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Performance of 5G mmWave Massive MIMO System with Hybrid Beamforming

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Abstract

Massive MIMO integrated with beamforming constitutes a fundamental physical layer mechanism in 5G, leveraging large-scale antenna arrays to realize spatial multiplexing gains and array gain for enhanced spectral efficiency (SE), particularly in high-frequency (mmWave) bands suffering from severe path loss. Hybrid beamforming (HBF) has the potential to reduce cost and power consumption compared to fully digital beamforming (DBF). This paper investigates the effectiveness of hybrid beamforming integrated with Joint Spatial Division Multiplexing using Joint Group Processing (JSDM-JGP) in reducing the number of required radio frequency (RF) chains. A comparative analysis between JSDM-JGP and DBF is conducted to examine the trade-offs between reduced system complexity and potential performance enhancements. Our numerical results demonstrate that HBF with JSDM-JGP can significantly improve system energy efficiency (EE) performance with a lower complexity than DBF system. On the other hand, the spectral efficiency (SE) of HBF is slightly lower compared to DBF. In terms of bit error rate (BER), both HDF and DBF show extremely similar results.

1. Introduction

The fifth generation (5G) technology was developed as a result of the rapid expansion of wireless communication systems. It is anticipated to satisfy the growing needs for ultra-high throughput, low latency, high user density, and improved dependability. The use of millimeter-wave (mmWave) frequency bands is one of the main factors enabling 5G because of its high bandwidth availability, which greatly increases data speeds. On the other hand, mmWave signals have limited penetration, narrow coverage areas, and significant route loss. Massive MIMO (Multiple Input Multiple Output) and beamforming technologies are crucial for getting over these restrictions [1]-[5]. Through the deployment of large-scale antenna arrays, massive MIMO increases network capacity by allowing base stations to serve multiple users concurrently, boosting energy efficiency (EE) and spectral efficiency (SE) [3]-[7].

Despite the benefits, DBF has practical drawbacks because of its high hardware complexity and power consumption, particularly at mmWave frequencies when a large number of RF chains are needed [5]-[8]. By integrating analog and digital processing, hybrid beamforming (HBF) is suggested as a workable method that successfully lowers the number of RF chains without significantly sacrificing performance. Additionally, by grouping users according to their spatial channel correlations and carrying out group-wise precoding, Joint Spatial Division Multiplexing (JSDM) improves hybrid beamforming [9]. This method is appropriate for dense 5G networks because it eliminates interference, promotes virtual sectorization, and lowers channel state information

(CSI) overhead. However, there are still issues with striking a balance between SE, EE, and Bit Error Rate (BER), particularly in situations with dense user populations and constrained RF chain resources [10].

Therefore, by assessing the performance of a 5G mmWave Massive MIMO system using hybrid beamforming combined with JSDM, this work seeks to overcome these issues. The study aims to: (1) produce a system model that uses JSDM and HBF for virtual sectorization and user grouping; (2) investigate the connection between the number of RF chains and system performance in terms of SE and EE; and (3) use MATLAB simulations to assess and contrast the system's SE, EE and BER performance against digital beamforming. The viability and effectiveness of utilizing HBF and JSDM for next-generation wireless communication systems will be clarified by these studies.

2. Methodology

This section describes the design framework and simulation methodology used to assess a hybrid beamforming architecture with Joint Spatial Division Multiplexing (JSDM) for virtual sectorization in a millimeter-wave (mmWave) massive MIMO system. Fig. 1 represents the research flowchart process is divided into some phases. Purpose of this flowchart is to develop, validate and optimize a 5G mmWave massive MIMO system with hybrid beamforming to address real-world challenges such as high path loss, user cluster and SE and EE. This provides a framework for looking at the performance of advanced wireless communication in the research.

