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Spectral Efficiency Analysis of Massive MIMO Using MRT and ZF Beamforming

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ABSTRACT: Massive Multiple-Input Multiple-Output (MIMO) technology has recently been identified as one of the major facilitators of high data rate wireless communication networks, especially in fifth-generation (5G) and beyond wireless networks. Massive MIMO technology uses a large number of antennas at the base station, which enables the simultaneous communication of multiple users using the same time-frequency resource, thus providing a substantial improvement in spectral efficiency. Beamforming techniques are used as major tools for achieving these benefits, and Maximum Ratio Transmission (MRT) and Zero-Forcing (ZF) are two popular linear precoding methods. This paper provides a detailed spectral efficiency analysis of massive MIMO technology using MRT and ZF beamforming methods. The performance analysis of the methods is carried out for different signal-to-noise ratio (SNR) values, antenna configurations, and user densities. Theoretical calculations and simulation results are compared to analyze the rate and interference suppression capabilities of the two methods. The results show that although MRT has lower computational complexity and noise robustness, ZF provides better spectral efficiency in an interference-dominated environment.

KEYWORDS: Massive MIMO, Spectral Efficiency, Maximum Ratio Transmission, Zero-Forcing Beamforming, Linear Precoding.

I. INTRODUCTION

The increasing wireless data traffic, fuelled by smartphones, IoT devices, and high-definition multimedia services, has led to unprecedented growth in the demand for faster data rates and efficient spectrum use. Conventional MIMO solutions, although efficient, are not capable of meeting the exponential demand for connected devices. The massive MIMO solution to this problem is the use of a very large number of antennas at the base station to simultaneously serve multiple users in the same frequency band. Spectral efficiency, measured as the maximum achievable data rate per unit bandwidth, is one of the most important performance metrics of modern wireless communication systems. Massive MIMO greatly improves spectral efficiency by leveraging spatial multiplexing. The ability to simultaneously transmit independent data streams to multiple users maximizes data rate without requiring additional bandwidth. Beamforming is a basic element of massive MIMO systems. Beamforming allows signals to be transmitted to intended users while minimizing interference to other users. Among the different beamforming techniques, linear precoding techniques such as Maximum Ratio Transmission (MRT) and Zero-Forcing (ZF) are popular because of their feasibility of practical implementation. MRT maximizes the received signal power at the desired user by aligning the transmitted signal with the channel vector. It is computationally efficient and effective in a noise-limited environment. Nevertheless, it does not have a mechanism to suppress inter-user interference explicitly. On the other hand, ZF beamforming orthogonally the user channels to cancel inter-user interference explicitly. Although ZF beamforming provides better interference suppression, it involves matrix inversion, which is computationally complex and sensitive to channel estimation errors. In a practical system, the selection of MRT or ZF beamforming depends on various system parameters, including the number of antennas, the number of users, and the channel conditions. Hence, a comprehensive analysis of the spectral efficiency of the systems under different system conditions is required to make optimal beamforming design choices.

This research work investigates the spectral efficiency performance of massive MIMO systems using MRT and ZF beamforming. The analysis is carried out for downlink transmission systems with perfect channel knowledge available at the transmitter. Analytical expressions are derived, and the performance comparison is carried out for different SNR conditions and antenna-to-user ratios.

II. LITERATURE REVIEW

The spectral efficiency (SE) analysis of massive MIMO systems utilizing Maximum Ratio Transmission (MRT) and Zero-Forcing (ZF) beamforming reveals significant insights into their performance under various conditions. MRT, which maximizes the received signal power, is shown to enhance SE, particularly in scenarios with time-variant channels, where channel prediction techniques can effectively mitigate SE reduction due to channel dynamics [4] [5]. Conversely,

