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Bit Error Rate (BER) Performance of Hybrid Beamforming for mmWave in 5G Massive MIMO Systems

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Abstract

mmWave massive MIMO is a promising technology for enhancing overall network performance in 5G and beyond 5G. Beamforming is employed in massive MIMO systems to spatially direct the transmitted signal toward intended users while suppressing interference. While analogue beamforming (ABF) offers a simpler signal implementation, its performance is inferior to that of fully digital beamforming (DBF). To overcome these issues, hybrid beamforming (HBF) is proposed to balance performance and hardware efficiency by combining ABF and DBF. The objective of the project is to develop a 5G mmWave massive MIMO system with hybrid beamforming that employs Joint Spatial Division Multiplexing with Per-Group Processing (JSDM-PGP). Next, the investigation of the effects of the number of transmit antennas in the multi-user system on overall performance. Finally, the system performance is measured in terms of bit error rate (BER). Results obtained using the JSDM-PGP technique indicate that increasing the number of transmit antennas from 128 to 512 leads to a noticeable reduction of 19.51% for BER. In addition, the proposed JSDM-PGP scheme is benchmarked against JSDM-JGP to assess the relative improvements in BER under different transmit antenna configurations. For future work, this study can be extended to more realistic mmWave communication scenarios by considering user mobility, dynamic blockage, imperfect CSI, adaptive bandwidth and power allocation, to further evaluate the robustness and practical suitability of JSDM-PGP and JSDM-JGP in next-generation wireless networks.

1. Introduction

Millimetre-wave (mmWave) massive multiple-input multiple-output (MIMO) technology has emerged as a key enabler for 5G and beyond wireless communication systems due to its ability to provide large bandwidth and support high data-rate services. However, mmWave signals suffer from severe path loss and signal attenuation, particularly in non-line-of-sight environments, posing significant challenges for reliable transmission [1]. To overcome these limitations, massive MIMO combined with advanced beamforming techniques is employed to enhance signal directivity, improve link reliability, and mitigate interference in multi-user scenarios.

Fully digital beamforming (DBF) offers high performance but requires a dedicated radio-frequency (RF) chain for each antenna element, resulting in excessive hardware complexity and power consumption that limit its practical deployment in large-scale mmWave systems [2]. In contrast, analogue beamforming (ABF) provides a simpler implementation but lacks the flexibility required for multi-user transmission. Hybrid beamforming (HBF), which integrates ABF and DBF, has therefore been proposed as a practical compromise that balances performance and hardware efficiency by reducing the number of RF chains while maintaining acceptable beamforming capability [3][4][5].

In multi-user mmWave massive MIMO systems, effective interference management is critical to achieving reliable communication [6]. Joint Spatial Division Multiplexing (JSDM) has been introduced as an efficient user grouping and precoding framework that exploits long-term channel statistics to reduce channel state information (CSI) feedback and computational complexity. Two main JSDM processing strategies are commonly used: Per-Group Processing (PGP) and Joint Group Processing (JGP). JSDM-PGP processes each user group independently, offering lower complexity and improved scalability, whereas JSDM-JGP jointly processes all user groups to achieve better interference suppression at the cost of increased computational overhead [7].

Despite extensive studies on HBF and JSDM, comparative analysis of JSDM-PGP and JSDM-JGP under varying massive MIMO antenna configurations in mmWave environments remains limited. Furthermore, the impact of increasing the number of transmit antennas, N_t on system performance metrics for bit error rate (BER) has not been sufficiently investigated within a unified simulation framework. Therefore, this study develops a 5G mmWave massive MIMO system employing HBF with JSDM-PGP and evaluates the effect of transmit antenna scaling on system performance.

This study aims to (1) develop a 5G mmWave massive MIMO system with HBF that employs JSDM with PGP, (2) investigate the effects of the number of transmit antennas, N_t used in the multi-user system, on the overall performance, and (3) evaluate system performance in terms of BER compared with JSDM-JGP.

