Performance analysis of massive MIMO hybrid neamforming using regularized zero forcing and phased zero forcing

Endah Setyowati*, Gita Alisrobia Nazarudin, Galura Muhammad Suranegara, and Ahmad Fauzi

Universitas Pendidikan Indonesia, Bandung, Indonesia

ABSTRACT

This research analyzed the performance of hybrid beamforming in a 256 x 256 Massive MIMO system, which aimed to reduce energy power consumption by applying two methods: Regularized Zero Forcing and Phased Zero Forcing. The approach used was an experimental method simulated through MATLAB software to evaluate the performance of hybrid beamforming using both methods. Based on the simulation results, the RZF and PZF methods achieved the target Bit Error Rate (BER) of 10^{-4} at Signal-to-Noise Ratios (SNRs) of 9.8 dB and 10 dB, respectively. In comparison, the system without hybrid beamforming required an SNR of 11.5 dB to achieve the same performance. These results showed that hybrid beamforming with the RZF method was more effective in improving the performance of Massive MIMO systems, as it had a regularization factor that helped balance between signal gain and interference suppression. Thus, the implementation of RZF in hybrid beamforming was identified as a potential solution to optimize wireless communication performance. This research provided a basis for the further development of 5th-generation communication technology and beyond, where massive MIMO and hybrid beamforming are crucial technologies. The results of this analysis could be applied to designing 5G networks to ensure high capacity and reliability.

*Corresponding author
Email Address: endahsetyowati@upi.edu
Date received: 10 September 2024
Date revised: 11 November 2024
Date accepted: 30 December 2024
DOI: https://doi.org/10.54645/202518SupPNE-95

INTRODUCTION

The increasing number of users and devices connected to communication networks had led to a growing demand for greater network capacity, higher data speeds, and more reliable connectivity. To optimize user experience, signal quality needed to be improved year over year. This was achieved through 5G technology, the latest generation in wireless communication, which was designed to meet users' needs for higher data speeds, lower latency, and more reliable connectivity compared to previous generations (Dangi et al. 2021). One of the key targets of 5G technology was the use of massive multiple-input multiple-output (MIMO). By utilizing a large number of antennas at transmitting and receiving stations, Massive MIMO

KEYWORDS

Hybrid Beamforming, Massive MIMO, PZF, RZF

simultaneously transmitted data to multiple devices (Hojatian et al. 2021; Kassam et al. 2020). This capability significantly increased network capacity and improved spectral efficiency, which was crucial for supporting 5G-based services (Trikolas et al. 2022).

However, the implementation of Massive MIMO required more complex infrastructure, including additional hardware to support numerous antennas, resulting in increased power consumption, particularly at the base station (Gani 2023). To address this issue, Hybrid Beamforming techniques were introduced. Hybrid beamforming was an antenna system design technique that combined analog and digital elements to reduce energy consumption caused by the use of massive MIMO (Usman and Irwan, 2019). By simultaneously incorporating analog and digital components in hybrid beamforming, signals were processed efficiently by leveraging the advantages of each (Payami et al. 2019). In the analog section, signal processing was performed using phase shifters and attenuators, allowing effective signal direction control with lower power consumption (Sheemar et al. 2022). On the other hand, the digital section provided greater flexibility in signal manipulation, such as performing complex precoding or decoding (J. Zhang et al. 2020).

One challenge of massive MIMO technology was the occurrence of inter-user interference caused by the large number of antennas used (Putra et al. 2023). PZF and RZF provided solutions to manage complex inter-antenna interference. In the context of hybrid beamforming, these methods served as two main approaches to address the problem of interaction between antenna elements. PZF aimed to eliminate interconnections between antennas, while RZF used a regularization approach to improve overall system performance (Albreem et al. 2019).

A study on the performance analysis of multi-user massive MIMO hybrid beamforming systems at millimeter wave frequency bands (Dilli 2021) analyzed the performance of hybrid beamforming in massive MIMO multi-user systems with 4 and 8 users, using OFDM and M-QAM modulation schemes (16-QAM, 64-QAM, 256-QAM), zero-forcing method, and antenna configurations of 64 BS, 128 BS, and 256 BS. The parameter tested was the RMS EVM value against the number of users. The results showed that increasing the number of independent data streams per user led to a decrease in RMS EVM values. The use of 256 BS and 128 BS antenna configurations was found to be more suitable for multi-user applications as it improved the quality of system transmission by lowering RMS EVM values.

