved performance in terms of energy efficiency.

In (Thurpati et al., 2021), In this study, the energy efficiency of two precoding schemes, namely maximal-ratio transmission (MRT) and zero-forcing (ZF), was evaluated and compared in the context of massive multi-user multiple-input multiple-output (MU-MIMO) systems. The evaluation considered scenarios with imperfect channel state information at the base station and aimed to explore the potential benefits of 5G networks. The results indicated that MRT precoding exhibited superior performance compared to ZF precoding in scenarios with a small M/K ratio, where M represents the number of base station antennas and K represents the number of users. The findings suggested that MRT precoding could achieve high data rates for a large number of independent terminals operating simultaneously as user terminals. Therefore, the use of simple techniques, such as massive MIMO, can lead to significant improvements in energy efficiency.

In (Ibrahim & Abdulhussien, 2022), The focus of the study was on developing and implementing a precoding system for multi-user multiple-input multiple-output (MU-MIMO) downlink transmission. The system incorporated turbo coding, low-density parity check (LDPC) coding, and polar coding channels. The challenge addressed was the double calculation of precoding matrices using singular value decomposition (SVD), which posed difficulties with conventional MU-MIMO precoding algorithms. To determine the superior precoding method, a comparison was made between zero-forcing (ZF) and maximum ratio transmitter (MRT) systems. The evaluation considered parameters such as throughput, supported number of users, and error rates in both downlink and uplink massive MIMO scenarios. The findings revealed that ZF-MU-MIMO with turbo coding outperformed MRT precoding in terms of throughput, supported number of users, and reduced error rates in both downlink and uplink massive MIMO systems. Additionally, the ZF-MU-MIMO approach exhibited greater spatial diversity.

In (Rebato et al., 2019), study focused on evaluating the performance of multi-user MIMO systems using SINR and capacity metrics, particularly in the downlink single-cell scenario. Various precoders were investigated, ranging from Grid of Beams (GoB) optimization techniques to linear precoders such as matched filtering and zero forcing.

The performance evaluation was conducted using two real mmWave 5G propagation channels simulated with the New York University (NYU) measurement campaign or the 3GPP channel model. The analysis also took into account the presence of imperfect channel estimates. The objective was to gain insights into the effectiveness of precoding techniques under practical mmWave conditions. The results indicated that the GoB optimization strategies performed exceptionally well when applied to real channel models with directionality. This study provided valuable findings regarding the efficiency of precoding methods in practical mmWave scenarios.

In (Wu & Wang, 2018), studied the inclusion of a substantial number of antennas in a system that allows linear precoding methods to exhibit near-optimal performance. Nonetheless, the computational complexity of conventional linear precoding systems, such as regularized zero-forcing (RZF) precoding, is significantly increased due to the need for large-scale matrix inversion.

In (Ketseoglou et al., 2019), In research, the focus was on investigating the impact of imperfect channel state information (CSI) at the receiver in the context of finite alphabets. A novel and a reliable technique called zero-forcing per-group precoding (ZF-PGP) was proposed, which achieved near-optimal mutual information. Unlike traditional zero-forcing (ZF) precoding methods, ZF-PGP eliminated the need for coordinated and collaborative decoding among the group's user equipment (UE). Additionally, ZF-PGP provided individually distinct streams to each UE, resulting in improved performance compared to ZF precoding approaches.

In (Dinh et al., 2020), study focused on large multiple-input multiple-output (MIMO) systems and introduced a low-complexity linear precoding algorithm known as Principal Component Analysis Linear Precoder (PCA-LP). This algorithm combines the principal component analysis technique with traditional linear precoders. The proposed PCA-LP precoder consists of two parts. The first part aims to reduce interference between neighboring users, while the second part utilizes principal component analysis (PCA) to enhance system performance. Compared to the low-complexity regularized block diagonalization using zero-forcing precoding (LC-RBD-LR-ZF) and PCA-aided Minimum Mean Square Error combination with block diagonalization (PCA-MMSE-BD) precoders, the proposed PCA-LP precoder exhibits significantly lower computational complexity. Additionally, its bit error rate (BER) performance is comparable to that of the LC-RBD-LR-ZF and PCA-aided precoders, thus offering an attractive trade-off between complexity and performance.

In (Onukwugha et al., 2023), In this study, linear precoding methods were employed to analyze the bit error rate (BER) in multiuser (MU) massive multiple-input multiple-output (MIMO) wireless systems. The primary objective of the research was to investigate the influence of minimum mean square error (MMSE) and linear zero-forcing (ZF) precoders on the BER performance of a massive MIMO system. The system under consideration included up to 32 base station antennas (BS) and up to 5 user mobile terminals (MTs).

(Asif et al., 2020), the proposed model incorporates the total power consumption of the power amplifier and circuit components at both the base station (BS) and single antenna user equipment (UE). It also calculates the optimal number of BS antennas required to serve all the UEs and determines the overall transmitted power. Simulation results demonstrate significant enhancements in area throughput gain and energy efficiency (EE). Additionally, the findings indicate that optimal area throughput and EE can be achieved by installing a larger number of antenna arrays at the BS to accommodate a greater number of UEs. The detection and precoding processes employ linear processing schemes such as minimum mean squared error (MMSE), zero-forcing (ZF), and maximum ratio transmission (MRT/MRC). Furthermore, a power dissipation model is proposed, which takes into account the overall power consumption in both uplink and downlink communications.

Table 2. 1: A Summary of some related work

Authors	Year	Title	Techniques	Gap
Asif et al.	2020	Energy Efficiency Augmentation in Massive MIMO Systems through Linear Precoding Schemes and Power Consumption Modeling	MMSE, ZF, and MRT	Complexity didn't define
Dinh et al.	2020	PCA-Aided Linear Precoding in Massive MIMO Systems with Imperfect CSI	Principal Component Analysis Linear Precoder (PCA-LP). Reduced the complexity.	Loss of information due to dimensionality reduction.
Thurpati et al.	2021	Performance Analysis of Linear Precoding in Downlink Based on Polynomial Expansion on Massive MIMO Systems.	MRT, ZF, RZF and TPE.	Didn't consider under imperfect channel state information.
Ibrahim & Abdulhussien.	2022	Performance evaluation of precoding system for massive multiple-input multiple-output.	Two advanced precoding, zero-forcing (ZF), and maximum ratio transmitter (MRT) systems with (LDPC).	High computational complexity, both ZF and MRT reduced the inversion of the channel matrix

CHAPTER THREE

3 MATERIALS AND METHODS

3.1 Overview

This thesis undertakes a comprehensive review of relevant papers and articles from esteemed journals including IEEE, Springer, and Elsevier. Additionally, books focusing on massive MIMO linear precoding techniques are extensively examined. Drawing from the insights gained through this literature review, the methodology outlined in the subsequent sections is developed and implemented to design and simulate the proposed methods, taking into consideration the problem statement at hand.

3.2 Materials

For this thesis work, the software utilized includes MATLAB/R2020a. MATLAB is a computational software package that incorporates various technical toolboxes and Simulink.

3.3 Method

The following structured methods are used in the thesis to achieve the mentioned objectives:

Literature Review: The thesis work is fundamentally related to earlier studies on the topic conducted by experts or scholars. Therefore, reading the works of these academics and learning pertinent information about the issue is essential. A variety of sources, such as papers, books, journals, the internet, etc., are reviewed. As a result, reading articles, conference papers, books, journals, and various online sources for relevant topics serves as the literature review (i.e., mm-wave massive MIMO precoding).

Problem Identification: based on the paper reviewed from different journals, articles, and conferences the problem (research gaps) is identified for the research study.

System Designing: after the identification of the research gap the systems are designed for the proposed work.

Simulation of designed System using MATLAB: after modeling of the proposed system the simulation is done using MATLAB tools.

Result and Discussion: depending on the results from the simulation, discussions are performed on the results, and performance evaluations are also done on proposed techniques.

Documentation: Upon thorough analysis of the obtained results from the designed system, the research study concludes by providing implicit recommendations and proposing areas for future work.

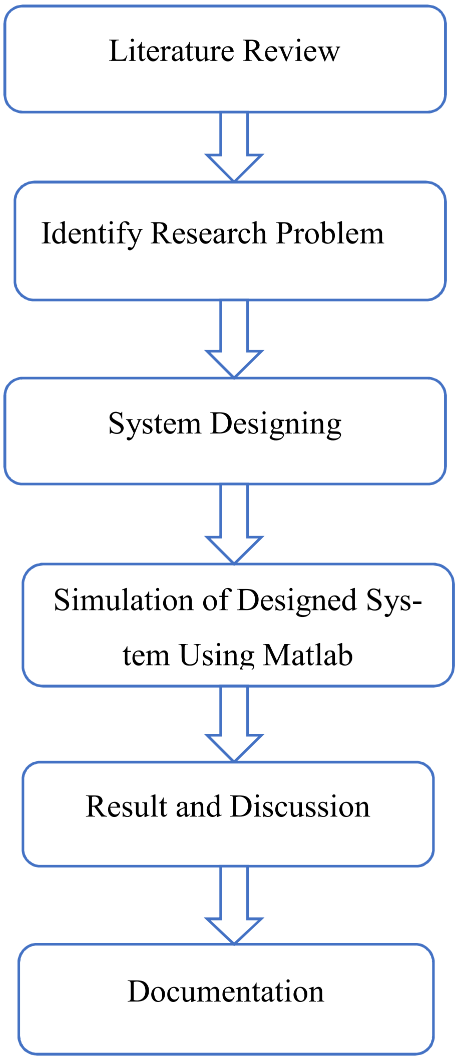

Figure 3. 1: Method of the thesis

The single-cell mmWave massive MIMO downlink with linear precoding is a wireless communication technology that capitalizes on a large number of antennas at the base station to facilitate simultaneous communication with multiple users. In this context, linear precoding techniques are employed to segregate the transmitted signals intended for each user and minimize interference. The system operates as a massive MIMO system, utilizing M antennas to transmit data to K users within the same frequency band. By leveraging linear precoding techniques like zero-forcing or maximum ratio transmission regularized zero forcing ,lower truncated polynomial expansion and lower truncated polynomial expansion –dirty paper coding precoding implemented in this single cell multi-user scenario to commodate a substantial number of users while ensuring high data rates, even in densely populated areas. However, the successful implementation of this scenario necessitates considerable computational resources and complex signal-processing algorithms.