2. System Model and Methodology

This section describes the system architecture, channel assumptions, processing schemes, system validation and performance metric evaluation used to evaluate the performance of HBF in a multi-user mmWave massive MIMO system. The proposed framework is implemented using simulation to compare the performance of JSDM with PGP and JGP.

2.1 System Architecture

A downlink multi-user mmWave massive MIMO system is considered, where a base station (BS) equipped with a large-scale uniform linear array (ULA) serves multiple user equipment (UE) simultaneously. HBF is employed at the BS, consisting of an ABF stage followed by a digital baseband precoder as illustrated in Fig. 1. This architecture significantly reduces the number of RF chains required compared to a fully DBF system, while maintaining sufficient spatial multiplexing capability. Users are grouped based on their spatial channel characteristics, and JSDM is applied to manage inter-user interference. The system supports multiple data streams per user, and downlink transmission is performed over an mmWave channel using orthogonal frequency-division multiplexing (OFDM). The BS transmits a total of 16 data streams, distributed to UE1-UE5, each receiving 2, 4, 3, 4, and 3 streams, respectively. The UEs are positioned at varying distances from the BS, with UE1 located nearest and UE4 positioned at the farthest distance, as illustrated in Fig. 2.

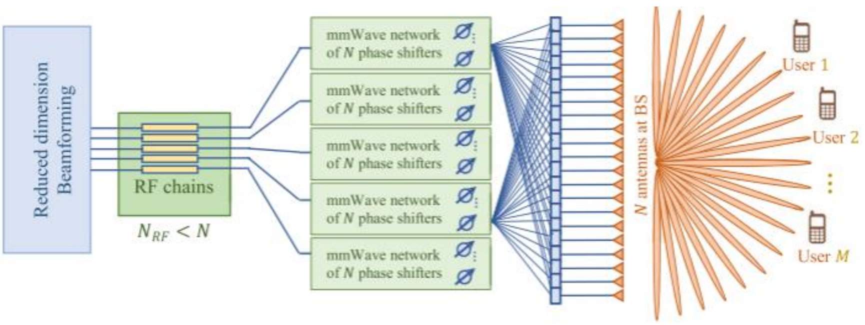

Fig. 1 *Hybrid beamforming [8]*

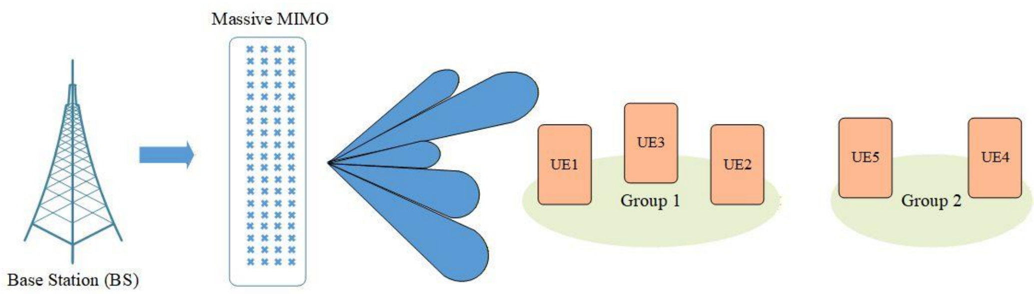

Fig. 2 *System topology of the multi-user mmWave massive MIMO system*

2.2 Channel and Simulation Parameters

The mmWave propagation environment is modelled using a scattering-based channel model to reflect the directional nature of mmWave communication. Perfect CSI at the BS is assumed to isolate the effects of beamforming and precoding strategies on system performance. To investigate the performance of BER in terms of each user, total network and antenna configurations, key simulation parameters, including carrier frequency, noise figure, number of UEs, spatial stream allocation, and antenna configurations, are summarised in Table 1.