However, the study conducted by (Dilli 2021) only used one precoding method, zero forcing, in the hybrid beamforming system. This research employed two precoding methods in the hybrid beamforming system: PZF and RZF to analyze the performance of hybrid beamforming in massive MIMO technology using a 256 × 256 antenna configuration with QPSK modulation. The parameter tested was Bit Error Rate (BER) against Signal-to-Noise Ratio (SNR).

METHODS

This research uses a type of quantitative research with an experimental approach. We conducted a trial to determine the performance of hybrid beamforming using massive MIMO 256 × 256 using the PZF precoding and RZF precoding methods. The design process and performance testing were measured and analyzed using Matlab R2020a software. Then, the results were obtained as a BER value against SNR as a parameter in this study. Then, an analysis was carried out regarding the results obtained. This research was conducted following the procedure shown in **Figure 1.**

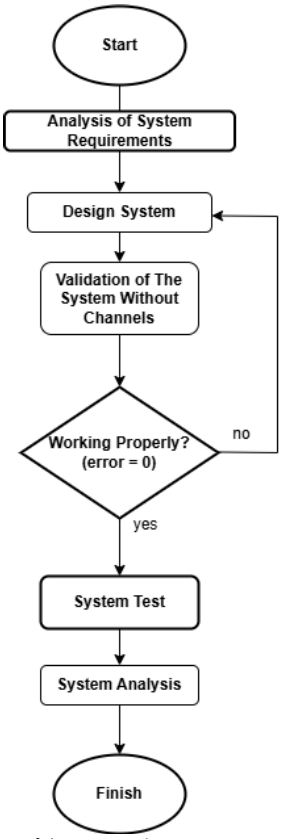

Figure 1: Flowchart of the research

Figure 2 shows the design to determine the performance of hybrid beamforming on massive MIMO using the PZF and RZF methods from the sender and receiver sides. This arrangement refers to (Dilli 2021) system block as shown in Figure 3. Figure 3 is a block diagram of a massive MIMO 256 x 256 hybrid beamforming system which involves the process of transmitting and receiving data.

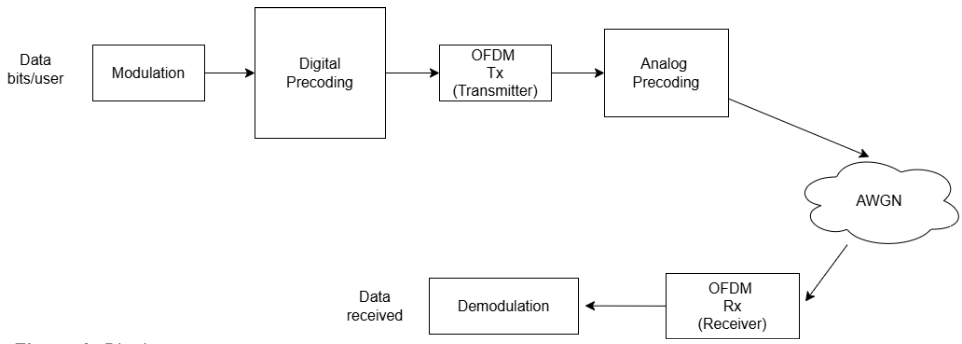

Figure 2: Block system

RESULTS AND DISCUSSION

Massive Multiple Input Multiple Output (MIMO)

Massive MIMO is a wireless communication technology that combines a large number of antennas at base stations or access points with fewer terminal devices (user devices) (Bindle et al. 2021). Its primary objective is to enhance capacity and spectral efficiency in cellular communication systems, particularly in 5G networks. (Abdelfatah et al. 2022; Akrout et al. 2023; Ammar et al. 2022; Björnson et al. 2017; Borges et al. 2021; Chataut and Akl, 2020; Elhoushy et al. 2022; Figueiredo, 2022; Guo et al. 2022; Khwandah et al. 2021; Marzetta and Thomas L, 2015). Massive MIMO antennas typically range from tens to hundreds in number. This study uses a 256 x 256 antenna because it can significantly increase network capacity. This site also allows users to study the effects of using hybrid beamforming on a large scale while providing results that are more relevant to real situations. Several previous studies have not used many antennae of this size. **Figure 3** illustrates the system architecture of massive MIMO.