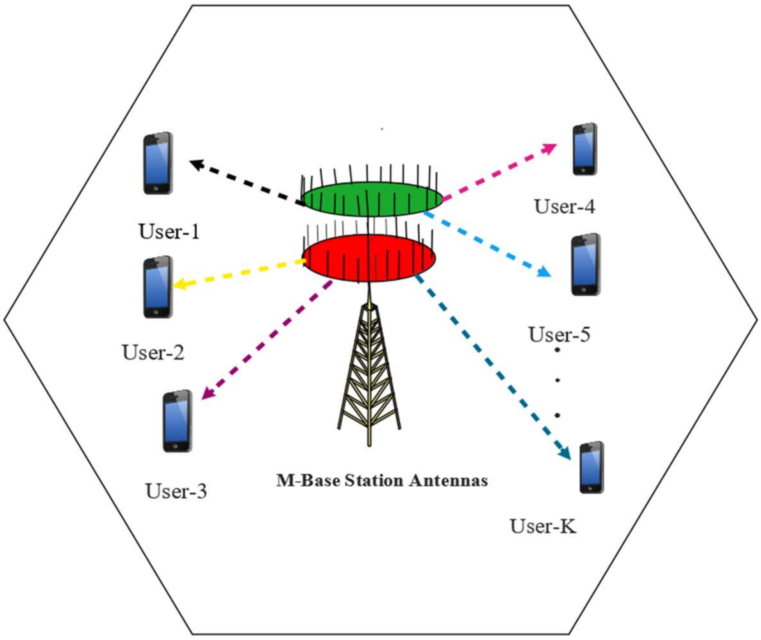

Figure 3. 2: Single-cell multi-user MIMO downlink

3.4 Mathematical model of precoding techniques

In a single-cell mmWave massive MIMO system, a base station (BS) with a multiple of antennas effectively serves multiple user terminals (UTs) using different precoding techniques. The integration of a large antenna array at the BS aims to minimize interference among users and optimize the received signal quality at the UTs. Before transmission, the BS employs a linear precoding matrix U to multiply the data symbols, ensuring enhanced performance through the antenna array and the dirty paper coding total cancel out the interefernce reduce the noise amplification . In the context of a massive mmWave MIMO system, where the BS is equipped with a substantial number of antennas, simultaneous connectivity to numerous UTs within a single-cell scenario is achieved. The utilization of directional antennas and a large antenna array at the BS addresses the challenges of significant path loss and high channel sparsity typically encountered in mmWave massive MIMO systems.

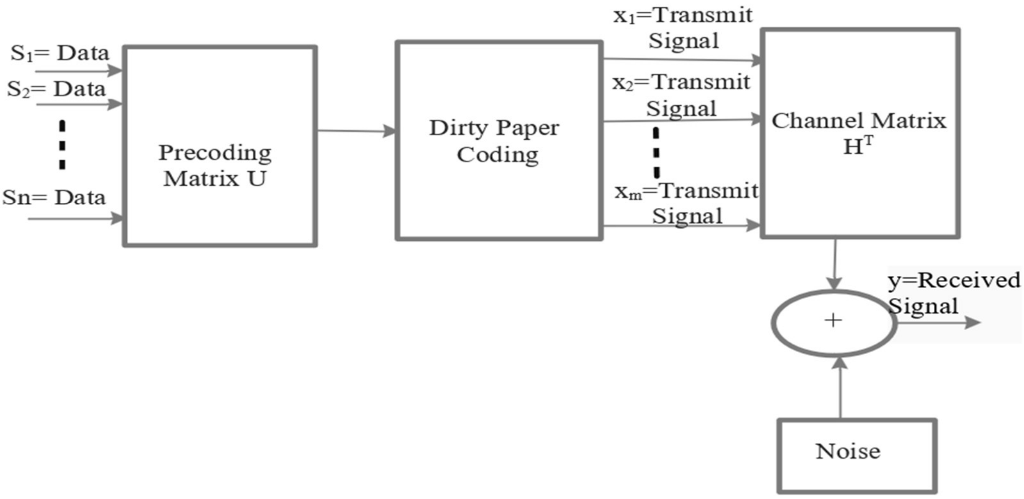

Figure 3. 3: Block diagram of proposed system model

3.4.1 Zero-forcing linear precoding (ZF) technique

Zero-forcing precoding is a linear technique used to eliminate inter-user interference at each user. It achieves this by implementing a pseudo-inverse of the channel matrix. During down-link transmission, the transmitted signal vector for K users can be mathematically represented when the number of antennas (M) is greater than the number of users (K).

$$x = \sqrt{\rho} U s \tag{3.1}$$

where;

In the TDD mode, the downlink channel is simply the transpose of the channel matrix H. Consequently, the set of signals received at K terminals can be expressed as follows:

The transmit signal is represented by $x \in C^{M\times 1}$.

U$\in C^{M\times K} S$ = is the linear precoding matrix $s \in C^{K\times 1}$ = is the transmitted source information before precoding.

ρ = represents the average transmit power at the base station (BS).

The precoding matrix U is dependent on the channel matrix $H \in C^{M\times K}$

The power of the transmitted source signal is normalized, indicated by $\|s\|^2$= 1.

To satisfy the power constraint at the BS, U is chosen such that $tr(UU)^H$= 1.

In the TDD mode, the downlink channel is simply the transpose of the channel matrix H.

$$y = H^T x + n = \sqrt{\rho} H^T U s + n \tag{3.2}$$

where;

The received signal is denoted by y.

$H^T \in C^{M\times K} =$ represents the transpose of the channel matrix.

$n \in C^{K\times 1}$ = represents the noise and interference in the system.

$$\hat{H} = \begin{bmatrix} \hat{h}_1 & \hat{h}_2 & \cdots & \hat{h}_k \end{bmatrix}$$

(3.3)

$$\hat{H} = \begin{bmatrix} \hat{h}_{11} & \hat{h}_{12} & \cdots & \hat{h}_{1k} \\ \hat{h}_{21} & \hat{h}_{22} & \cdots & \hat{h}_{2k} \\ \vdots & \vdots & \ddots & \vdots \\ \hat{h}_{m1} & \hat{h}_{m2} & \cdots & \hat{h}_{mk} \end{bmatrix}$$

where; H$\in C^{M\times K}$ = is the channel matrix

$$U = \begin{bmatrix} u_{11} & u_{12} & \cdots & u_{1k} \\ u_{21} & u_{22} & \cdots & u_{2k} \\ \vdots & \vdots & \ddots & \vdots \\ u_{M1} & u_{M2} & \cdots & u_{Mk} \end{bmatrix}$$

where; U $\in C^{M\times 1}$ = is a Precoding matrix.

$$S = \begin{bmatrix} s_{11} & s_{12} & \cdots & s_{1k} \\ s_{21} & s_{22} & \cdots & s_{2k} \\ \vdots & \vdots & \ddots & \vdots \\ s_{M1} & s_{M2} & \cdots & s_{Mk} \end{bmatrix}$$

Where; $S \in C^{K\times 1}$= is the data vector signal.

$$C = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1N} \\ c_{21} & c_{22} & \cdots & c_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ c_{N1} & c_{N2} & \cdots & c_{NN} \end{bmatrix}$$

where; $C \in CN(0, \sigma^2)$ represents a complex matrix with elements that are drawn from a complex Gaussian distribution with zero mean and variance σ^2.

The un-normalized ZF linear precoding matrix

$$U_{ZF} = H\left(\hat{H}H^{H}\right)^{-1} \tag{3.4}$$

Normalized ZF linear precoding matrix at the BS

$$U_{ZF} = \beta \hat{H}\left(\hat{H}\hat{H}^{H}\right)^{-1}$$

$$\beta = \sqrt{\frac{pd}{tr\left(U_{ZF}{}_{ZF}^{H}\right)}} \tag{3.5}$$

where; $\beta =$ is the normalized power factor.

Assuming multiple users and the presence of additive noise, let's consider a situation where the kth user experiences interference from other users. We can define the power of the desired signal, interference, and noise in this scenario, $S_{n,}$ I_n and N_n respectively, the SINR at the kth user can be obtained.

$$SINR_k = \frac{\left|h_k^H u_k\right|^2}{\left|h_k^H u_k\right|^2 + \sigma^2} \tag{3.6}$$

We can define the power of the desired signals_k, Interference, I_K and Noise, n_k respectively.

$$\left|S_k\right|^2 = \frac{P_d}{tr\left(U_{ZF} U_{ZF}^{H}\right)} \tag{3.7}$$

$$\left|I_k\right|^2 = P_d \sigma^2 \tag{3.8}$$

$$\left|n_k\right|^2 = n = 1 \tag{3.9}$$

By substituting the value of S_K, I_k, and n_k in the SINR experienced by the kth user it becomes in the following manner:

$$SINR_k^{ZF} = \left(\frac{S_n}{I_n + N_n} \right) \tag{3.10}$$

Equation (3.3) must be expressed now let as substitute equations (3.1) and (3.3) for equation we will get the Kth user SINR of zero forcing pre-coding looks like as follows (Israr et al., 2017).

$$SINR_k^{ZF} = \frac{P_d}{tr\left(U_{ZF}U_{ZF}^H\right)}\left(\frac{1}{P_d\sigma^2 + 1}\right)$$

$$= \frac{P_d}{tr\left(U_{ZF}U_{ZF}^H\right)\left(P_d\sigma^2 + 1\right)} \tag{3.11}$$

$$\frac{P_d}{tr\left(U_{ZF}U_{ZF}^H\right)} = \frac{(M - K)\left(1 - \sigma^2\right)P_d}{K}$$

Since α=M/K covariance/correlation between the antennas.

$$SINR_k^{ZF} = \frac{(\alpha - 1)\left(1 - \sigma^2\right)P_d}{P_d\sigma^2 + 1} \tag{3.12}$$

3.4.2 Maximum ratio transmission linear pre-coding (MRT) technique

MRT precoding at the base station (BS) is designed to maximize the signal gain and SNR of the intended user (Mukubwa et al., 2017). The mathematical expression for MRT precoding is as follows:

$$U_{MRT} = \beta H^H \tag{3.13}$$

Where;

$$\beta = \sqrt{\frac{P_d}{MK\left(1 - \sigma^2\right)}}$$

The Kth user $SINR_{MRT}$

$$SINR_k^{MRT} = \frac{\left(1 - \sigma^2\right)P_d\alpha}{(P_d + \sigma^2) + 1} \tag{3.14}$$

3.4.3 Regularized zero forcing (RZF) precoding techniques

Regularized Zero Forcing (RZF) precoding is a linear precoding technique that mitigates the interference between users while maintaining a balance between signal quality and interference suppression. The RZF precoding method involves the application of a regularization parameter to control the trade-off between interference cancellation and noise amplification. This precoding technique aims to minimize the effects of inter-user interference while maintaining reliable communication between the base station and the users. We have considered that the total power constraint

$$\frac{1}{K} tr\left(UU^{H}\right) = P \tag{3.15}$$

where; $tr\ (.)$ = is the trace function and its scaling factor $\frac{1}{K}$ neutralizes the corresponding channel variance scaling, which is possible via the (3.3) account.

The un-normalized RZF linear precoding matrix.

$$U_{RZF} = \hat{H}\left(\hat{H}\hat{H}^{H} + \gamma I_{k}\right)^{-1} \hat{H}\left(\hat{H}\hat{H}^{H} + \gamma I_{k}\right)^{-1}$$
$$\gamma = \frac{K}{P} \tag{3.16}$$

Normalized RZF linear precoding matrix at the base station.

$$U_{RZF} = \beta \hat{H}^{H}\left(\hat{H}\hat{H}^{H} + \gamma I_{K}\right)^{-1} U_{RZF} = \hat{H}^{H}\beta\left(\hat{H}\hat{H}^{H} + \gamma I_{K}\right)^{-1} \tag{3.17}$$

where;

$\beta = \sqrt{\frac{P_d}{tr\left(U_{RZF}U_{RZF}^{H}\right)}}$ = The power normalization parameter β is set such that U_{RZF} satisfies the power constraint.

P is a fixed diagonal matrix, whose diagonal elements are power allocation weights for each user terminal.

P satisfies the diagonal values p_k, k= $\cdots K$ in

$$P = diag(p_1 \ldots p_k) \tag{3.18}$$

Are positive and of order $0\left(\frac{1}{K}\right)$. The scalar registration coefficient γ can be selected in different ways depending on P, σ2, α, and the system dimension.