Table 1 *Simulation parameters for BER evaluation*

Parameter	Value
Carrier frequency	28GHz
Channel model	Scattering
Number of scatterers	50
Noise figure	6 dB
Total data streams	16
Transmit antenna, N_t	128, 256 and 512
Users, UE	5
Beamforming technique	JSDM-PGP
CSI	Perfect CSI
Array geometry	ULA

Each user in the system is characterised by individual parameters, including spatial location, group assignment, number of data streams, receive antenna configuration, and channel conditions, to reflect realistic user diversity in a multi-user network. Table 2 summarises the UE configuration employed in the simulation by presenting the user grouping, allocated spatial streams, and corresponding distances from the base station. The configuration follows the previously defined network topology in Fig. 2 and is designed to represent realistic user distribution and stream allocation in a multi-user mmWave massive MIMO environment.

Table 2 *UE Configuration*

UE	Group	Number of spatial streams allocated	Distance from BS (m)
User 1	1	2	493.8
User 2	1	4	520
User 3	1	3	516.6
User 4	2	4	782.5
User 5	2	3	780.7

The configuration follows the previously defined network topology in Fig. 2 and is designed to represent a realistic user distribution and stream allocation in a multi-user mmWave massive MIMO environment.

2.3 JSDM Processing Schemes

JSDM is adopted in this work to enable efficient multi-user transmission in a mmWave MIMO system employing HBF. By exploiting long-term channel statistics, JSDM partitions UEs into spatially separable groups, allowing the BS to reduce processing complexity while supporting multiple spatial streams. This grouping strategy facilitates scalable precoding design and mitigates inter-user interference in large antenna systems. Two JSDM processing approaches are considered: PGP and JGP. In PGP, digital precoding is performed independently for each UE group, thereby reducing computational complexity and improving scalability. In contrast, JGP jointly designs the digital precoder across all UE groups, enabling more effective interference suppression at the cost of increased processing overhead. Both approaches share the same RF precoder, ensuring a fair comparison under identical HBF configurations. The effectiveness of the JSDM framework is evaluated using BER as the primary performance metric. By comparing PGP and JGP under varying SNR levels and transmit antenna configurations, the trade-off between BER performance and processing complexity in JSDM-based HBF MIMO systems is systematically assessed.

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2.4 System Validation

The developed mmWave MIMO system with HBF and JSDM was validated to ensure the correctness and reliability of the simulation framework. Validation was performed by verifying fundamental BER trends with respect to SNR, where BER consistently decreases as SNR increases, indicating proper signal detection behaviour. In addition, increasing the number of BS transmit antennas resulted in improved BER performance, confirming the expected beamforming gain in large-scale MIMO systems. The relative performance between PGP and JGP was also examined to ensure consistency with established JSDM behaviour. JGP consistently achieved lower BER than PGP, particularly at higher SNR levels, due to its more effective joint interference suppression. These observations confirm that the implemented system model and processing schemes operate as intended, providing a valid basis for subsequent performance evaluation.

3. Result and Discussion

This section presents the BER performance of the proposed mmWave MIMO system employing HBF with JSDM. BER is a critical metric that reflects the reliability of data transmission, particularly in noise- and interference-limited wireless systems. The analysis focuses on overall network BER performance, per-user BER, and the impact of different transmit antenna configurations. This metric provides a clear and practical basis for comparing PGP and JGP schemes.

3.1 Overall Network BER Performance

The overall network BER performance is shown in Fig. 3 by combining the error results from all users. The comparison aims to evaluate how different group processing schemes influence error performance across varying SNR levels.