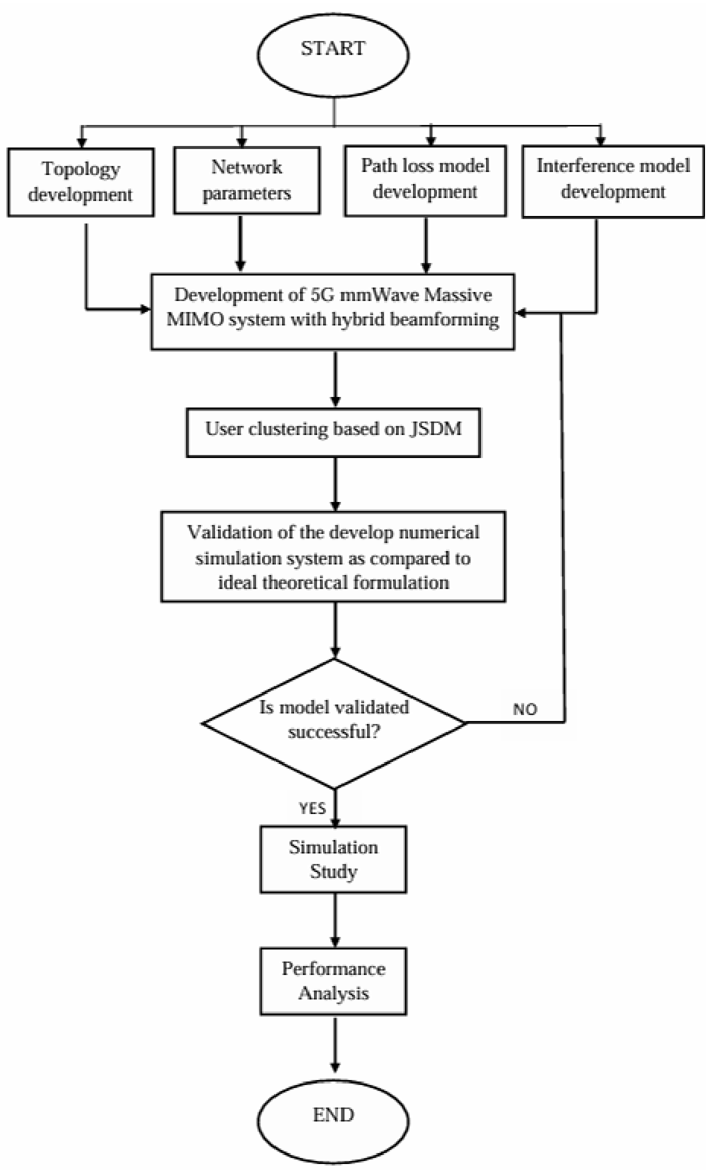

Fig. 1 *Flowchart of the research*

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2.1 Flowchart of Research Design

As shown in Fig. 1, the flow chart starts by the foundation steps including the formulation of network topology, the specifications of the network parameter, the development of the path loss model and the development of the impact model. These procedures are part of the 5G communication design. Topology formation specifies the spatial and structural organization of the network, whereas network parameters prescribe the main modulation. Between-signal degradation factors of environment and signal are modeled by path loss and interference models to have a reasonable consideration for system behavior. These factors are key to realize the function of the 5G mmWave communication system in both theory and practice.

The 5G mmWave massive MIMO system using hybrid beamforming is the crucial of the project. Once is ready, JSDM is further utilized to cluster users so as to maximize resource allocation and performance. Before going further, the system is validated, such that the numerical results match with an ideal theoretical formulation. A branch is then added to evaluate whether the validation is successful. When not, the system is enhanced and tuned. Once verified, the system is simulated to be tested under different situations, and a performance analysis is conducted. Finally, the model is analyzed and validated based on key performance metrics such as SE, EE and BER, such that the system satisfies the expected performance of validation stage. Overall, these stages form a complete framework to fine-tune and validate a reliable 5G mmWave massive MIMO system.

2.2 System Model

A massive MIMO network model with spatial user grouping for hybrid beamforming in 5G mmWave systems is illustrated in Fig. 2. In topology development, users and antennas are arranged in such pattern that spatial channel information can be exploited for system performance improvement. JSDM is based on clustering users according to their channel covariances, comparable spatial directions or angular spreads. This clustering of UEs enables the use of a two-step beamforming scheme, a pre-beamforming step is performed in which cross-cluster interference is suppressed with the help of long-term channel statistics, and then a precoder optimum for eliminating intra-cluster interference is found with instantaneous channel state information (CSI). By doing so, the base station can be equipped with a large antenna array in the topology and meet the need of several user groups located at different angular sectors for the base station, which is conducive to the spatial resource allocation and mitigates the requirement of the full CSI, useful for the massive MIMO system at mmWave frequency.