The performance of each UT under RZF pre-coding is studied in the large (M, K) regime.

M and K tend to infinitely at time speed (Thurpati, 2021).

$0 < \lim \frac{K}{M} \leq \lim \frac{K}{M} < +\infty$

$$SINR_k^{RZF} = \frac{h_k^H u_k u_k^H h_k}{h_k^H U_k U_k^H h_k + \sigma^2} \quad (3.19)$$

By substituting equation (3.12) into equation 3.16 numerator

$$\frac{1}{K} tr(UU^H) = P$$

$$UU^H = KP$$

$$\text{Channel matrix} = \left| h_k^H h_k \right| = M \quad (3.20)$$

$$\text{Interference signal} = \left| h_k^H U_k U_k^H h_k \right| \approx 1 \quad (3.21)$$

3.4.4 Truncated polynomial expansion precoding

The new linear pre-coding class that much easier to implement in large systems. The pre-coding is based on rewriting the matrix inversion by a polynomial expansion, which is then truncated. They provide a major motivation behind the use of polynomial expansions. Instead of using RZF precoder matrix inversion, which is then shortened, it employs a polynomial expansion with J terms. To obtain TPE, the inverse matrix in RZF is approximated with a (J-1) -degree matrix polynomial, enabling a multi-stage hardware implementation with minimal complexity. Performance transitions with MRT (J = 1) and RZF (J = min (M, K)) occur when J is adjusted. The inverse of any Hermitian matrix can be expressed as a matrix polynomial, any positive definite Hermitian matrix X (Mueller, 2016).

$$X^{-} = k\left(I - \left(I - kX\right)\right) \quad (3.22)$$

$$\sum_{l=0}^{\infty} (I - kX)^l$$

Where;

The second equality holds if the parameter k is selected such that

$$0 < k < \frac{2}{max_n \lambda_n (X)}$$

More importantly, the low-order terms are the most influential ones, since the Eigenvalue of $(I - \mu X)^l$ go to zero as l grows large.

Thus, it makes sense to consider a TPE using only the first J terms. TPE has been successfully applied for low-complexity multi-user detection in(Access, 2021).

Now it is better to apply this technique to approximate RZF pre-coding by a matrix polynomial.

$$U_{RZF} = \beta \left(\hat{H}\hat{H}^H + \gamma I_M \right)^{-1} \hat{H}^H \tag{3.23}$$

$$= \beta k \sum_{l=0}^{\infty} I_M - k \left(\hat{H}\hat{H}^H + \gamma I_M \right)^l \hat{H}^H \tag{3.24}$$

$$U_{TPE} = \sum_{l=0}^{J-1} u_i \left(\hat{H}\hat{H}^H \right)^l \hat{H}^H \tag{3.25}$$

Where;

$u_1, u_2 ... u_{j-1} =$ is a scalar coefficient the bracketed term provides a potential expression for u_l, these are not the optimal values for J $< \infty$ · The pre-coding TPE defines a whole class of pre-coding matrix for different J. As we see in the above description For J = 1, it equals MRT. Furthermore, RZF pre-coding can be obtained by choosing J = min (M, K) = K and coefficients based on the characteristic polynomial of $\left(\hat{H} \, \hat{H}^H + \gamma I_M \right)$ (this follows from Cayley Hamilton's theorem). We refer to J as the TPE order.

Analysis of TPE pre-coding

Recall the SINR and observe that, $u_k = U_{ek}$ and $h_k^H U_k U_k^H h_k = h_k^H U U^H h_k - h_k^H u_k u_k^H h_k$ where the kth column of the identity matrix is I_K. The TPE precoding matrix of the SINR written as

$$SINR_k^{TPE} = \frac{U^H U \left(M/_K \right) \alpha}{U^H U (M - K) \sigma^2 + \sigma^2} \tag{3.26}$$

Where;

$U = \left[U_0 \; ... \; U_{J-1}^T \;\; \right]$ and the matrices k, k∈ $C^{J \times J}$

$SINR_K$ Converges almost surly as follows in the large (M, K) regime.

$$SINR_k = \frac{U^H U \left(M/K\right)\alpha}{U^H U \left(M - K\right)\sigma^2 + \sigma^2} \quad \lim_{M,K\to +\infty} a.s \tag{3.27}$$

3.4.5 Dirty paper coding Non linear precoding techniques

Dirty Pper Coding (DPC) is often considered more effective than Zero-Forcing (ZF) and Minimum Mean Squared Error (MMSE) precoding techniques, especially in high signal-to-noise ratio (SNR) rgimes where the interference can be dominant. The reason for this is that DPC is designed to cancel out interference in a way that is optimal in terms of achievable rate, whreas ZF and MMSE precoding are designed to minimize the mean squared error between the transmitted and received signals. In other words, while ZF and MMSE precoding techniques can reduce interference to some extent, they are not optimized for maximizing the achievable rate in the presence of interference. In summary, while ZF and MMSE precoding techniques can reduce interference, they are not optimized for maximizing the achievable rate in the presence of interference. DPC, on the other hand, is designed specifically to cancel out interference in a way that is optimal for achieving the highest possible rates in multi-user MIMO systems (Kebede et al., 2022).

$$C_{DPC} = \max \log 2 \det\left(I + \rho_k \left(H_l^{(f)}\right)^H P_l H_l^{(f)}\right) \tag{3.28}$$

3.4.6 Proposed lower order truncated polynomial expansion-dirty paper coding

The proposed LTPE-DPC technique combines two key components, polynomial expansion and dirty paper coding, to address the challenges of complexity and system performance in multi-user MIMO scenarios. Polynomial Expansion: In multi-user MIMO systems, interference from other users can limit the system performance. Dirty paper coding (DPC) is a technique that enables the cancellation of interference at the transmitter side based on the estimated interference information. It pre-cancels the interference caused by other users, allowing for cleaner transmission to the intended users. In the LTPE-DPC technique, the polynomial expansion is utilized to estimate the interference terms caused by other users. This estimated interference information is then used during the dirty paper coding stage to encode the data symbols in a way that minimizes the interference at the receiver side. Overall, the combination of polynomial expansion and dirty paper coding in the LTPE-DPC technique offers several benefits: Complexity Reduction: The LTPE-DPC technique reduces the complexity of interference cancellation by using polynomial expansion to approximate the interference and enable efficient representation and processing.

Enhanced System Performance: By effectively canceling the interference at the transmitter side, the LTPE-DPC technique improves the signal quality at the receiver side. This leads to higher data rates, increased spectral efficiency, and improved overall system performance in multi-user MIMO scenarios.

Flexibility and Adaptability: The LTPE-DPC technique can be adapted to different multi-user MIMO scenarios, allowing for customization based on specific system requirements and conditions. By combining these two components, the LTPE-DPC technique achieves a balance between complexity reduction and enhanced system performance, making it a promising approach for multi-user MIMO systems. LTPE-DPC can effectively mitigate inter-user interference in multi-user scenarios and offers better performance than other precoders such as RZF (Yang et al., 2022).

$$\mathrm{SINR}_{\mathrm{TPE-DPC}} = \left(\frac{\mathrm{pd}\left|\mathrm{h}_k^H \mathrm{U}_k\right|^2}{\mathrm{pdN_0B}\left|\mathrm{h}_k^H \mathrm{U}_k\right|^2 + \mathrm{N_0B}} \right) \tag{3.29}$$

where; N_0 is noise power

B is channel Bandwidth

3.5 Performance parameter analysis

The Shannon Theorem, which establishes the maximum rate at which the transmitter may transmit via a channel, is the method that follows an achievable rate as a way to measure the system's performance.

$$R = \log_2\left(1 + SINR\right) bits/s \tag{3.30}$$

As stated earlier, SINRk describes the user performance that is possible. In addition to this, SINR is a random quantity that depends on the random quantity that depends on the random quantity that depends on the random user’s channels in H and the instantaneous estimate H’. It can be approximated in the large (M, K) regime using deterministic quantities. Deterministic equivalents relate to these numbers because they are nearly certainly tight in the asymptotic limit and only depend on the channel statics. The deterministic equivalents are frequently referred to as large-scale approximations when they are applied at finite M and K. Then, for K users, the achievable rate is given as follows.

$$R_k = K \log_2\left(1 + SINR_k\right) \tag{3.31}$$

$$R_k^{ZF} = K\log_2\left(1+SINR_k\right) \tag{3.32}$$

Then the achievable rate of ZF linear pre-coding is calculated by substituting equation (3.9) into equation (3.25)

We will get

$$R_k^{ZF} = K\log_2(1+\frac{(\alpha-1)(1-\sigma^2)p_d}{p_d\sigma^2+1}) \tag{3.33}$$

$$R_k^{RZF} = K\log_2\left(1+SINR_k^{RZF}\right) \tag{3.34}$$

$$R_k^{RZF} = K\log_2\left(1+\frac{h_k^H u_k u_k^H h_k}{h_k^H U_k U_k^H h_k}\right) \tag{3.35}$$

As the number of base station antennas and user terminals becomes large in a massive MIMO system, the signal-to-interference-plus-noise ratio (SINR) of regularized zero-forcing (RZF) linear precoding can be approximated by the following formula.

$$R_k^{RZF} = K\log_2\left(1+\frac{kP_dM}{1+\sigma^2}\right) \tag{3.36}$$

Where;

$$tr(UU^H) = P_d \ \ , UU^H = kP_d$$

$$|h_k^H h_k| = M$$

$$|h_k^H U_k U_k^H h_k| = 1$$

The achievable rate of TPE linear precoding is calculated as follows.

$$R_k^{TPE} = K\log_2\left(1+SINR_k^{TPE}\right)$$

$$R_k^{TPE} = K\log_2\left(1+\frac{U^HU\left(M/K\right)\alpha}{U^HU\left(M-K\right)\sigma^2+\sigma^2}\right) \tag{3.37}$$

$$\mathrm{R}_\mathrm{k}^{\mathrm{TPE-DPC}} = \mathrm{K}\log 2\left(1+\mathrm{SINR}_\mathrm{k}^{\mathrm{TPE-DPC}}\right) \tag{3.38}$$

3.5.1 Spectral efficiency

Spectral efficiency is a metric that quantifies the ability of a communication system to transmit data over a specific frequency band or bandwidth. It measures the efficiency with which the available spectrum is being utilized for transmitting information. This is particularly important in wireless communication systems where spectral efficiency determines the system's capacity to support more users and higher data rates. The spectral efficiency is usually expressed in bits per second per Hertz (bps/Hz) and depends on various factors such as modulation scheme, coding rate, channel bandwidth, and signal-to-noise ratio (Liu et al., 2022).

$$R_{SE} = \sum_{k=1}^{K} \frac{R_k}{B} (bits / s / Hz) \tag{3.39}$$

3.5.2 Energy efficiency

Refers to the ability of a system to achieve a balance between power consumption and spectral efficiency. It is calculated as the ratio of the system's realized spectral efficiency, which is measured in bits per second per hertz, to the power consumed by the system, which is measured in watts. In linear massive MIMO systems, the system's power consumption, antenna count, and linear precoding are optimized to achieve energy efficiency. The goal is to maximize spectral efficiency while minimizing power consumption, which can enhance overall system performance. By achieving a balance between spectral efficiency and power consumption, energy-efficient systems can help reduce energy costs and minimize their environmental impact.

$$\eta = \frac{R_{SE}}{P_{tr}} (bits / J / Hz) \tag{3.40}$$

$$\eta = \frac{KB \log 2 \left(1 + \frac{Mpd\gamma}{1 + pdk\beta} \right)}{\frac{Kptx}{\mu} + p_{circuit} + \left(M + K \right) p_{antenna}} \tag{3.41}$$

Where; K= the number of user terminals.