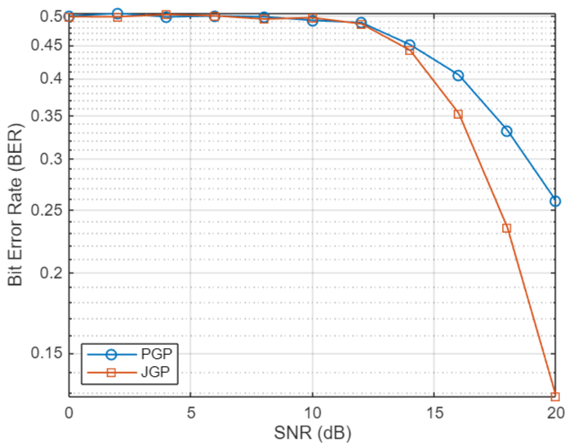

Fig. 3 *BER versus SNR for JSDM-PGP and JSDM-JGP*

At low SNR levels between 0 dB and 10 dB, both PGP and JGP exhibit high BER values of around 0.5, indicating that system performance is mainly limited by noise. In this region, both schemes show similar performance, as beamforming and interference suppression have a limited impact. For example, at 2 dB, PGP records a BER of 0.505, while JGP achieves a slightly lower BER of 0.499, corresponding to a 1.21% reduction.

As the SNR increases beyond 12 dB, a clearer performance difference emerges. At 14 dB, the BER of PGP decreases to 0.451, while JGP achieves a lower BER of 0.442, representing a 1.96% improvement. From 4 dB to 14 dB, the BER reduction is 10.59% for PGP and 11.27% for JGP, indicating that JGP benefits more from increasing SNR. At higher SNR levels between 15 dB and 20 dB, JGP shows a much steeper BER reduction. At 20 dB, JGP reaches a BER of approximately 0.10, whereas PGP only achieves about 0.26. This performance advantage is due to JGP's ability to jointly suppress both intra-group and inter-group interference, while PGP processes each group independently, leaving residual interference.

Although JGP consistently provides lower BER, PGP offers lower computational complexity and remains a practical solution for scenarios where system complexity and implementation constraints are important considerations.

3.2 Per-User BER Performance

Fig. 4 shows the per-user BER performance versus SNR for the PGP scheme. The system supports a total of 16 spatial streams, with 2, 4, 3, 4, and 3 streams allocated to User 1 through User 5, respectively. Users are divided into two groups, where Group 1 (User 1 to User 3) is located within 550 m from the BS, while Group 2 (User 4 to

User 5) is placed at a farther distance of 800 m. Overall, all users exhibit a decreasing BER trend as SNR increases, indicating improved detection performance with better signal quality. At low SNR values between 0 dB and 8 dB, the BER for all users remains close to 0.5, showing that performance is mainly limited by noise. As SNR increases beyond 10 dB, differences in per-user performance become more noticeable.

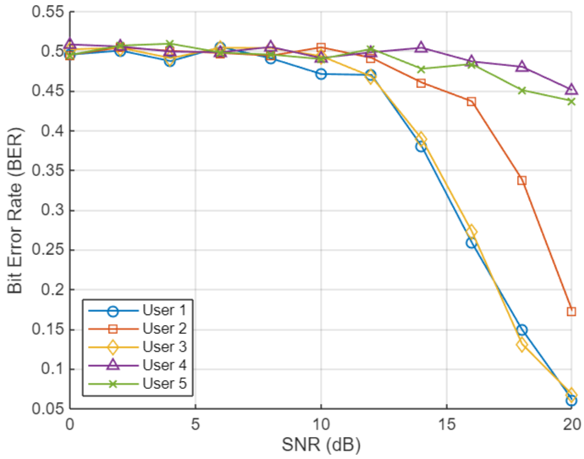

Fig. 4 *Per-user BER vs SNR (JSDM-PGP)*

Within Group 1, User 1 and User 3 achieve the lowest BER, dropping below 0.1 at high SNR, while User 2 records a higher BER of around 0.17. This difference is mainly due to User 2 being located farther from the BS within the group and having a higher number of allocated spatial streams, which increases its sensitivity to residual inter-user interference under PGP processing. In contrast, the closer proximity and stream allocation of User 1 and User 3 allow them to benefit more effectively from increased SNR.

For Group 2, both User 4 and User 5 show slower BER improvement as SNR increases, with BER values remaining relatively high at approximately 0.4 even at 20 dB. This behaviour is primarily caused by their greater distance from the BS, leading to higher path loss and weaker received signals. Under PGP processing, interference within the group is only partially suppressed, causing residual inter-user interference to dominate for users with poorer channel conditions and limiting BER improvement at high SNR.