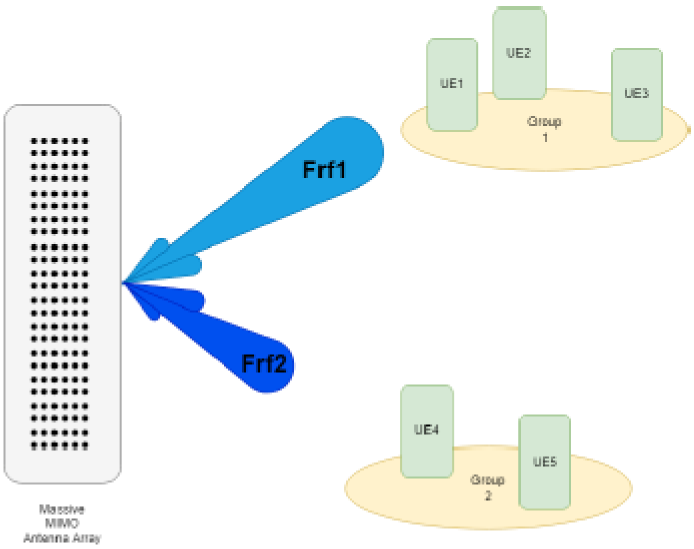

Fig. 2 *Network topology*

The former referred to as being in proximity to the mobile terminal are clumped together into cluster of users Group 1 and Group 2 having similar characteristics of the channel covariance. The base station can employ group dependent hybrid precoding techniques, as each group is associated with a dedicated RF chain (Frf1 and Frf2). The joint use of this partitioning should reduce inter-group interference and permit simple digital baseband processing due to the alignment with the essential idea of Joint Spatial Division and Multiplexing (JSDM). JSDM exploits that the users within the cell are spatially clustered and combining these clusters, to form virtual sectors by RF analog beamforming to these groups. The spatial covariance matrices of the groups are accordingly associated with the spatial direction of the groups relative to the base station antenna array. These matrices are calculated based on the channel estimates collected across the sounding signals and the analogue RF beams are formed based on these matrices. These beams concentrate transmitted energy into the corresponding groups and reduce intergroup interference.

2.3 Network Parameter Specifications

A downlink massive MIMO system operating at mmWave frequencies is proposed, with the base station (BS) using a uniform linear array (ULA) with 64 transmit antennas. The user devices are spatially classified based on angular correlation and covariance data. Three unique user groups are developed, each occupying their own spatial sectors, allowing efficient use of the JSDM approach. Table 1 is a network parameter setup.

Table 1 *Simulation parameters*

Parameter(s)	Specification(s)
Carrier Frequency	28 GHz
Sampling Rate	100 MHz
Noise Figure	8 dB
Data Streams per User	[4, 3, 2, 4, 3]
BS Transmit Antennas	128
Number of RF chains	16
JSDM Type	Joint Group Processing (JGP)

For this research on the 5G mmWave massive MIMO system with HBF, the system parameter specification subtopic concentrates on parameters that are important for an evaluation of performance. Using JSDM, can improve the performance of channel separability and user grouping that are important requirements in terms of frequency band, HBF architecture and number of antennas. These characteristics are tuned to strike an appropriate balance between hardware complexity, SE, EE and energy consumption as shown in Fig. 3.

```
prm.fc = 28e9;                % 28 GHz system
prm.chanSRate = 100e6;        % Channel sampling rate
prm.ChanType = 'MIMO';        % Channel options:'MIMO'
prm.NFig = 8;                 % Noise figure (5-10 dB)
prm.nRays = 500;              % Number of rays for Frf, Fbb partitioning

prm.bitsPerSubCarrier = 2;          % 2: QPSK, 4: 16QAM, 6: 64QAM, 8: 256QAM
prm.numDataSymbols = 10;            % Number of OFDM data symbols

prm.numSTSVec = [4 3 2 4 3];        % Number of independent data streams per user
prm.numSTS    = sum(prm.numSTSVec); % Must be a power of 2
prm.numTx     = prm.numSTS*8;       % Number of BS transmit antennas (power of 2)
prm.groups    = [1 1 1 2 2];        % Describes which users are in which groups
prm.jsdmType = 'JGP';               % JSDM option
```