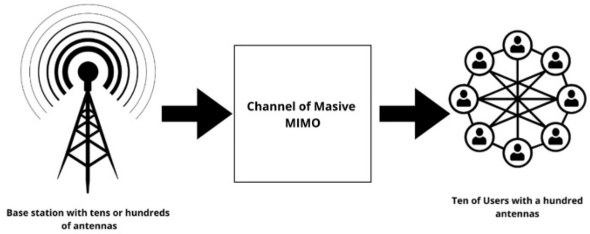

Figure 3: The architecture of massive MIMO

Hybrid beamforming

Hybrid Beamforming is a method that combines digital and analog beamforming techniques in its application. This method is used to address the hardware complexities that arise in the implementation of massive MIMO (Hussein and Kıvanç Türeli 2023; Li et al. 2019; J. Zhang et al. 2020). Hybrid Beamforming plays a crucial role in improving throughput and reducing power consumption in wireless communication systems, especially in the deployment of massive MIMO (Hamid et al. 2023). **Figure 4** illustrates the architecture of hybrid beamforming.

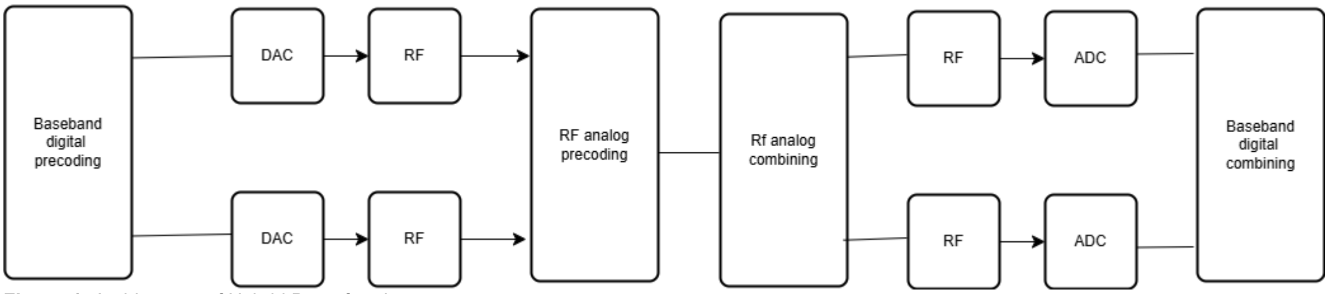

Figure 4: Architecture of Hybrid Beamforming

Hybrid beamforming combines the use of digital and analog techniques simultaneously, as illustrated in Figure 4. The stages within digital and analog beamforming can be explained as follows.

(i). Digital Precoding

In this stage, the baseband signal from the input data is digitally processed and optimized before transmission through the antennas. Subsequently, digital precoding is applied to the signal. (Rezaei and Tadaion, 2019). Digital precoding involves calculating weights that are applied to the signal to reduce inter-user interference and enhance transmission efficiency based on estimated Channel State Information (CSI). This process involves operations in the digital baseband domain. (Li et al. 2021). This research employs the techniques of RZF and PZF.

RZF is a variation of zero-forcing precoding that is modified by adding a regularization component that aims to overcome some disturbances that may occur when using ZF precoding, such as sensitivity to errors in the channel (Kebede et al. 2022; Nguyen et al. 2019). This regularization helps balance noise reduction and signal conditioning requirements, resulting in better performance than ZF precoding. Mathematically, it can be represented by **equation (1).**

$$W_{RZF} = \beta(HH^H + \alpha I_k)^{-1} H^H \tag{1}$$

where, W_{RZF} is the RZF precoding matrix, β is the power normalization parameter, α is the regularization factor, H is the channel matrix, and I_k is the identity matrix

PZF is a precoding technique used to minimize interference. By considering antenna phases, PZF can better direct power, enhance received signal strength, and reduce power transmitted in undesired directions (Kebede et al. 2022). Mathematically, it can be represented by **equation (2)**:

$$W_{PZF} = H_{eq}^H(H_{eq}H_{eq}^H)^{-1}\lambda \tag{2}$$

where λ is the positive diagonal matrix for the power normalization of columns, H_{eq} is the Channel matrix, and H_{eq}^H is the Conjugate transpose of the channel matrix