3.3 Impact of Transmit Antenna Configuration on BER

Fig. 5 compares the BER performance versus SNR for different numbers of transmit antennas, $N_t = 128, 256$ and 512, under both PGP and JGP schemes. At low SNR values between 0 dB and 10 dB, BER remains high and nearly constant for all antenna configurations, indicating that system performance in this region is mainly limited by noise. As the SNR increases beyond 10 dB, a rapid reduction in BER is observed, showing that improved signal quality allows beamforming to become more effective.

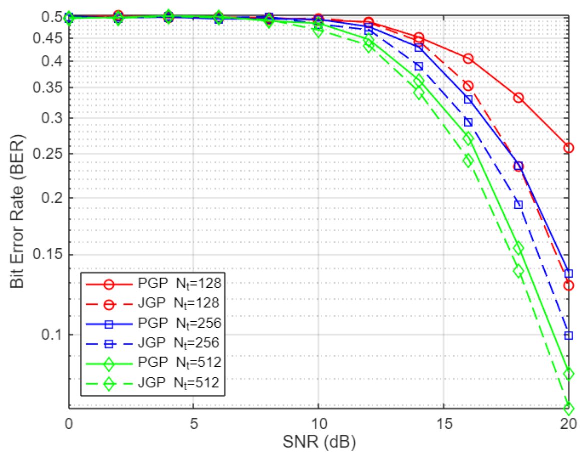

Fig. 5 *BER vs SNR (Different* $\mathbf{N_t}$*: (JSDM-PGP vs JSDM-JGP)*

Increasing the number of transmit antennas significantly improves BER performance, especially at higher SNR levels. At 14 dB, the BER of PGP decreases from 0.451 with 128 antennas to 0.429 with 256 antennas, and further to 0.363 with 512 antennas, confirming that larger antenna arrays provide better beamforming gain and spatial resolution. Across all antenna configurations, JGP consistently achieves lower BER than PGP. At 4 dB, the BER difference between PGP (0.504) and JGP (0.502) is small, corresponding to a 0.36% reduction, indicating noise-limited performance. However, at 14 dB, JGP achieves a BER of 0.342 compared to 0.363 for PGP, resulting in a 5.79% improvement. From 4 dB to 14 dB, the BER reduction is 27.90% for PGP and 31.83% for JGP, indicating that JGP benefits more from increased SNR because of its stronger interference suppression capability as noise becomes less dominant.

4. Conclusion

This study aimed to develop and evaluate a 5G mmWave massive MIMO system using HBF with JSDM-PGP. A multi-user system was successfully built by combining ABF and DBF, assuming users are separated into different groups and perfect CSI is applied at the transmitter and receiver. The developed system assumes spatially separable user groups and perfect channel state information, enabling a two-stage beamforming process that reduces computational complexity while maintaining effective spatial multiplexing. The simulation framework provides a practical and scalable representation of JSDM-PGP for mmWave massive MIMO systems. The results show that increasing the number of transmit antennas from 128 to 256 and 512 clearly reduces BER, as larger antenna arrays can focus signals more accurately toward users. When comparing the two processing schemes, JGP achieves lower BER than PGP, especially at higher SNR values, because it reduces interference more effectively. However, PGP still provides acceptable BER performance with lower system complexity, making it suitable for practical large-scale systems.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Shafiah Aienn Ahmad Ridauddin, Norshidah Katiran;* ***data collection:*** *Shafiah Aienn Ahmad Ridauddin;* ***analysis and interpretation of results:*** *Shafiah Aienn Ahmad Ridauddin, Norshidah Katiran;* ***draft manuscript preparation:*** *Shafiah Aienn Ahmad Ridauddin, Norshidah Katiran. All authors reviewed the results and approved the final version of the manuscript.*

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