Fig. 3 *Network parameters setup using MATLAB coding*

2.4 Validation of System Model

The performance validation of the 5G mmWave Massive MIMO system with hybrid beamforming is performed through an analysis of Bit Error Rate (BER) versus Signal to Noise Ratio (SNR). This procedure verifies the ability of a system to transmit information in the presence of noise and interference. Through simulating various SNR values and recording BER values therefrom, the effectiveness of the hybrid beamforming method in improving the quality of transmission quality is evaluated in high-frequency mmWave. The lower BER for higher SNR values is the evidence of robustness and effective performance of the system against the channel impairments as shown in Fig. 4.

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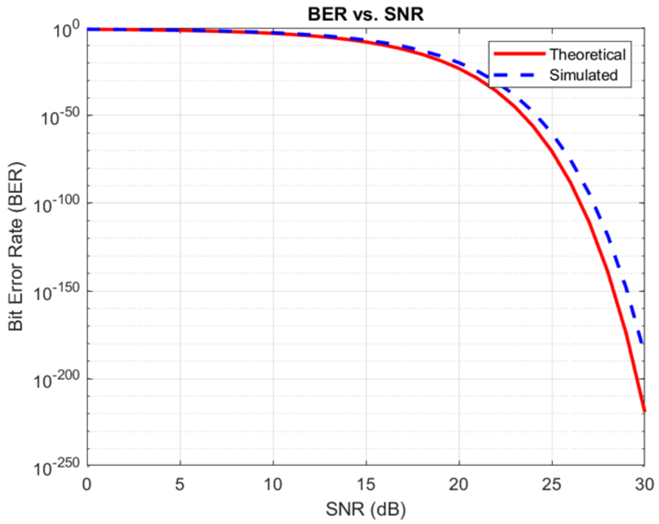

Fig. 4 *Validation for BER versus SNR (theoretical versus simulated)*

BER vs SNR in Fig. 4 shows the BER performance of a typical QPSK modulation scheme as function of the signal-to-noise ratio (SNR). Two curves are shown, one for the theoretical BER performance with ideal condition and the other one for the simulated BER including real system impairments.

2.5 Performance Metrics

Performance metrics are measurable parameters that evaluate the functionality and efficiency in a communication system, these metrics are important for evaluating the performance. This includes differences in high data rates, SE and EE which measures how effectively the spectrum is utilized. By analysing these metrics, we can optimize the system configurations and see the impact of wireless communication in HBF and JSDM on performance that guides the development of high and sustainable network performance.

2.5.1 Network Spectrum Efficiency

Spectrum Efficiency (SE) function is to measure the value of data transmitted per bandwidth and time. But usually expressed in bits per second per hertz (bps/Hz). This shows how effectively the frequency spectrum is needed by the 5G network. We can improve SE in HBF in 5G mmWave massive MIMO system by optimizing inter user interference with larger spatial multiplexing. SE can be evaluated by simulating the system with adjusting numbers of users, antenna array configurations and HBF that concentrates on how efficient the given bandwidth is used. This is the most important thing in a dense environment with high multi user demands that influence impacts of network SE performance and capability. Formula of network *SE* in Equation 1 as follows.

$$\text{Spectrum Efficiency, } SE = \text{Total Data Throughput (bps)} \,/\, \text{Total Bandwidth (Hz)} \quad (1)$$

2.5.2 Network Energy Efficiency

Network energy efficiency (EE) provides the amount of data transmitted per unit total power consumption. This is expressed in bits per joule (bps/J) that reflects how the performance of the system balances with power consumption. EE is a critical parameter to the high demands of massive MIMO and HBF techniques for the 5G communication network. Using HBF methods, reducing the number of RF chains compared to fully DBF using JSDM can simplify clusters of users that improve EE by optimizing power consumption usage. To simulate the system in EE, usually under various power constraints, HBF and antenna configurations. Differences of power consumption in subsystems such as RF chains and BS operation. Formula of network *EE* in Equation 2 as follows.

$$\text{Energy Efficiency, } EE = \text{Total Data Throughput (bps)} \,/\, \text{Total Power Consumption (W)} \quad (2)$$