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ZF beamforming, which nullifies interference, demonstrates superior performance in achieving higher SE, albeit at the cost of increased computational complexity [3]. Additionally, the trade-off between spectral and energy efficiency (EE) is critical, as both MRT and ZF can optimize SE while considering circuit power consumption, highlighting the need for a balanced approach in 5G and beyond communications [2]. Overall, the integration of advanced beamforming techniques and channel estimation methods significantly enhances the SE in massive MIMO systems. Massive MIMO has emerged as a prominent research topic owing to its ability to significantly enhance spectral efficiency. Initial theoretical studies revealed that as the number of antennas becomes large, the channel vectors among users become asymptotically orthogonal. Numerous studies have examined the achievable rate formulas for massive MIMO systems in various fading environments. It has been shown that linear precoding methods are close to optimal as the number of antennas becomes large. Analytical models developed based on Rayleigh fading channels yield closed-form SINR expressions, which form the foundation for spectral efficiency analysis. Maximum Ratio Transmission has been widely studied owing to its low computational complexity. Analytical studies have shown that MRT provides a substantial array gain that is directly proportional to the number of antennas. Nevertheless, in multi-user systems, MRT fails to provide interference suppression, leading to system degradation when there is correlation among user channels or when the number of users is close to the number of antennas. Zero-Forcing beamforming has been studied as a remedy for multi-user interference. By using the inverse of the channel matrix, ZF ensures the orthogonality of user signals. Analysis shows that ZF offers a higher spectral efficiency than MRT for a sufficiently large antenna-to-user ratio. However, ZF involves complex matrix inversion. Comparative analysis has been conducted for MRT and ZF in different SNR environments. In a low-SNR environment, noise is the dominant factor, and MRT performs closely to ZF. In a high-SNR environment, interference becomes a bottleneck, and ZF outperforms MRT by a large margin. Further analysis has been conducted to study the effect of channel estimation errors [9-10]. It has been observed that channel estimation errors affect ZF more than MRT because of the complex matrix inversion involved in ZF. Precoding techniques have been developed to overcome this problem, but with increased complexity. Energy efficiency has also been compared with spectral efficiency. Analysis shows that although ZF offers higher spectral efficiency, its complexity increases power consumption. MRT, being less complex, may be more energy-efficient in some cases. Analysis has also been conducted in correlated fading channels, pilot contamination, and hardware impairments. These issues affect the effectiveness of beamforming techniques. Analysis shows that although massive MIMO offers robustness against small-scale fading, interference management is still important in dense networks [10-14].

A. Problem Statement

Massive MIMO significantly improves the spectral efficiency, but the choice of beamforming technique is a very important handle to control the overall performance. MRT is very simple and easy to be implemented, but it allows inter-user interference to pass through. ZF, on the other hand, removes the interference, but it increases the computational complexity and may amplify the noise in some cases. The trade-off between the suppression of interference, increased computational complexity, and the achievable spectral efficiency is a major practical issue. To identify the exact comparison of MRT and ZF for the optimal deployment strategy to extract the maximum spectral efficiency in massive MIMO, a wide comparison is required.

B. Research Objectives

- To derive analytical expressions for spectral efficiency of massive MIMO using MRT and ZF.
- To compare performance under varying SNR and antenna configurations.
- To evaluate interference suppression capabilities of both techniques.
- To analyze trade-offs between computational complexity and achievable throughput.

C. Research Gap

- Lack of comprehensive evaluation of MRT and ZF performance over wide range of SNRs.
- Absence of a common framework studying complexity vs spectral efficiency trade-offs.
- Few simulation studies considering realistic-channel conditions and interference model.
- Not much comparative analysis for practical deployment scenarios under different ratios of antennas to users.

D. Methodology

This study research is based on the methodology of studying spectral efficiency performance of massive MIMO downlink communication system with MRT and ZF beamforming methods. The research includes model system modeling, generating channel, beamforming application, and performance analysis based on simulation by MATLAB. The initial stage entails the definition of the system parameters. The base station is presumed to have a high number of antennas, which is normally represented by M, and the number of users is represented by K. The base station in this work has 64 antennas set in the base station and supports 8 users with a single antenna. Such a setup is a standard multi-user massive MIMO system. A wireless channel model is then chosen. It is represented by a Rayleigh fading channel model, which models real-world propagation conditions where the existence of multipath fading of signals takes place. In this model,

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generation of the channel matrix is done based on complex Gaussian random variables in terms of amplitude and phase variations of the wireless channel.