(ii). RF Analog

These RF signals serve as input for the analog beamforming process. The incoming RF signals are distributed to each antenna element within the antenna array. Subsequently, the RF signals are calculated using **equation (3)**:

$$X_{RF} = F_{RF}S_{baseband} \tag{3}$$

where X_{RF} is the Vector of RF signals transmitted by the transmitting antenna, F_{RF} is the Precoding matrix in the RF domain, and $S_{baseband}$ is the Baseband signal vector

Results

The test scenario in this research is to compare the performance of the RZF, PZF, and without hybrid beamforming methods. Then an analysis was carried out regarding the performance of each method which was measured by BER against SNR and coding gain value. The hybrid beamforming simulation results using the RZF, PZF, and without both methods are shown **in Figure 5**. This figure shows that the hybrid beamforming communication system using the RZF, PZF, and without both methods can achieve a BER target of 10^{-4}.

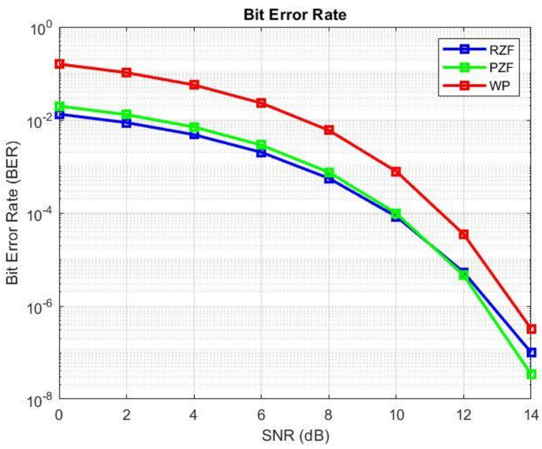

Figure 5: Simulation of massive MIMO 256 x 256 hybrid beamforming

The blue line depicts the simulation results using the RZF method, the green line depicts the simulation results using the PZF method, and the red line depicts the results without hybrid beamforming. In the massive MIMO 256 x 256 simulation without hybrid beamforming and precoding methods, an SNR of 11.5 dB is required. In comparison, the simulation using the PZF method only requires an SNR of 10 dB, while the simulation using the RZF method requires an SNR of 9.8 dB to achieve the target BER of 10^{-4}.
The detail of the SNR value to achieve BER target 10^{-4} can be seen **in Table 1**.

Table 1: SNR value to achieve BER target 10-4

Precoding	SNR values	Coding Gain
Without Precoding	11.5 dB	Reference
RZF	9.8 dB	1.7 dB
PZF	10 dB	1.5 dB

Discussion
Based on Figure 5, the RZF method achieves a target BER of 10^{-4} at an SNR value of 9.8 *dB* with a coding gain of 1.7 dB. Coding Gain is the enhancement (additional power) produced by the use of RZF and PZF coding. This represents the best achievement compared to other methods, as the RZF method has a regularization factor that can be seen **in equation (1)** to help balance between signal amplification and interference suppression. With the addition of this factor, it can reduce the impact of noise in maintaining better signal quality and decreasing BER (Kebede et al. 2022).

The PZF method achieves the BER target at an SNR value of 10 dB, slightly higher than RZF, but still more efficient compared to not using hybrid beamforming at all. The use of the PZF method has a coding gain difference of 1.5 dB. From this data, the performance of the PZF method is not more effective than the RZF method in reducing BER, but it is still better than that of not using hybrid beamforming. The PZF method works by modifying the phase of the signals sent from each antenna so that the interference between these signals cancels each other out at the receiver's end. This results in a received signal that is much better compared to not using hybrid beamforming, although it is not as optimal as the RZF method. The PZF method has a lower computational level compared to RZF and is simpler to implement in systems (Kebede et al. 2022).

Meanwhile, without using hybrid beamforming, the new target BER is achieved at an SNR value of 11.5 dB, indicating that without the hybrid beamforming technique, the system requires a higher SNR to reach the desired BER. This proves that the use of hybrid beamforming can provide better performance compared to those that do not use it (Singh and Joshi, 2021). This indicates that hybrid beamforming, particularly with the RZF method, is very effective in improving BER performance in modern communication systems.