B= is the bandwidth of mm-wave in GHz.

M=is the number of base station antennas.

Pd= is the downlink power.

Ptx= is the total power transmitted.

P_antenna = the power antenna consumption.

P_circuit = is the power radio frequency consumption.

β = the path loss

γ = the channel state information quality

μ = the amplifier efficiency

3.6 Millimeter wave channel model

Unlike traditional low-frequency channels, the propagation characteristics of millimeter-wave channels are no longer subject to Rayleigh fading. Due to the high path loss in free space, the spatial selectivity of millimeter-wave propagation is limited. In addition, large-scale dense antenna arrays will result in obvious antenna correlation in millimeter-wave channels. Therefore, the traditional channel model is not suitable for the millimeter-wave channel in the massive MIMO system. For simplicity, this work adopts the geometric Saleh-Valenzuela model in most literature (Zhang & Zhao, 2021). The channel matrix is given by

$$\mathrm{H_k} = \sqrt{\frac{N_t N_r}{L_k}} \sum_{l=1}^{Lk} \alpha_{k,l} \mathrm{a}_{k,r}\left(\theta_{k,l}\right) \mathrm{a}_{k,t}^{H}\left(\phi_{k,l}\right) \tag{3.42}$$

Where;

Where $\alpha_{k,l}$ represents the complex gain of l^{th} path. It contains path-loss with $E\left|\alpha_{k,l}\right|^2 = \beta$ (normalization constant). $\phi_l \in [0, 2\pi]$ and $\theta_l \in [0, 2\pi]$ are l^{th} the azimuth angles of AoDs and AoAs) of the transmitter and receiver respectively. $\mathrm{a}_{k,t}\left(\phi_{k,l}\right)$ and $\mathrm{a}_{k,r}\left(\theta_{k,l}\right)$ denotes the antenna array response vector of the transmitter and receiver respectively with their respective antenna array response vector of Kth UTs. L_k is the number of propagation paths for the channel of kth UTs with $l \in [1, 2 \cdots, L_k]$. The BS and MS get knowledge about the propagation paths for the channel of kth UTs with ∈ structure of their antenna arrays. If a ULA is considered, the array response vectors at the transmitter $\mathrm{a}_t(\phi) l$ are defined as

$$\mathrm{a}_t(\phi_l) = \frac{1}{\sqrt{N}} \left[1, e^{j\left(\frac{2\pi}{\lambda}\right) d \sin(\phi_l)}, \cdots, e^{j(N_t - 1)\left(\frac{2\pi}{\lambda}\right) d \sin(\phi l)}\right]^T$$

On the other hand, the receiver’s array of response vectors is

$$\mathrm{a}_r\left(\theta_l\right)=\frac{1}{\sqrt{N}}\left[1,e^{j\left(\frac{2\pi}{\lambda}\right)d\left(x\sin(\phi)\sin(\theta)+y\cos(\theta)\right)},\ldots\times e^{j\left(\frac{\pi}{\lambda}\right)d\left(\left(W_1-1\right)\sin\left(\phi\right)\sin\left(\theta\right)+\left(W_2-1\right)\cos\left(\theta\right)\right)}\right]^T$$

$C^{M\times K}$ of the matrix of channel coefficients$H = C^{M\times K}$. Let $\widetilde{H} \in C^{M\times K}$be the channel estimation error matrix. We assume that the entries of both H and $\widetilde{H}$ are independent identically distributed complex Gaussian random variables with zero mean and unit variance(Nguyen & Truong, 2022). In addition, for tractability, we adopt the following model where H is decomposed as

$$H=\sqrt{1-\alpha^2}\hat{H}+\alpha\tilde{H} \tag{3.43}$$

where $\alpha \in [0, 1]$ represents the level of estimation accuracy. Note that $\alpha = 0$ corresponds to perfect channel estimation, i.e. $\widehat{H} = H$ and that $\alpha = 1$ corresponds to the case that $\widehat{H}$is independent of H. For notational convenience, denote $\bar{\alpha}=\sqrt{1-\alpha^2} \in [0, 1]$. Since the mmWave propagation environment has limited scattering. where Ĥ is the estimated channel matrix, $0 \le t \le 1$ presents the CSI accuracy, geometric channel model with L scatters. Moreover, for ease of illustration, it is assumed that each scatterer contributes a propagation path between the transmitter and the receiver. Let $\phi_t, \ell \in [0,\ 2\pi]$and $\phi_r, \ell \in [0,\ 2\pi]$are angles of departure (AoD) and angles of arrival (AoA) corresponding to the l^{th} path, for ℓ = 1, 2... L. Denote $\mathrm{a}_t\left(\phi_t,\ell\right)$ as the antenna array's steering vector at the transmitter and $\mathrm{a}_r\left(\phi_r,\ell\right)$ as the antenna array's response vector at the receiver for the l^{th} path. As a result, the channel matrix can be decomposed as

$$\hat{\mathrm{H}} = \alpha\sum_{l=1}^{L}\beta_l a_t\left(\phi_{t,l}\right)a_r^H\left(\phi_{r,l}\right) \tag{3.44}$$

where α is the normalization factor such that E|hh^^H |= 1 and βℓ is the complex gain of the ℓth propagation path loss.

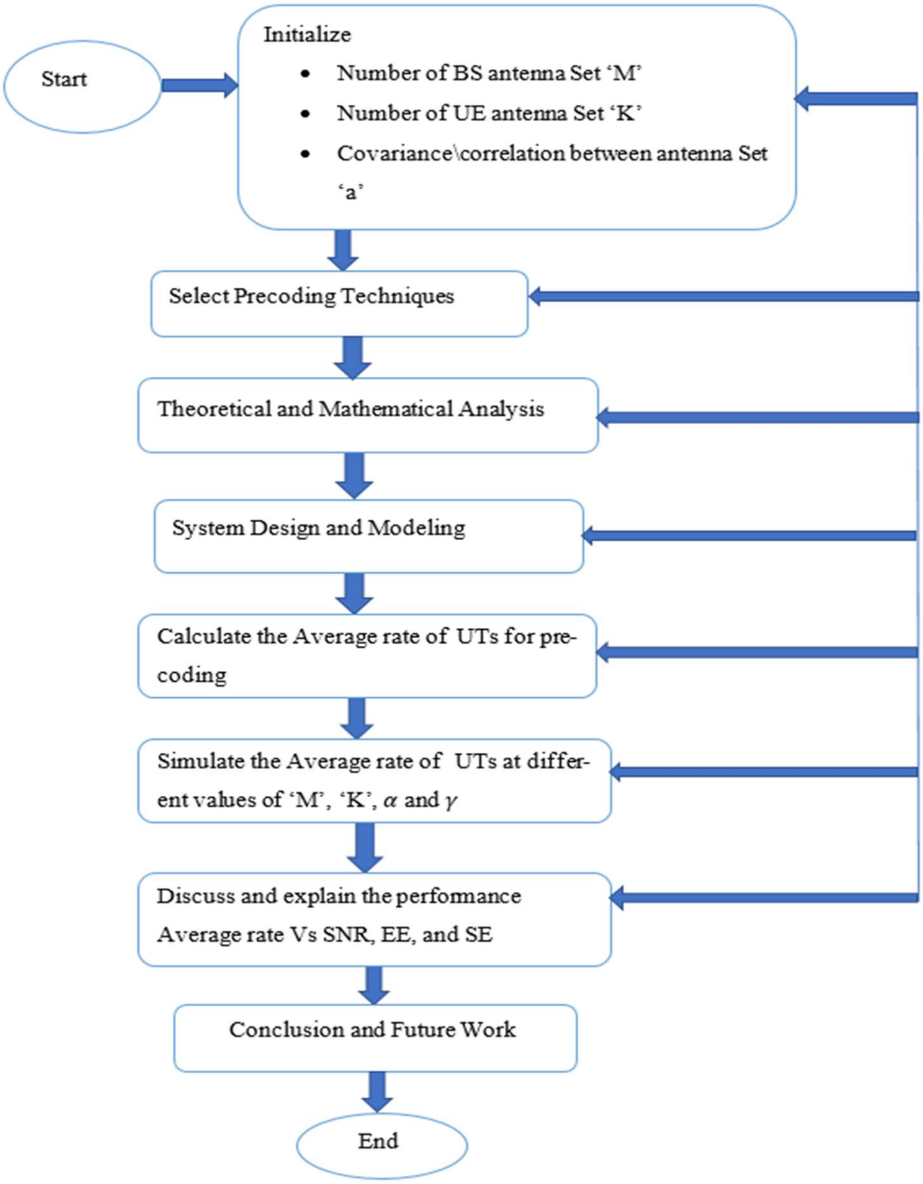

Figure 3. 4: Flow chart of the system

The flow chart shows the steps of the system work and simulation results. Determining the channel and signal models. The pre-coding techniques are defined very well. Formulation of the SINR of the pre-coding scheme. At low CSI quality, the pre-coding techniques are evaluated under low and high numbers of BS and UT antennas. At high CSI quality, the pre-coding techniques are evaluated under low and high numbers of BS and UT antennas. The high covariance/correlation between antennas is considered for all pre-coding techniques. The performance analysis is observed by the achievable sum rate.

CHAPTER FOUR

4 SIMULATION RESULTS AND DISCUSSIONS

The system setup, including the number of antennas, users, and channel conditions, determines how well these precoders work. Therefore, to choose the best linear precoding technique for a specific system, a thorough simulation analysis is essential. Linear precoding and non-linear precoding techniques aim to optimize system performance by manipulating the transmitted signal to reduce interference and enhance transmission efficiency in multi-antenna communication systems commonly used in massive MIMO systems. Various simulation studies have compared the performance of these methods under different scenarios. MRT optimizes the transmit power in the direction of the desired user and performs well in a single-user scenario with a high signal-to-noise ratio (SINR). However, its performance degrades significantly in multi-user scenarios due to interference. ZF and RZF aim to nullify interference from other users. ZF projects the transmitted signal onto the null space of the interference subspace, while RZF adds a regularization term to improve the conditioning of the channel matrix. These methods require accurate channel state information (CSI) and can suffer from noise amplification. Simulation results have demonstrated that LTPE with DPC can achieve better performance than MRT, ZF, and RZF in various massive MIMO scenarios, including multi-user scenarios with imperfect CSI.

Table 4. 1: System design considered and simulation parameter values

Parameters	Description	Value	Remarks
SC	Number of cells	Single-cell	Assumption
(Pd)	Power of downlink	1 dBm-10dBm	Variable
M	Number of base station antennas	64-256	Variable
K	Number of user terminals	50-100	Variable
Pt	Transmit power constraint	$\frac{1}{K} tr(UU^H)$	Assumption
α	Estimation accuracy	$0 \le \alpha \le 1$	Standard
γ	Regularized factor	0.05	
J	TPE order	3, 4 and 5	
B	Bandwidth	4 GHz	5G Standard
M/K	Covariance/correlation	M>K	Variable

4.1 Results of precoders at different parameters

The performance of linear precoding techniques in massive MIMO systems is evaluated in terms of the system's sum rate as a function of the number of user terminals and base station antennas. In this discussion, the performance analysis has been simulated for different scenarios are taken into consideration to compare the effectiveness of the linear pre-coders. Average rates of linear precoding UTs at various parameter levels are listed below.