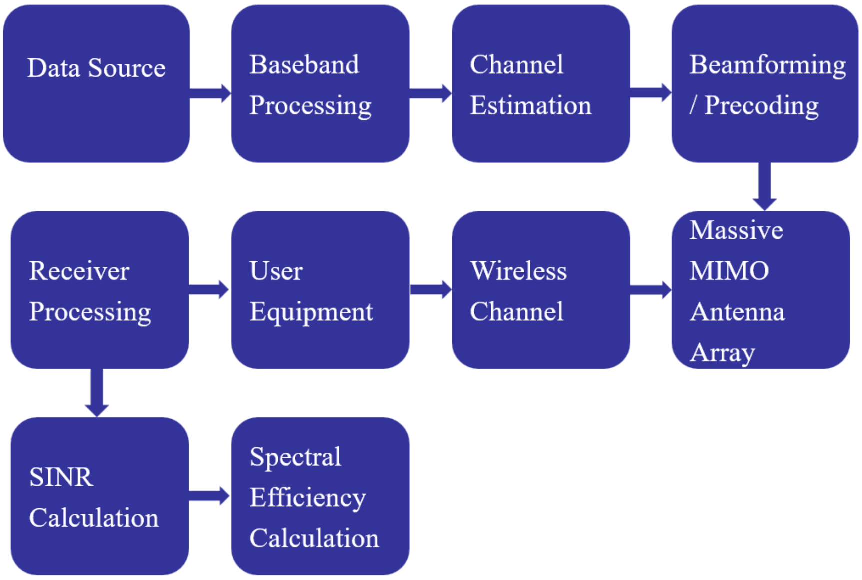

Fig.1 Block Diagram of Massive MIMO System

Beamforming is applied after the creation of the channel matrix. In the maximum ratio transmission method the beamforming vectors are oriented at the conjugate transpose of the channel matrix. The method will maximize the signal power received by each user. In Zero Forcing method a precoding matrix is calculated as a pseudo-inverse of the channel matrix. This makes sure that the signals transmitted are orthogonal to those of other users, and hence inter-user interference is canceled. When the beamforming vectors are implemented, the signal that gets received at each user is computed. Signal-to-Interference-plus-Noise Ratio (SINR) is subsequently calculated of individual users. SINR is the ratio of the desired signal power and the total signal power of interference and noise.

The spectral efficiency is determined as the Shannon capacity formula, which is a formula concerning SINR with the attainable data rate per unit bandwidth. The values of spectral efficiency are tested in accordance with the Signal to Noise ratios. Lastly, the simulation of MATLAB is carried out to compare the performance of both the MRT and ZF beamforming methods. The output is plotted in the form of spectral efficiency Vs SNR curves to compare the performance of the two techniques.

III. SPECTRAL EFFICIENCY ANALYSIS OF MASSIVE MIMO USING MRT AND ZF BEAMFORMING

The spectral efficiency is a very important performance measure of a wireless communication system since it defines how efficiently one uses the available radio spectrum. It is explained as the number of bits that can be passed through per unit bandwidth and it is normally denoted in bits per second per Hertz (bps/Hz). As the high-speed data services gain in demand and radio spectrum is scarce, spectral efficiency has become one of the key objectives of recent communication technologies like 5G and further. Massive Multiple Input Multiple Output (Massive MIMO) technology is significant towards this goal. Massive MIMO systems are based on a large set of antennas at the base station to serve many users in the same time-frequency resource. This method permits spatial multiplexing, in which a number of independent data streams are sent to varying users. Consequently, there is a high enhancement in the overall system capacity and spectral efficiency as compared to the traditional wireless systems. The efficiency of massive MIMO systems however is greatly determined by the beamforming or precoding methods applied at the transmitter.

In an ideal case of a massive MIMO downlink system, the base station has a set of antennas and each user device has a single antenna. The base station also sends transmissions to a large number of users using a wireless channel. The system model of the received signal at the user is as below:

$$y = Hx + n$$

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In which y is the received signal vector, H is the channel matrix between the base station and the users, x is the transmitted signal vector and n is the additive noise. The channel matrix is used to define the propagation of the wireless channel, and it is important in fixing the performance of the communication system.

This paper has taken a Rayleigh fading model to represent the wireless channel. Rayleigh fading is a realistic wireless propagation system where the transmitter and receiver do not have a direct line-of-sight. Rather, the signal is sent to the receiver via multiple reflected paths and this results in random changes in signal amplitude and phase. The model has been popular in the analysis of wireless communication systems that are used in urban settings. Beamforming methods are used at the base station to enhance the quality of signals and limit interference by different users. Beamforming can regulate the direction of the signals being emitted by modulating the strength and phase of the signals that are being emitted by the antennas. The Maximum Ratio Transmission (MRT) as well as the Zero Forcing (ZF) are widely employed linear precoding methods in massive MIMO systems. One of the simplest beamforming methods employed in a massive MIMO system is maximum Ratio Transmission. In MRT the conjugate transpose of the channel matrix gives the beamforming vector. The general principle of MRT is that the signal sent should be synchronized with the channel of the targeted user. This alignment gives the maximum signal power at the user and increases the signal quality. MRT is computationally efficient and it is simple to implement, thus is appealing in terms of practical systems.