The system designed in this research can be categorized as 5G communication, where the BER value concerning SNR meets the standards for 5G communication set by the 3rd Generation Partnership Project (3GPP) TS 38.211 version 16.2.0 Release 16. A system can be considered 5G if the BER value reaches 10^{-6}. In this study, it has been proven that hybrid beamforming using the RZF and PZF methods is capable of reducing power consumption in the implementation of massive MIMO 256 × 256.

CONCLUSION

The use of the RZF method and the PZF method has an impact on the hybrid beamforming system of massive MIMO 256 x 256 to reduce interference and errors. Among the two, the RZF method is the one with the best performance compared to the PZF method. This is evidenced by a coding gain of 1.7 dB. Meanwhile, the use of the PZF method is not better than the RZF method, as shown by a coding gain of 1.5 dB. On the other hand, the use of hybrid beamforming also impacts the communication system by reducing interference among massive MIMO antennas. This is demonstrated by the graph results, which show that without hybrid beamforming, the required SNR value is the highest among the RZF and PZF methods, at 11.5 dB. The use of precoding RZF and PZF also reduces the power consumption.

ACKNOWLEDGMENT

We thank Prof. Dr. Eng. Asep Bayu Nandiyanto, S.T., M. Eng. and colleagues at Universitas Pendidikan Indonesia who provided valuable insights and expertise that greatly assisted the research. Special appreciation goes to the anonymous reviewers whose comments and suggestions significantly improved the quality of this manuscript.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

CONTRIBUTIONS OF INDIVIDUAL AUTHORS

Endah Setyowati is the main contributor, provided grant support, and edited the final manuscript. Gita Alisrobia primarily conducted the experiments and wrote the first draft. Galura Muhammad Suranegara and Ahmad Fauzi supported the research and provided advice.".

REFERENCES

Abdelfatah, M ElSayed S, Zekry A. A Study on the basics processes of massive MIMO. Journal of Communications 2022; 17(2): 167–179.

Albreem, M A, Juntti, M, Shahabuddin, S. Massive MIMO detection techniques: A survey. IEEE Communications Surveys , Tutorials 2019; 21(4): 3109–3132.

Ammar, H A, Adve, R, Shahbazpanahi, S, Boudreau, G, Srinivas, K V. User-centric cell-free massive MIMO networks: a survey of opportunities, challenges and solutions.

IEEE Communications Surveys, Tutorials 2022; 24(1): 611–652.

Bindle, A, Gulati, T, Kumar, N. A detailed introduction of different beamforming techniques used in 5G. International Journal of Communication Systems 2021; 34(5): e4718

Björnson, E, Hoydis, J, Sanguinetti, L. Massive MIMO networks: spectral, energy, and hardware efficiency. Foundations and Trends® in Signal Processing 2017; 11(3–4): 154–655.

Borges D, Montezuma P, Dinis R, Beko, M. Massive MIMO techniques for 5g and beyond—opportunities and challenges. Electronics 2021; 10(14): Article 14.

Chataut, Robin, Robert Akl. Massive MIMO systems for 5g and beyond networks—overview, recent trends, challenges, and future research direction. Sensors 2020; 20(10) : 2753.

Dangi, Ramraj, Praveen Lalwani, Gaurav Choudhary, Ilsun You, Giovanni Pau. Study and investigation on 5G technology: a systematic review. Sensors 2021; 22(1): 26.

Dilli, R. Performance analysis of multi user massive MIMO hybrid beamforming systems at millimeter wave frequency bands. Wireless Networks 2022; 27(3): 1925–1939.

Elhoushy, Salah, Mohamed Ibrahim, Walaa Hamouda. Cell-free massive MIMO: a survey. ieee communications surveys , tutorials 2022; 24(1): 492–523.

Figueiredo. An Overview of Massive MIMO for 5G and 6G. Ieee Latin America Transactions 2022; 20(6): 931-940

Gani, A. Implementation of massive MIMO in 5g networks: strategy and technical studies in Indonesia. Indonesian Journal of Advanced Research 2023; 2(3): 189–200.

Guo, Jiajia, Chao Kai Wen, Shi Jin, Geoffrey Ye Li. Overview of Deep learning-based csi feedBack in massive MIMO systems. IEEE Transactions on Communications 2022; 70(12): 8017–8045.