- Sum rate of user terminals at the low number of users and base station antennas.
- Sum rate of user terminals when the number of M and K converges to a large regime.
- The energy efficiency of precoders at the different user terminals and base station antennas.

4.1.1 The sum rate of ZF and RZF at M=256 and K=50

A significant difference between zero-forcing (ZF) and regularized zero-forcing (RZF) lies in the addition of a regularization term in RZF precoding to tackle the issue of noise amplification when the channel matrix is nearly singular. This situation often occurs when there are a large number of antennas compared to the number of users in the system. By including the regularization term, RZF can effectively manage the amplification of noise, resulting in improved performance and system stability. Figure 4.1 and Table 4.2 illustrate the comparison between ZF and RZF precoding for various numbers of base station antennas.

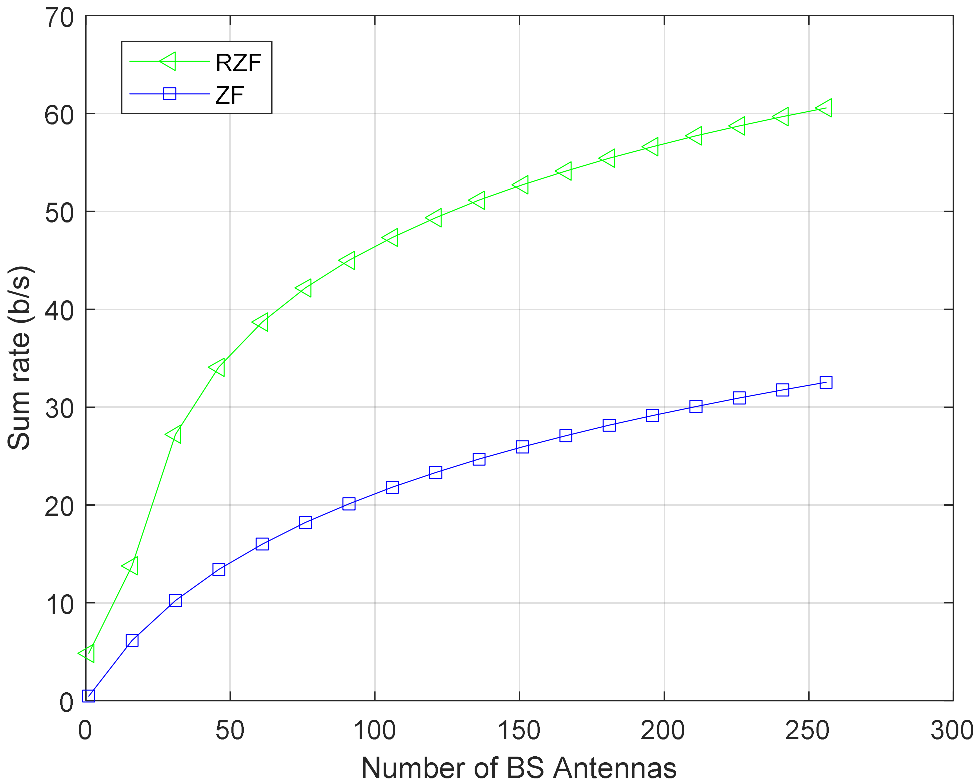

Figure 4. 1: Sum rate versus number of base station antenna at k=10 and M= 256

Table 4. 2: Sum rate versus number of base station antenna at k=10 and M= 256

Precoding Techniques	Sum rate vs base station				
	M=50	M=100	M=150	M=200	M=250
ZF	13.41	21.81	25.93	30.06	32.53
RZF	34.06	47.33	52.71	57.71	60.57

4.1.2 Sum rate of Regularized Zero Forcing at M= 64, K=10 and K=20

The number of user terminals in a communication system has a significant impact on the performance of Regularized Zero Forcing (RZF) precoding. The observation indicates that when the number of user terminals is doubled while the number of base station antennas is fixed, the sum rate of RZF precoding is affected. Specifically, the sum rate of RZF precoding decreases when the number of user terminals increases from 10 to 20.

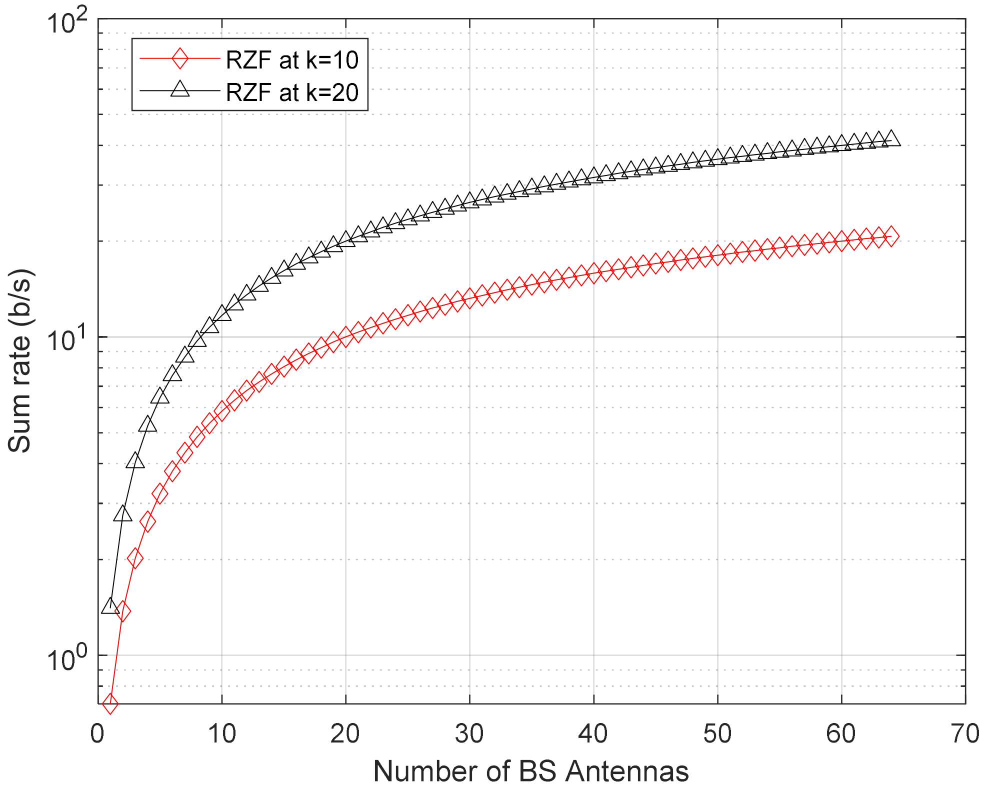

Figure 4. 2: The sum rate of regularized zero-forcing at different users

Table 4. 3: The sum rate of regularized zero-forcing at different users

Precoding Techniques	Sum rate vs. base station				
	M = 8	M =16	M = 24	M = 32	M = 64
RZF, K=10	4.854	8.48	11.38	13.79	20.7
RZF, K=20	9.709	16.96	22.75	27.57	41.41

From the above observation at fixed base station antennas and user terminals are increasing by a factor of two for the RZF precoder. The sum rate of regularized zero-forcing at 10 UTs is lower than regularized zero-forcing at 20 UTs.

4.1.3 When the base station antennas M=256 at, K=10 and K=20 for RZF

Figure 4.3 and Table 4.4 describe the sum rate of regularized zero-forcing at different user terminals scenarios at K=10 and K= 20 respectively. When the number of user terminals increased by double the sum rate of the RZF user terminal at 20 exhibits logarithm function as an increase in the number of the base station antennas. To balance the trade-off between interference reduction and noise amplification. Due to the higher spatial multiplexing gain of massive MIMO, the sum rate of the system likewise rises as the number of users increases.

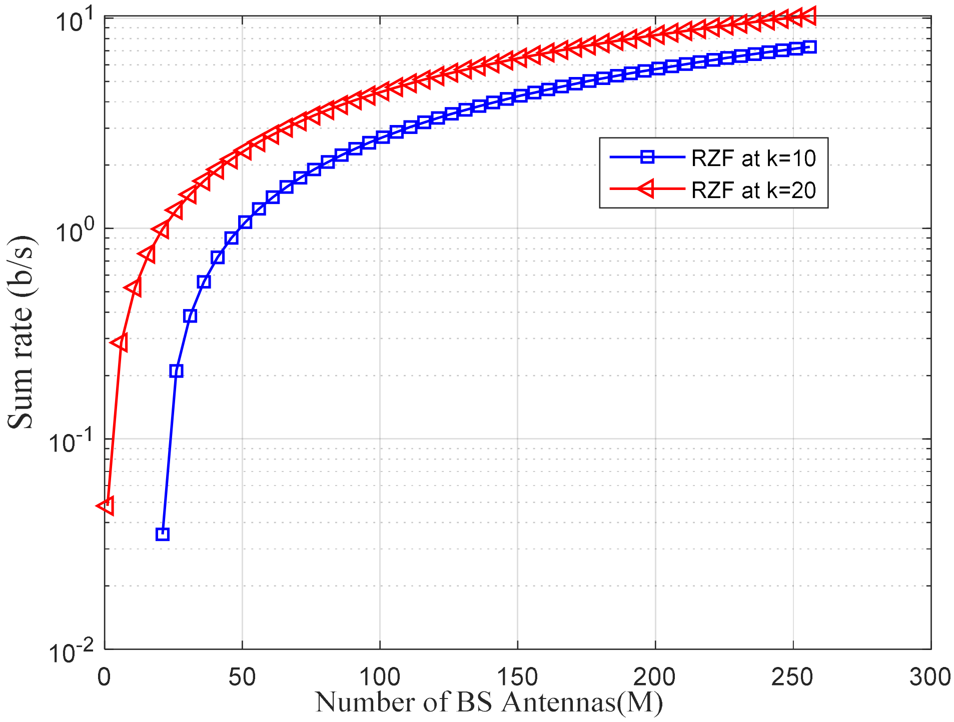

Figure 4. 3: The sum rate of regularized zero-forcing at M= 256

Table 4. 4: The sum rate of regularized zero-forcing at M= 256

Precoding	Sum rate vs Base station(M)			
	M=100	M=150	M=200	M=250
RZF_10	2.071	4.718	5.70	7.161
RZF_20	4.489	6.477	8.337	10.008

4.1.4 Sum rates versus SNR of different precoding at K=100

Figure 4.4 and Table 4.5 compare different precoding techniques in massive MIMO systems. This comparison will focus on ZF, RZF, DPC, and three versions of TPE (j=3, j=4, j=5). ZF is a linear precoding technique that aims to nullify interference from other users while maintaining the desired user's transmitted power. However, it requires complete CSIT and may suffer from noise amplification at high SNR levels. RZF is a modified version of ZF that adds a regularization term to enhance the conditioning of the channel matrix. This modification improves performance over ZF, particularly with accurate CSIT. However, RZF also requires full CSIT and may have higher computational complexity. DPC is a nonlinear precoding technique that treats interference from other users as noise and cancels it out. It has the potential for improved performance over linear precoding techniques but requires precise CSI and can be computationally intensive. TPE is a linear precoding technique that approximates the optimal DPC solution using a low-complexity polynomial expansion. By adjusting the truncation degree (j=3, j=4, j=5), we can examine different trade-offs between complexity and performance. By comparing the sum rate versus SNR plots, we can observe how these techniques perform across varying SNR levels. ZF performs well in low SNR scenarios but may experience noise amplification challenges at high SNR levels. RZF can offer performance improvements, particularly in high SNR scenarios.