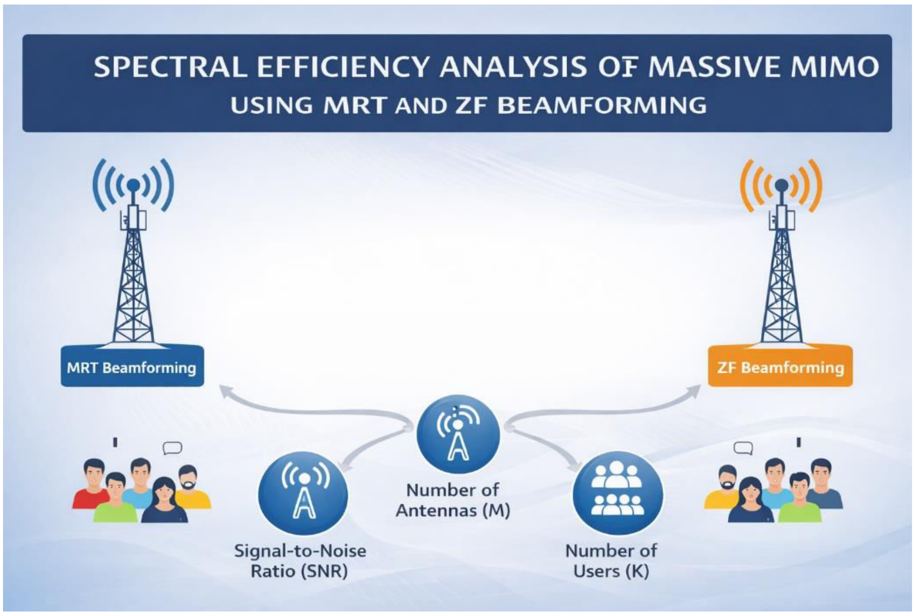

Fig.2 Spectral Efficiency Analysis of Massive MIMO Using MRT and ZF Beamforming

MRT however does not absolutely rule out interference among users. Interference in signals being used by another user may occur in a multi-user system where a number of users share the same time and frequency resource. Such inter-user interference may restrict the overall performance of the system particularly as the number of users grows. Zero Forcing beamforming is implemented to solve this problem. Zero Forcing is a precoding method used in linear fashion, that tries to entirely cancel inter-user interference. The pseudo-inverse of the channel matrix is used to compute the precoding matrix in the ZF beamforming. This makes the signals being relayed to be orthogonal to the channels of other users. Consequently, only the intended signal is transmitted to every user with limited interference by other users. Whereas the ZF beamforming is an effective interference suppressor, it is limited to some extent.

Signal-to-Interference-plus-Noise Ratio (SINR) is a metric that is utilized to measure the system performance. SINR is expressed as the ratio of the desired signal power to the sum of power of Interference and noises. When SINR is high, it implies high quality of the signal and reliability of communication. The spectral efficiency is computed by using the Shannon capacity formula which involves a relationship between SINR and the available rate of data:

$$SE = \log 2(1 + SINR)$$

This equation demonstrates the fact that spectral efficiency rises with the rise of SINR. Thus, spectral efficiency is directly increased with better SINR that is generated by efficient beamforming methods. Both MRT and ZF technique can be

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good in large scale massive MIMO systems where the number of base station antennas is much more than the number of users. The oversized array of antennas offers spatial diversity as well as the ability to bring the energy to targeted users. The decision between MRT and ZF however lies on the system requirements.

Accordingly, comparison and analysis of the MRT and ZF beamforming methods is necessary in designing of efficient massive MIMO communication systems. Their pros and cons are understood to make the correct choice of the best technique to use in future wireless networks.

IV. RESULT AND DISCUSSION

In this study, MATLAB simulations were performed to evaluate the performance of a massive MIMO downlink system using two linear beamforming techniques: Maximum Ratio Transmission (MRT) and Zero Forcing (ZF). The system model considers a base station equipped with multiple antennas communicating with multiple single-antenna users simultaneously through a Rayleigh fading channel. The performance of the system is evaluated in terms of Signal-to-Interference-plus-Noise Ratio (SINR) and spectral efficiency under different Signal-to-Noise Ratio (SNR) conditions. The received signal at the user can be expressed using the downlink system model:

$$y = Hx + n$$

where yrepresents the received signal vector, His the channel matrix, xis the transmitted signal vector, and nrepresents the additive noise. The wireless channel is modeled using Rayleigh fading, which captures the effect of multipath propagation in non-line-of-sight communication environments.