2.5.3 Bit Error Rate

In the aspect of system performance analysis, especially in massive MIMO with hybrid beamforming systems, Bit Error Rate (BER) is also one of the most important performance metrics. BER is the likelihood that a bit gets improperly received given it was transmitted. In QPSK, as for each bit error performance is determined by how well the receiver can resolve the different phases, this is in turn affected by noise, fading, interference and channel degradation (whilst for mmWave frequencies path loss also comes into play). The following is a general formula for BER in Equation 3 [4].

$$BER = \text{The Number of Bits Received with Error} / \text{Total Transmitted Bits} \quad (3)$$

3. Results and Discussion

This section provides the performance results and analysis for the 5G mmWave massive MIMO system with the hybrid beamforming, covering the key performance metrics including the spectral efficiency (SE), energy efficiency (EE) and bit error rate (BER). The results are provided from MATLAB simulations and comparisons of hybrid vs. digital beamforming as well as an analysis of Joint Spatial Division Multiplexing (JSDM) processing strategies which is Joint Group Processing (JGP) and Per Group Processing (PGP).

3.1 Network Spectral Efficiency Comparison

From the simulation results in Fig. 5, it is observed that the DBF scheme generally achieves larger SE as it can make full use of the channel when there is dedicated RF chain at each antenna, leading to more accurate processing and multiplexing the signals. But it also needs much more hardware and power consumption. On the other hand, HBF provides a more practical and energy-efficient alternative by integrating analog and digital processing with much less RF chains. It is worth noting that, HBF may have lower SE when compared with DBF, but the difference is small under the optimal conditions, especially when the RF chains are enough. Thus, the results show that HBF can achieve a trade-off between spectral efficiency and system cost, which is attractive to 5G real implementation.

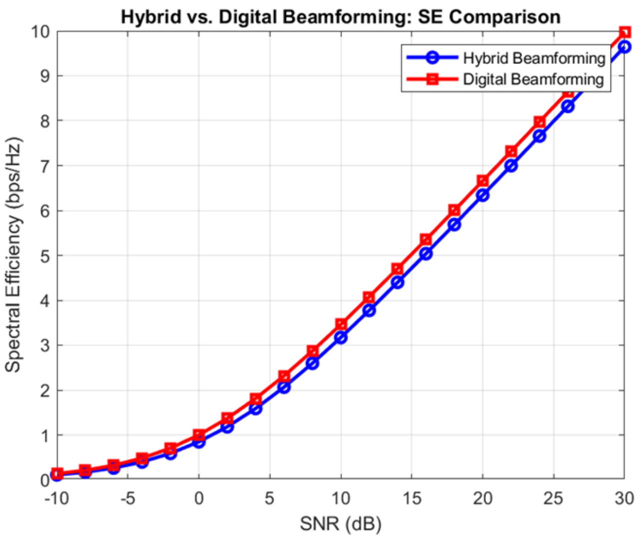

Fig. 5 *SE comparison for HBF and DBF*

The graph in Fig. 5 shows the x-axis value (SNR in dB) represents the signal strength, while its y-axis value (SE in bps/Hz) measures how effectively all bandwidth available gets used within a system. The two curves in this figure reflect the different links between spectral efficiency at various SNRs for hybrid vs. digital beamforming. Normally, because it can handle every signal purely in digital form and has overall RF chain resources fully distributed across the system then digital beamforming enjoys a higher SE. However, hybrid beamforming, which uses less RF chains but maintains competitiveness with respect to SE performance still striking a balance between hardware complexity and energy consumption for signal processing is another matter entirely.