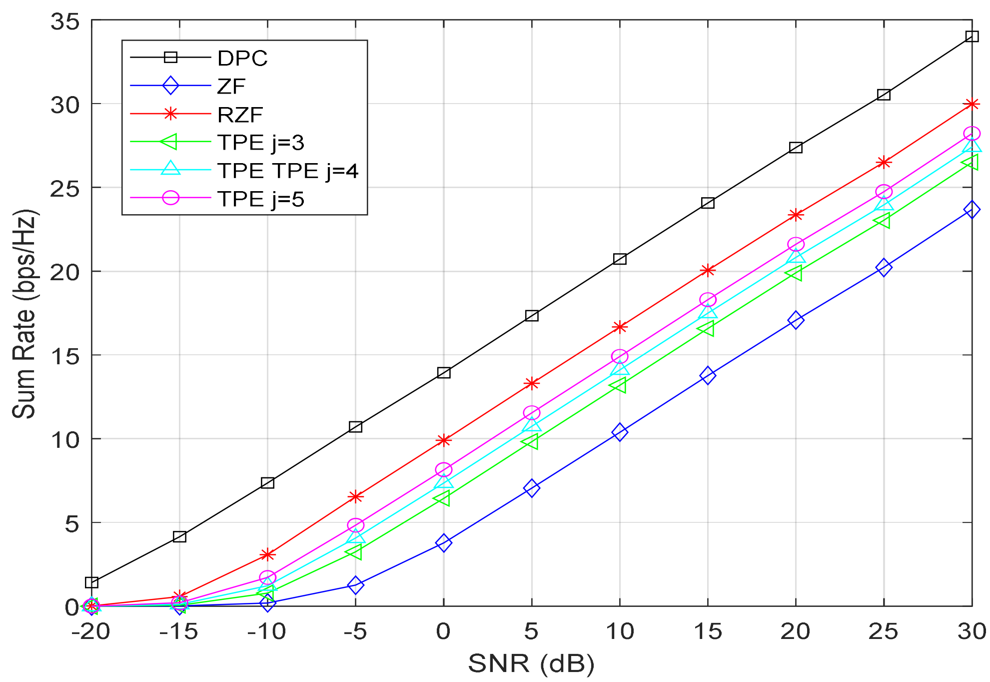

Figure 4. 4: Sum rates versus SNR of different precoding at K=100

Table 4. 5: Sum rates versus SNR of different precoding at K=100

Precoding	Sum rate values		
	SNR=-10dB	SNR=-510dB	SNR=10dB
ZF	0.1929	1.255	10.38
TPE j=3	0.7818	3.34	13.19
TPE j=4	0.7818	4.074	14.11
TPE j=5	1.713	4.831	14.91
RZF	3.083	6.544	16.66
DPC	7.361	10.7	20.72

4.1.5 Energy efficiency at proposed precoding at user terminals, K=50

The effects on the transmitted signal being mitigated by RZF's addition of a regularization factor to the precoding matrix's inversion. This results in more effective use of energy efficiency or low power consumption, especially in systems with multiple users. The LTPE-DPC is more energy efficient than RZF because TPE utilizes the channel matrix and doesn't use matrix inversion to reduce interference and enhance system performance.

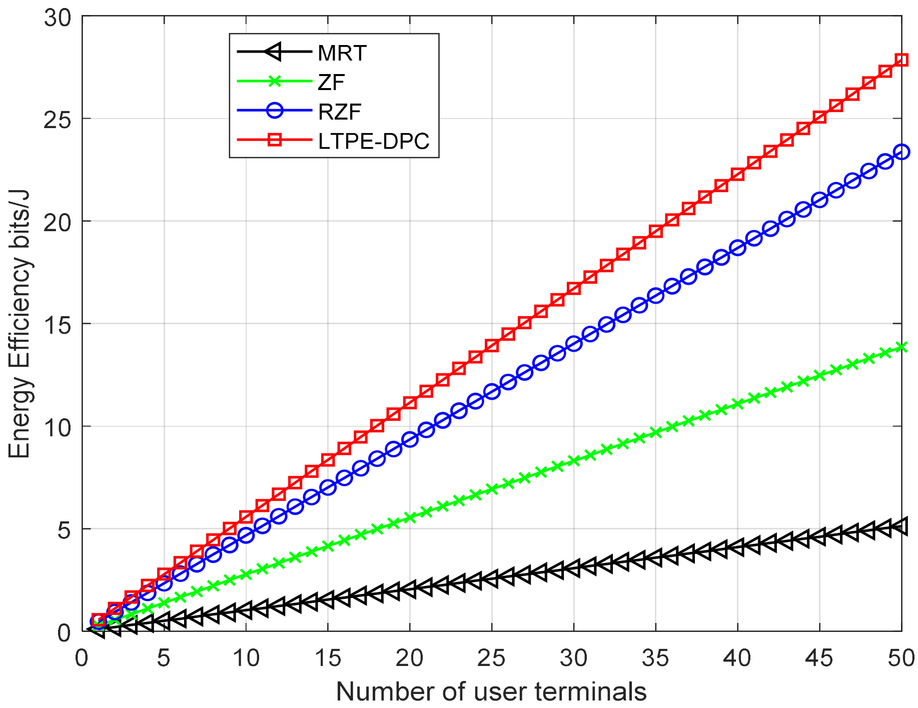

Figure 4. 5: Sum Rates of UTs versus SNR for M=128 and K=50

Table 4. 6: Sum Rates of UTs versus SNR for M=128 and K=50

Precoding Techniques	Energy Efficiency (bits/J/Hz)			
	K=5	K=10	K=15	K=20
MRT	0.8089	1.618	2.427	3.236
ZF	0.9839	1.968	2.952	3.936
RZF	2.336	4.673	7.009	9.346
LTPE-DPC	2.785	5.57	8.355	11.14

4.1.6 Energy efficiency versus transmit power

The energy efficiency of the number of base station antennas in a mmWave massive MIMO system is shown in Figure 4.6 and Table 4.7 for the four precoding techniques: MRT, ZF, RZF, and TPE. The energy efficiency is calculated for three different transmit power levels: 3dB, 6dB, and dB The TPE precoder with power allocation achieved the maximum energy efficiency among the four approaches, followed by RZF, ZF, and MRT. These results are consistent with the results of energy efficiency versus transmit power. Because more power is needed to transmit data over the wireless channel, every technique becomes less energy efficient as transmit power increases. The figure demonstrates that, at all transmit power levels, the MRT precoder has the lowest energy efficiency of the four techniques. Why the MRT precoder has the lowest energy efficiency of the four techniques reason for has highest power consumption is that MRT does not take into cancels the interference from other users. This can lead to significant interference to the other users, reducing the overall energy efficiency of the system while ZF, RZF, and TPE are achieved better energy efficiency by optimizing the use of proper power allocation and reducing interference. In the MRT, ZF, RZF, and TPE precoders, the relationship between transmit power and energy efficiency can be summed up as follows:

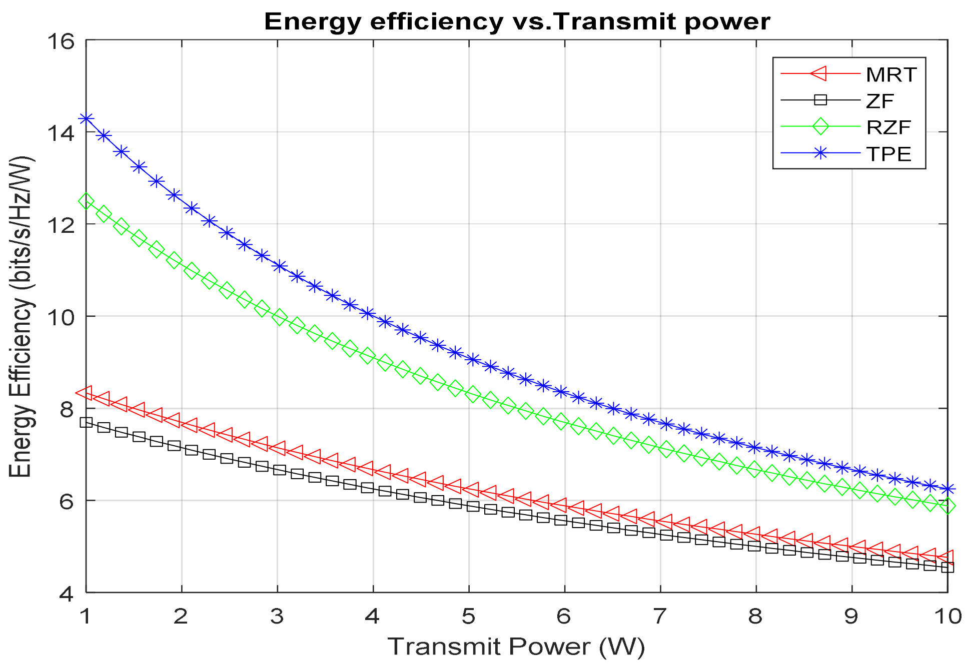

Figure 4. 6: Energy efficiency of base station antennas versus transmit power

Table 4. 7: Energy efficiency of base station antennas versus transmit power

Precoding Techniques	Energy Efficiency of User Terminals (bits/J/Hz)		
	Pt=3W	Pt=6W	Pt=9W
MRT	7.692	6.25	5.263
ZF	7.143	5.882	5.010
RZF	6.25	5.263	4.527
TPE	5.995	5.128	4.427

4.1.7 Energy efficiency vs Signal to interference plus noise ratio

Figure 4.7 and Table 4.8 below illustrate the energy efficiency of user terminals while applying various precoding techniques, including Maximum Ratio Transmission (MRT), Zero Forcing (ZF), Regularized Zero Forcing (RZF), and LTPE-DPC, at various Signal-to-Interference-plus-Noise Ratio (SINR) levels. The MRT and RZF methods have energy efficiencies of 12.9 and 12.97, respectively, and the LTPE-DPC approach has an energy efficiency of 12.97, which is the same as the RZF technique. The ZF precoding technique has the lowest energy efficiency with an SINR of -5 dB, coming in at 5.055. All precoding methods indicate an increase in energy efficiency as the SINR values rise. The energy efficiencies of the ZF and MRT techniques at an SINR of 15 dB are 43.34 and 47.71, respectively, whereas the efficiencies of the RZF and LTPE-DPC techniques are higher at 72.33 and 78.13, respectively. The Figure 4.7 describes the energy efficiency of various precoding methods for user terminals at various SINR levels (-5 dB, 5 dB, 10 dB, 15 dB) for (MRT, ZF, RZF, LTPE-DPC) respectively. The system's overall power consumption is divided by the attained sum rate to determine the system's energy efficiency. The system's energy efficiency is calculated by dividing the total power consumption by the achieved sum rate. Overall, the results indicated that, particularly at moderate to high SNR values, RZF and LTPE-DPC are more energy-efficient than MRT and ZF.