To evaluate system performance, the Signal-to-Interference-plus-Noise Ratio (SINR) is calculated for each user. SINR represents the ratio between the desired signal power and the combined interference and noise power. It can be expressed as:

$$\mathrm{SINR}_k = \frac{P|h_k w_k|^2}{\mathrm{sum}_{i\,!=\,k} P|h_k w_i|^2 + \mathrm{sigma}^2}$$

where Prepresents the transmit power, $h_k$is the channel vector of the k^{th}user, $w_k$is the beamforming vector, and σ^2represents noise power. The denominator includes the interference caused by other users in the system.
The spectral efficiency of each user is then calculated using the Shannon capacity formula:

$$\mathrm{SE} = \log_2(1 + \mathrm{SINR})$$

This equation shows that spectral efficiency increases with increasing SINR. Therefore, beamforming techniques that improve SINR will directly improve spectral efficiency. The simulation results demonstrate the relationship between SNR and spectral efficiency for both MRT and ZF beamforming techniques. At low SNR values, both MRT and ZF provide relatively low spectral efficiency because the received signal is dominated by noise. For example, at an SNR of −10 dB, the spectral efficiency for MRT is approximately 10 bps/Hz, while ZF achieves around 11 bps/Hz. This shows that under very noisy conditions, both techniques perform similarly. As the SNR increases, the spectral efficiency of both techniques improves. However, the improvement is more significant for Zero Forcing beamforming. For instance, at 0 dB SNR, the spectral efficiency for MRT increases to about 17 bps/Hz, while ZF achieves approximately 24 bps/Hz. This difference occurs because ZF effectively suppresses interference between users. MRT beamforming focuses on maximizing the received signal power but does not completely eliminate interference between users. As a result, its spectral efficiency increases initially but eventually reaches a saturation point around 37 bps/Hz. On the other hand, ZF beamforming eliminates inter-user interference by using the inverse of the channel matrix, allowing the system to achieve significantly higher spectral efficiency values.

The graphical representation of the spectral efficiency performance of MRT and ZF beamforming techniques is illustrated in Figure 1. The figure clearly shows that as the SNR increases; the spectral efficiency of both techniques improves. However, the performance gap between the two methods becomes more prominent at higher SNR levels.

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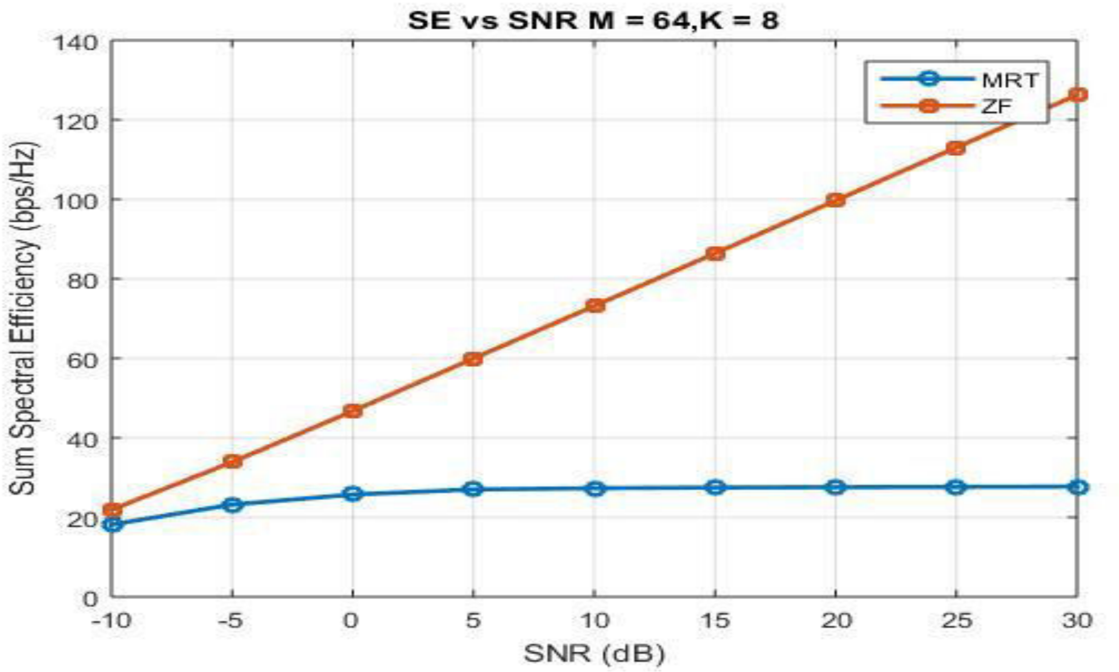


Fig .2 Spectral Efficiency vs SNR for MRT and ZF Beamforming

The results demonstrate that ZF beamforming provides better spectral efficiency performance than MRT in multi-user massive MIMO systems, particularly at higher SNR values. This improvement is mainly due to the ability of ZF precoding to suppress interference among users.