Hamid, Shahid, Shakti Raj Chopra, Akhil Gupta, Sudeep Tanwar, Bogdan Cristian Florea, Dragos Daniel Taralunga, Osama Alfarraj, Ahmed M. Shehata. Hybrid beamforming in massive MIMO for next-generation communication technology. Sensors 2023; 23(16): Article 16.

Hojatian, Hamed, Jeremy Nadal, Jean Francois Frigon, Francois Leduc Primeau. Unsupervised deep learning for massive MIMO hybrid beamforming. IEEE Transactions on Wireless Communications 2021; 20(11): 7086–7099.

Hussein, Abdirahman Abdikarim, Didem Kıvanç Türeli. Hybrid beamforming for multi user massive MIMO systems. Orclever Proceedings of Research and Development 2023; 2(1): 50–58.

Kassam, Joumana, Manar Miri, Roberto Magueta, Daniel Castanheira, Pedro Pedrosa, Adao Silva, Rui Dinis, Atilio Gameiro. Two-step multiuser equalization for hybrid mmwave massive MIMO GFDM systems 2020. Electronics; 9(8): 1220.

Kebede, Tewelgn, Yihenew Wondie, Johannes Steinbrunn, Hilau Belay Kassa, Kevin T. Kornegay. Precoding and beamforming techniques in mmwave-massive MIMO: performance assessment 2022. IEEE Accesses; 10: 16365–16387.

Khwandah, Sinan A, John P Cosmas, Pavlos I Lazaridis, Zaharias D Zaharis, Ioannis P Chochliouros Massive MIMO systems for 5g communications. Wireless Personal Communications 2021; 120(3): 2101–2115.

Li, Wengang, Wang Yang, Liuyan Yang, Hailiang Xiong, Yilong Hui. Hybrid beamforming for millimeter wave systems using the mmse criterion. IEEE Transactions on Communications 2019; 67(5): 3693–3708.

Li, Wengang, Wang Yang, Liuyan Yang, Hailiang Xiong, Yilong Hui. Bidirectional positioning assisted hybrid beamforming for massive MIMO systems. IEEE Transactions on Communications 2021; 69(5): 3367–3378.

Marzetta and Thomas L. Massive MIMO: an introduction 2015. Bell Labs Technical Journal, 20, 11–22.

Nguyen, L. D, Tuan, H. D, Duong, T. Q, , Poor, H. V. Multi-user regularized zero-forcing beamforming. IEEE Transactions on Signal Processing 2019; 67(11): 2839–2853.

Payami, Sohail, Mathini Sellathurai, Konstantinos Nikitopoulos . Low-complexity hybrid beamforming for massive MIMO systems in frequency-selective channels. IEEE Access 2019; 7: 36195–36206.

Putra, F. P. E, Riski, M, Yahya, M. S, , Ramadhan, M. H. Mengenal teknologi jaringan nirkabel terbaru teknologi 5g. Jurnal Sistim Informasi dan Teknologi 2023; 5(2): 167.

Rezaei, F, Tadaion, A. multi-layer beamforming in uplink/downlink massive MIMO systems with multi-antenna users. Signal Processing 2019; 164: 58–66.

Sheemar, C. K, Thomas, C. K, Slock, D. Practical hybrid beamforming for millimeter wave massive MIMO full duplex with limited dynamic range. IEEE Open Journal of the Communications Society 2022; 3: 127–143.

Singh, A, Joshi, S. A survey on hybrid beamforming in mmwave massive MIMO system. Journal of Scientific Research 2021; 65(01): 201–213.

Trikolas, T, Sungkowo, A, Al Hakim, R. R, , Jaenul, A. Kelebihan, kekurangan, peluang teknologi 5g di indonesia. INSOLOGI: Jurnal Sains dan Teknologi 2022; 1(1): 43–49.

Usman, U. K, , Irwan, M. A. Key teknology 5g mmwave, small cell and massive MIMO. Seminar Inovasi dan Aplikasi Teknnologi Di Industri 2019; 5(4): 65.

Zhang, J, Yu, Xianghao, Letaief, Khaled B. Hybrid beamforming for 5g and beyond millimeter-wave systems: a holistic view. IEEE Open Journal of the Communications Society 2020; 1; 77–91.