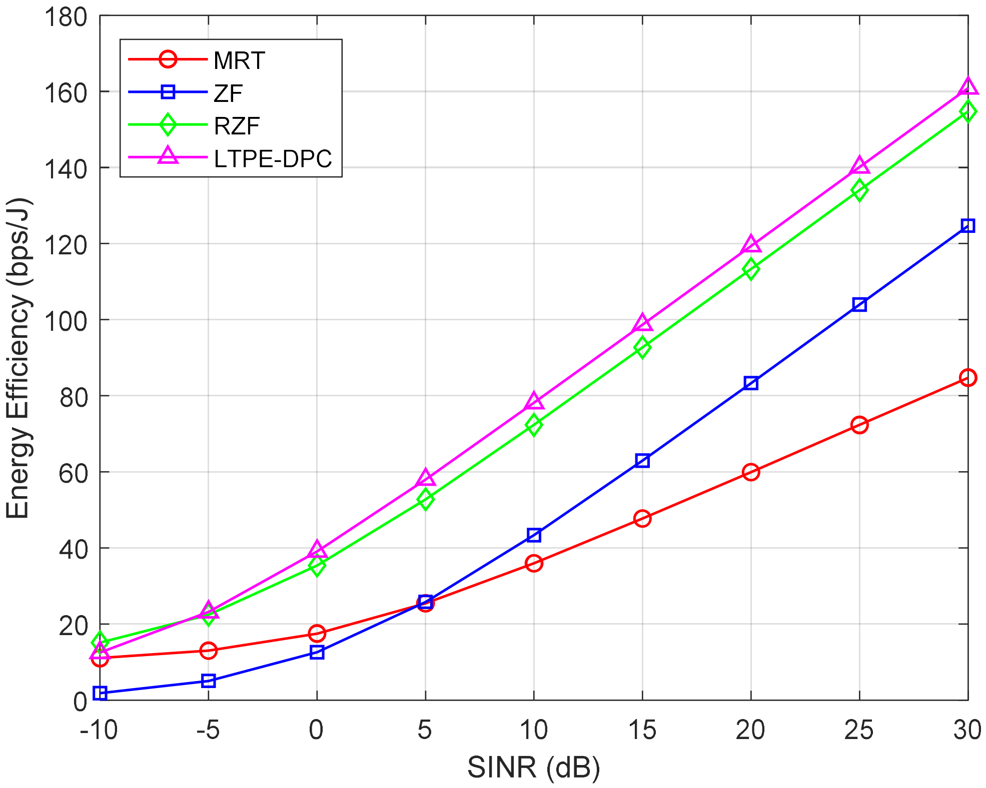

Figure 4. 7: Energy efficiency versus signal to interference plus noise ratio

Table 4. 8: Energy efficiency versus signal to interference plus noise ratio

Prcoding	Energy Efficiency of user terminals at different SINR values			
	SINR=-5dB	SINR=5dB	SINR=10dB	SINR=15dB
MRT	12.9	25.82	35.95	47.71
ZF	5.055	25.82	43.34	62.69
RZF	12.97	52.79	72.33	92.69
LTPE-DPC	12.97	58.01	78.13	98.69

4.1.8 Energy efficiency versus the number of antennas at M=64

Figure 4.8 shows the energy efficiency of user terminals (UTs) measured in Gbps per Joule (Gbps/J) using different precoding techniques, namely Maximum Ratio Transmission (MRT), Zero Forcing (ZF), Regularized Zero Forcing (RZF), and (LTPE-DPC), for different numbers of antennas (M) in a massive MIMO system. The results show that the RZF and TPE precoding techniques have significantly higher energy efficiencies compared to the ZF and MRT techniques for all values of M. At M=32, for example, the RZF and TPE techniques have energy efficiencies of 0.2298 and 0.267 Gbps/J, respectively, whereas the ZF and MRT techniques have energy efficiencies of 0.1101 and 0.09243 Gbps/J, respectively. It is worth noting that these results are consistent with the reality of massive MIMO energy efficiency. Massive MIMO systems are known to be highly energy-efficient due to their ability to spatially separate users and focus energy where it is needed. By using a large number of antennas, massive MIMO systems can achieve higher spectral efficiency and energy efficiency compared to traditional MIMO systems. In conclusion, the RZF and LTPE-DPC precoding techniques are recommended for achieving higher energy efficiency in massive MIMO systems.

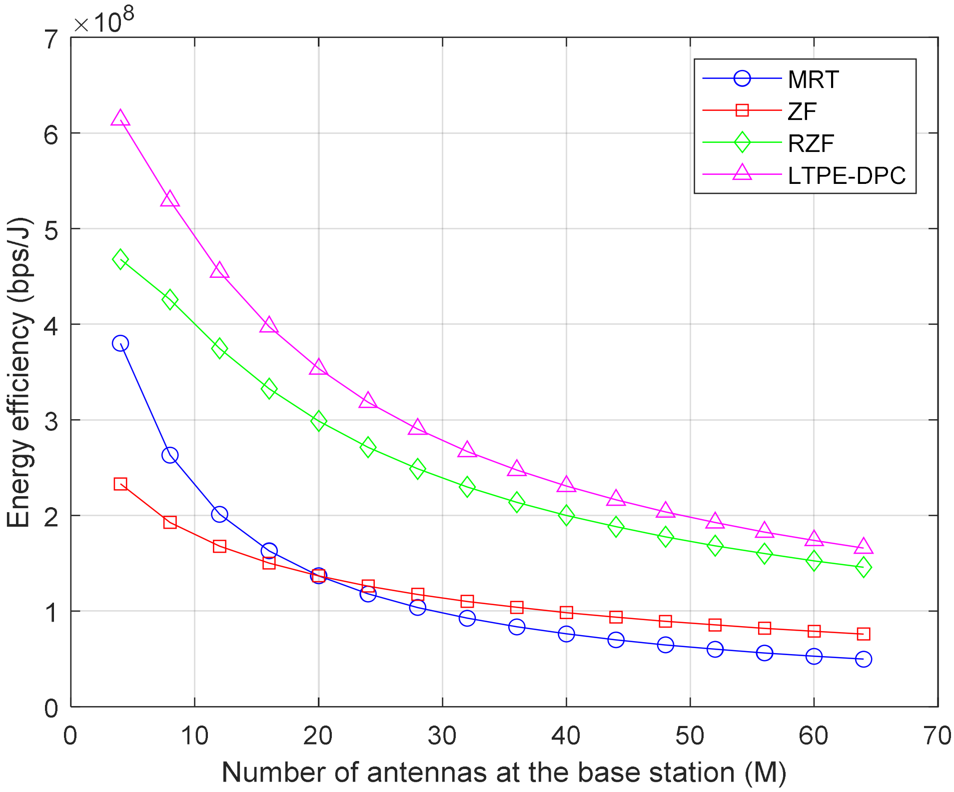

Figure 4. 8: Energy efficiency versus the number of antennas

4.1.9 The energy efficiency of the proposed precoding at M=128

Massive MIMO is a wireless technology that utilizes numerous antennas at the base station to enhance the system's performance. There are several precoders, such as MRT, ZF, RZF, and LTPE-DPC,. MRT maximizes SNR, ZF eliminates interference, RZF enhances robustness, and LTPE-DPC provides good performance at moderate complexity. The linear precoders' energy efficiency is influenced by specific factors such as channel conditions, modulation type, and precoder implementation. At M=128 antennas, the choice of linear precoder will be determined by the system's requirements and constraints. MRT and ZF are suitable for well-conditioned channels with low interference while RZF and LTPE-DPC are better suited for channels that are poorly conditioned or have high interference levels and balance the complexity of dirty paper coding precoding.

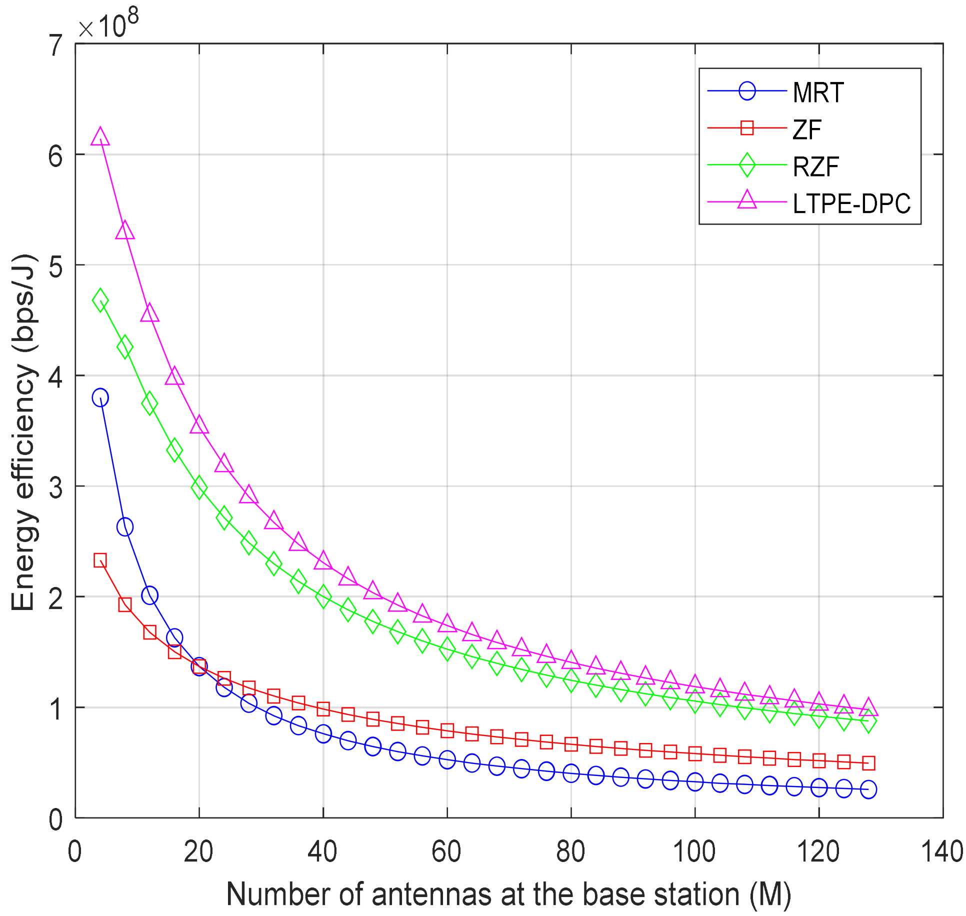

Figure 4. 9: Energy efficiency versus the number of antennas at M=128

4.1.10 The energy efficiency of proposed precoding versus transmit power

The above Figure 4.10 illustrates, as the number of antennas increases, the energy efficiency of the system can improve due to the increased spatial multiplexing and channel quality.

However, this improvement is not linear, and several factors can limit the energy efficiency gains as the number of antennas increases. One factor that can limit the energy efficiency gains is the power consumption of the system. As the number of antennas increases, the power consumption of the system also increases due to the higher number of RF chains, ADCs, and DACs. This increase in power consumption can offset the energy efficiency gains from the increased spatial multiplexing and channel quality.