Table 1: Spectral Efficiency Comparison of MRT and ZF Beamforming

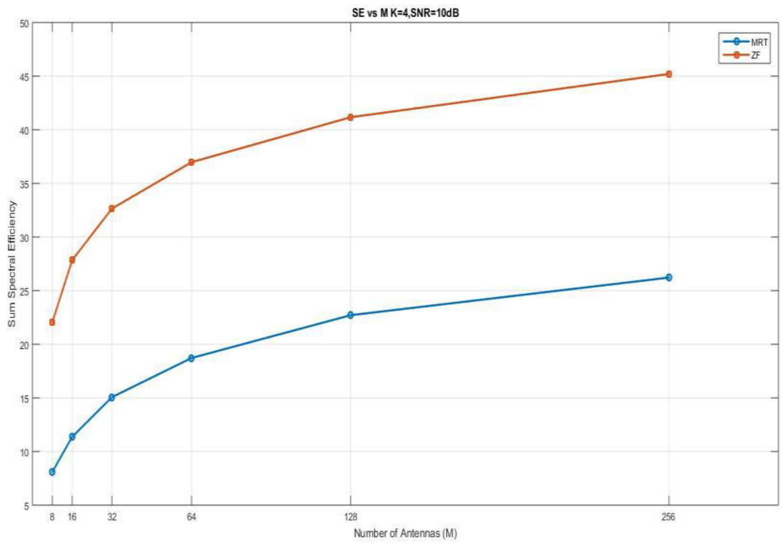
SNR (dB)	MRT SE (bps/Hz)	ZF SE (bps/Hz)
-10	19	22
-5	23	34
0	25	46
5	26	58
10	26	70
15	26	82
20	26	95
25	**26**	**107**
30	**26**	**118**

Table 1 presents the variation of sum spectral efficiency with respect to SNR for both MRT and ZF precoding techniques. It is observed that the spectral efficiency of ZF increases significantly as SNR increases, ranging from 22 bps/Hz at -10 dB to 118 bps/Hz at 30 dB. This indicates that ZF effectively utilizes the increase in signal power by eliminating inter-user interference, thereby improving the overall system performance. In contrast, MRT shows only a marginal increase in spectral efficiency, rising from 19 bps/Hz to approximately 26 bps/Hz and then saturating at higher SNR values. This saturation occurs due to the presence of inter-user interference, which becomes dominant when noise effects are reduced at high SNR. Hence, ZF outperforms MRT significantly in high SNR conditions.

The graphical representation illustrates the variation of spectral efficiency with respect to the number of base station antennas (M) for both MRT and ZF beamforming techniques at a fixed SNR of 10 dB and K = 8 users. The graph shows that spectral efficiency increases as the number of antennas increases for both techniques. The ZF curve shows a steep rise at lower antenna values and then gradually increases at higher values. This indicates that ZF beamforming effectively utilizes the additional spatial degrees of freedom provided by more antennas to suppress interference and improve system performance. On the other hand, the MRT curve shows a slower and more gradual increase in spectral efficiency.

Fig.4 Spectral Efficiency vs Number of Antennas (K = 10, SNR = 10 dB)

Although MRT benefits from the increase in antennas, its performance gain is limited due to the presence of inter-user



interference. As a result, the improvement becomes less significant at higher antenna values. Overall, the graph clearly demonstrates that Zero Forcing beamforming provides better spectral efficiency compared to Maximum Ratio Transmission when the number of antennas increases, making it more suitable for massive MIMO systems.

Table 2: Spectral Efficiency Comparison for Different Number of antennas(M)

M	MRT SE (bps/Hz)	ZF SE (bps/Hz)
8	9	23
16	14	51
32	20	63
64	27	72
128	35	80
256	41	86

Table 2 illustrates the impact of increasing the number of base station antennas on spectral efficiency. As the number of antennas increases from 8 to 256, both MRT and ZF exhibit improvement in spectral efficiency. MRT increases from 9 bps/Hz to 41 bps/Hz, while ZF increases from 23 bps/Hz to 86 bps/Hz. However, the rate of increase is not linear; instead, it shows a diminishing growth pattern. This is due to the logarithmic relationship between SINR and spectral efficiency, where initial increases in M provide significant beamforming gains, but further increases yield smaller improvements. ZF achieves higher gains compared to MRT because it effectively exploits the additional spatial degrees of freedom to suppress interference.

Figure illustrates the variation of spectral efficiency with respect to the number of users (K) for both MRT and ZF beamforming techniques. The graph clearly shows that spectral efficiency increases as the number of users increases for

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both techniques. The ZF curve exhibits a steep and nearly linear increase, indicating that Zero Forcing effectively utilizes the system resources to support more users while maintaining high performance. This is because ZF eliminates inter-user interference, allowing multiple users to be served simultaneously without significant degradation in signal quality. On the other hand, the MRT curve shows a slower and more gradual increase. Although MRT benefits from serving more users, its performance is limited by the presence of interference among users. As the number of users increases, this interference becomes more dominant, reducing the efficiency gain.

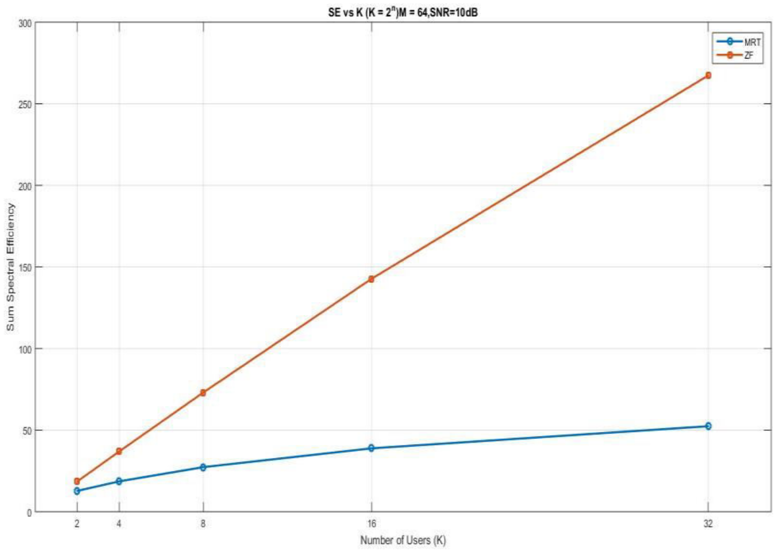

Fig.5 Spectral Efficiency vs Number of Users (K) for MRT and ZF Beamforming

Overall, the graph demonstrates that Zero Forcing beamforming is more suitable for systems with a higher number of users, as it provides significantly better spectral efficiency compared to Maximum Ratio Transmission.

Table 3: Spectral Efficiency Comparison of MRT and ZF for Different Number of users(K)

K	MRT SE (bps/Hz)	ZF SE (bps/Hz)
2	14	20
4	20	38
8	30	75
16	45	145
32	62	260

Table 3 shows the variation of spectral efficiency with respect to the number of users. It is observed that the spectral efficiency increases with an increase in the number of users for both MRT and ZF precoding techniques. MRT increases from 14 bps/Hz to 62 bps/Hz, whereas ZF increases from 20 bps/Hz to 260 bps/Hz as the number of users increases from 2 to 32. The increase in ZF is nearly linear, as each additional user contributes an independent data stream and interference is effectively canceled. On the other hand, MRT experiences a slower and non-linear increase due to the rise in inter-user interference as more users are added. This demonstrates that ZF is more scalable and efficient in multi-user environments.

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From the above results, it is evident that the performance of a massive MIMO system is significantly influenced by the choice of beamforming technique, Signal-to-Noise Ratio (SNR), number of antennas (M), and number of users (K). Maximum Ratio Transmission (MRT) provides a simple and low-complexity solution that enhances signal strength; however, its performance is limited due to the presence of inter-user interference, leading to saturation of spectral efficiency at higher SNR levels. In contrast, Zero Forcing (ZF) beamforming consistently achieves higher spectral efficiency across all scenarios by effectively canceling interference among users. The results also show that increasing the number of antennas improves spectral efficiency for both techniques, but the improvement is more significant in ZF due to better utilization of spatial degrees of freedom. Similarly, as the number of users increases, ZF continues to maintain superior performance, whereas MRT shows limited growth. Overall, the tabulated results clearly indicate that ZF precoding consistently outperforms MRT in all scenarios, particularly in systems with higher SNR, larger antenna arrays, and increased number of users..

V. CONCLUSION

This research presented a spectral efficiency analysis of a massive MIMO downlink communication system using Maximum Ratio Transmission and Zero Forcing beamforming techniques. Massive MIMO technology enables simultaneous communication with multiple users using a large number of antennas at the base station, thereby significantly improving system capacity and spectral efficiency. A Rayleigh fading channel model was used to simulate realistic wireless propagation conditions. MATLAB simulations were performed to evaluate system performance in terms of Signal-to-Interference-plus-Noise Ratio and spectral efficiency. The results indicate that both MRT and ZF beamforming techniques improve system performance in massive MIMO systems. MRT provides strong signal gain with lower computational complexity, making it suitable for practical implementations. However, it does not fully eliminate inter-user interference. Zero Forcing beamforming effectively suppresses interference between users and achieves higher spectral efficiency, particularly at high SNR levels. However, it requires higher computational complexity due to matrix inversion operations. Overall, the comparative analysis highlights the trade-off between complexity and performance in beamforming techniques. The findings of this study can assist in selecting appropriate beamforming strategies for future wireless communication systems. From all the above results, it is evident that Zero Forcing beamforming consistently outperforms Maximum Ratio Transmission in terms of spectral efficiency across different system configurations, including variations in SNR, number of users, and number of antennas. MRT provides lower computational complexity but suffers from inter-user interference, leading to performance saturation at higher SNR levels. In contrast, ZF effectively suppresses interference and achieves significantly higher spectral efficiency, especially in high SNR and high user-density scenarios. Furthermore, increasing the number of antennas improves system performance for both techniques, but the improvement is more pronounced for ZF. These observations highlight the importance of selecting appropriate beamforming techniques for efficient spectrum utilization in massive MIMO systems.