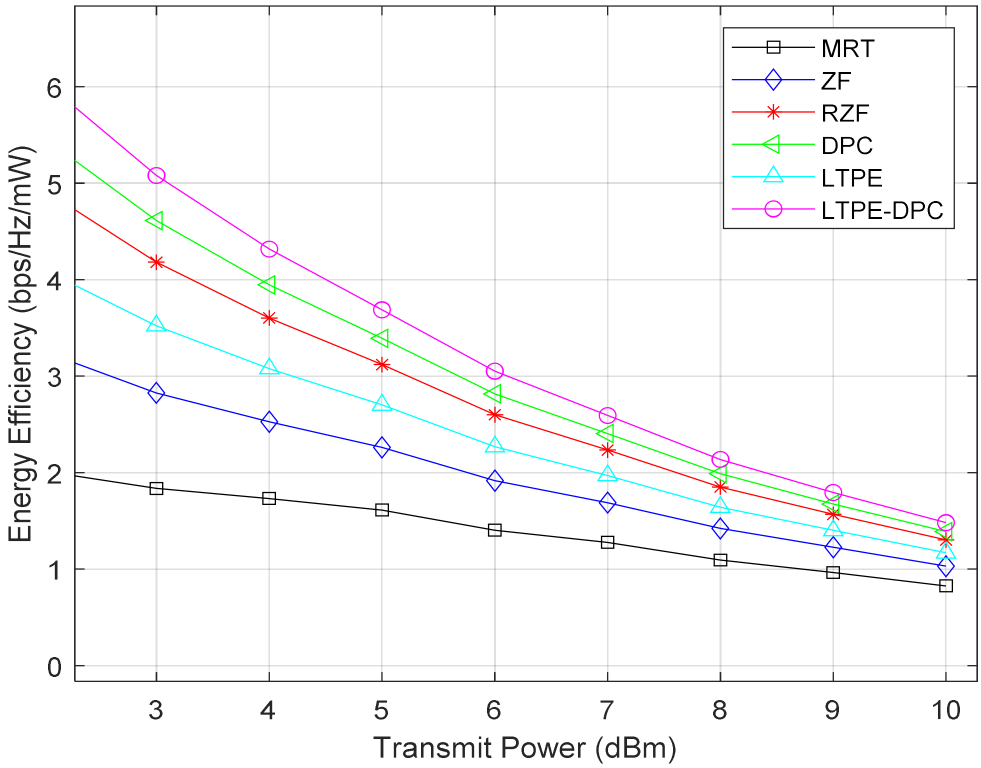

Figure 4. 10: Energy efficiency of proposed precoding versus transmit power

Table 4. 9:Energy efficiency of proposed precoding versus transmit power

Precoding	The values of energy efficiency		
	Ptx=3dBm	Ptx=6dBm	Ptx=9dBm
MRT	1.835	1.404	0.9642
ZF	2.827	1.916	1.227
RZF	4.181		1.567
LTPE	3.522	2.816	1.676
DPC	4.612	2.268	1.401
LTPE-DPC	5.08	3.051	1.793

4.1.11 Sum rate of proposed precoding versus signal-to-noise ratio

To compare the performance of different precoding techniques in mmWave massive MIMO systems, this Figure 4.11 provides insights into the trade-offs between the techniques and their respective abilities to achieve higher data rates under varying SNR conditions. The considered precoding techniques include MRT, ZF, RZF, LTPE, DPC, and LTPE-DPC. Each technique can be evaluated based on its sum rate at different SNR levels, allowing for a comprehensive comparison of their performance. ZF can effectively mitigate interference but relies on accurate channel state information and may suffer from noise amplification at high SNR. RZF addresses some limitations of ZF through regularization but has similar requirements for accurate channel state information. LTPE and DPC leverage channel diversity to mitigate interference, with DPC being more complex and demanding accurate channel state information. LTPE-DPC combines the benefits of LTPE and DPC to achieve improved performance in certain scenarios.

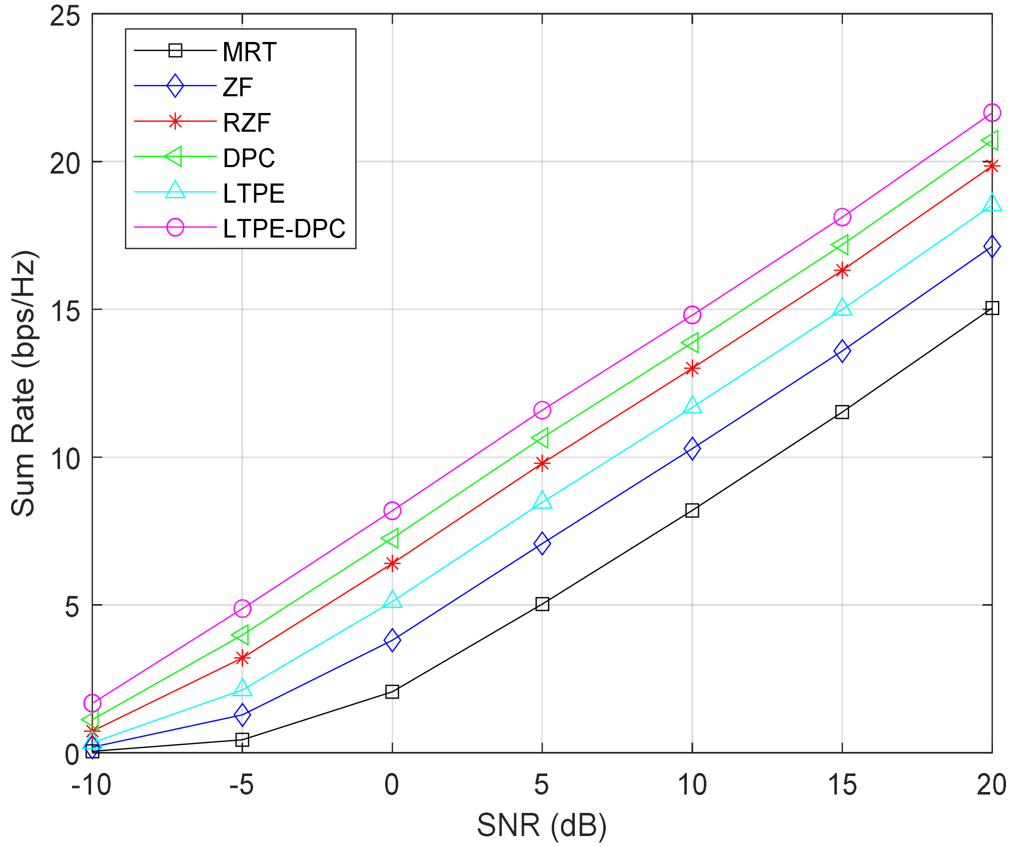

Figure 4. 11: Sum rate of proposed precoding versus signal-to-noise ratio

Table 4. 10: Sum rate of proposed precoding versus signal-to-noise ratio

Precoder	Sum rate versus SNR			
	SNR=-5dB	SNR=5dB	SNR=10Db	SNR=15dB
MRT	0.4408	5.061	8.257	11.54
ZF	1.29	7.116	10.33	13.65
LTPE	2.13	8.502	11.71	15.06
RZF	3.217	9.822	13.04	16.39
DPC	3.999	10.68	13.9	17.25
LTPE-DPC	4.882	11.62	14.83	18.19

4.1.12 Spectral efficiency of proposed precoding versus carrier frequency

In mmWave communication, higher carrier frequencies provide access to wider bandwidths, which can facilitate higher data rates. However, these frequencies also introduce challenges such as increased path loss and susceptibility to blockage, which can degrade signal quality and restrict coverage range. Figure 4.12 exhibits an initial increase in spectral efficiency as the carrier frequency rises, as the wider bandwidth allows for greater data transmission. Nevertheless, beyond a certain point, the spectral efficiency may start to decline due to the amplified effects of path loss and blockage. The proposed LTPE-DPC precoder controls the linear and nonlinear effects of the mmwave channel characteristics.

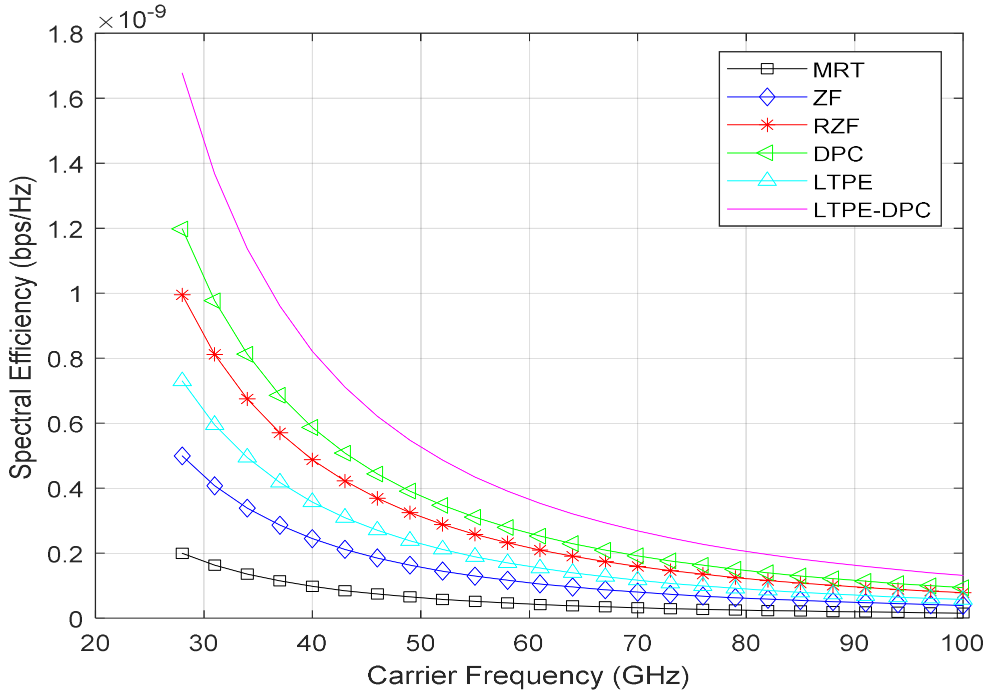

Figure 4. 12: Spectral efficiency of proposed precoding versus mmwave carrier frequency.

5 CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In this thesis, we analyzed the performance of different classes of precoding techniques in mmwave massive MIMO systems, and different precoding techniques such as MRT, ,ZF , RZF, and LTPE , from nonlinear precoding dirty paper precoding (DPC) improve the performance and LTPE-DPC of mmWave massive MIMO systems by mitigating interference and noise amplification. , evaluate the energy efficiency of base station antennas in a massive MIMO system and analyze the spectral efficiency of mmwave wave frequency bands and the proposed LTPE-DPC precoder has better sum rate and spectral efficiency than the existing precoders. Each precoding technique, namely MRT, ZF, LTPE, RZF, DPC, and LTPE-DPC, has been evaluated sum rate at SNR levels of -5dB, 5dB, 10dB, and 15dB respectively. At a low SNR of -5dB, the sum rates for all precoding techniques are relatively low. As the SNR increases, the sum rates improve significantly for all techniques. This is expected because higher SNR levels allow for better signal quality and improved transmission performance. Comparing the precoding techniques:MRT (Maximum Ratio Transmission): MRT achieves lower sum rates compared to other techniques across all SNR levels. It provides basic spatial diversity gain but does not effectively mitigate interference. ZF (Zero-Forcing): ZF achieves higher sum rates than MRT at all SNR levels. It cancels interference among users to enhance the signal quality. LTPE (Lower Truncated Polynomial Expansion): LTPE shows improved sum rates compared to MRT and ZF. By approximating the interference using a polynomial expansion, LTPE-DPC better captures the interference characteristics, leading to enhanced performance.

5.2 Recommendation

After analyzing different precoding techniques in mmWave massive MIMO systems, we recommended that future researchers should focus on multi-cell multi-user massive MIMO scenario for both linear and non-linear precoding techniques to improve the performance of mmwave massive MIMO systems and to reduce the complexity of the large antenna system.

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