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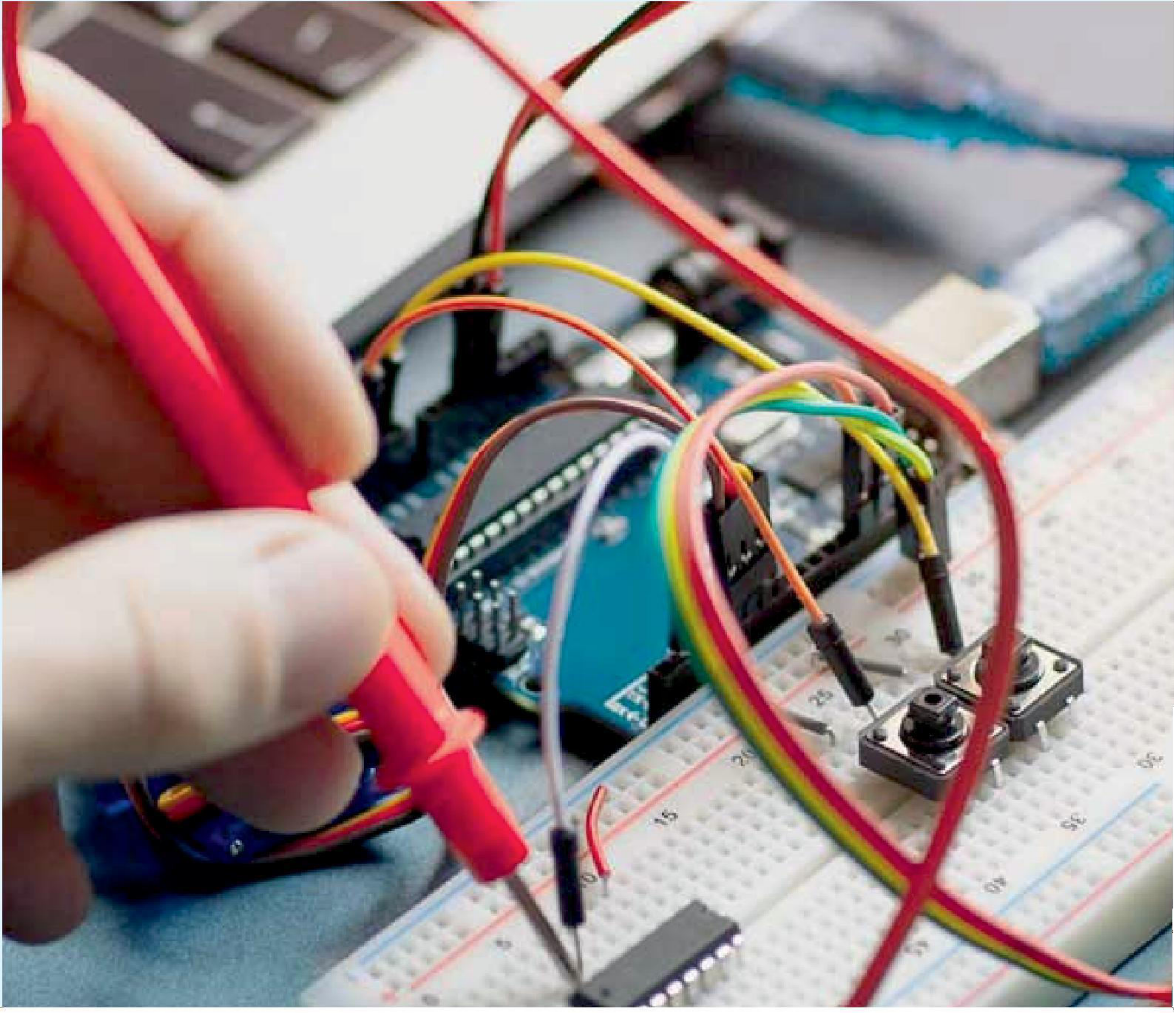

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