3.1.1 SE Comparison with Cost and Hardware

Our numerical results show that SE of both DBF and HBF grows linearly in SNR, which implies that a higher SNR will lead to a higher data rate. Guided by its high-level digital signal processing capability, which allows more flexible and accurate control of the beam, DBF is generally observed to outperform HBF in SE. For example, at 10 dB = SNR, DBF has an optimum 3.4594 bits/s/Hz and HBF has an equal 3.1699, and at SNR = 30 dB, DBF has a peak of 9.9672, and HBF, 9.6457. With its lower hardware overhead, HBF is also very similarly performing to that of DBF, with a tiny performance discrepancy (often below 0.4 units SE). Yet this minimal difference of SE has proved to be relatively cheaper for HBF. Each of the individual peripherals, including DACs, ADCs, mixers and power amplifiers, at each antenna element in DBF must have its own RF chain. In the case of large systems like 5G base stations adopting 64 or 128 antennas, this leads to expensive hardware and high-power consumption. On the other hand, HBF employs fewer RF chains in conjunction with analogue phase shifters, which means that the number of power hungry and expensive circuits is remarkably decreased. For instance, an HBF system may for instance enable up to 75% less RF chains and hence reduce hardware costs by 50–70% and cooling/power needs. Hence, HBF provides a practical trade-off by preserving competitive SE with significant hardware complexity and cost reduction, which is highly practical for commercial deployment in cost-efficient scenarios.

3.2 Network Energy Efficiency Comparison

The Energy Efficiency (EE) difference comparison of HBF and DBF demonstrates the trade-off between the system performance and power consumption of the 5G mmWave Massive MIMO system. The simulation results suggest that even though DBF can achieve better spectral efficiency, its energy efficiency is much worse because of the high-power consumption of the dedicated RF chain and ADC of each antenna module. Owing to the topology loss, HBF can achieve significantly higher energy efficiency by a smaller number of RF chains while not losing much performance with the aid of the hybrid analog and digital precoding. This simplified hardware and circuit reduces the complexity and power of the circuit, resulting in significant energy saving. Collectively, our results indicate that HBF is an overall more power-efficient architecture than DBF, particularly for large antenna systems, which is suitable for green and energy-aware 5G network deployments as shown in Fig. 6.

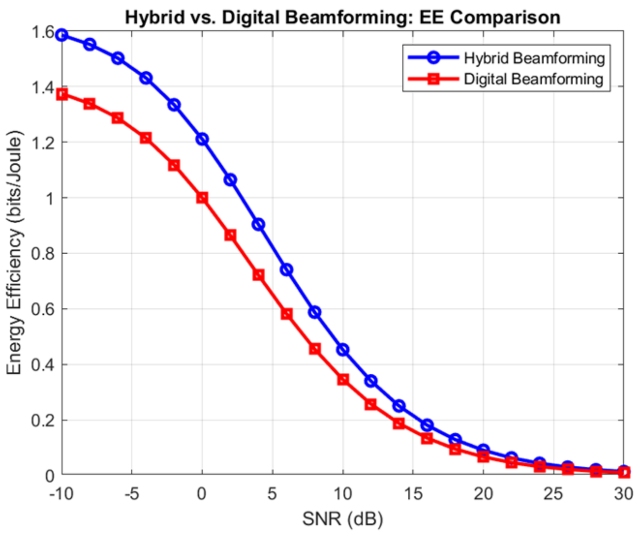

Fig. 6 *EE comparison for HBF and DBF*

On the Energy Efficiency (EE) versus Signal-to-Noise Ratio (SNR) diagram shown in Fig. 6, we can see how much efficiency your power produces at last when data exchange is going on and noise is not that high. EE, the number of bits transferred smoothly per joule of energy consumed, can be seen as the ratio between transmission efficiency and power output. The horizontal axis (SNR in dB) shows how strong the signal is, while the vertical axis (EE in bps/J) tells how effectively power is converted into useful data throughput. As might have expected, the graphs of SNR and EE are in an upward trend. The plot clearly shows that higher SNR indeed makes EE better, so a lower noise level is effectively utilizing more energy for transmission. This jump at moderate SNR values shows that optimization for beamforming has a significant and positive impact on EE while maintaining reliable transmission. Beyond a certain mid to high SNR level, the curve begins to slacken. This indicates that EE improvement cannot continue indefinitely. Power usage grows disproportionately with gains in spectral efficiency, so that adding more and more energy does not bring about very much greater EE.

3.2.1 EE Comparison with Cost and Hardware

Unlike SE, energy efficiency (EE) has a decreasing behaviour with respect to SNR for both types of beamforming. However, HBF also has substantially higher EE at all time points. For instance, at 0dB, EE for HBF is 1.2114 while for DBF, it is 1.0, and at 20dB, HBF obtains 0.09057 as opposed to 0.066582 for DBF. The performance loss spreads larger as SNR increases since DBF requires a full complement of RF chains and ADC/DAC components per antenna element, which results in higher power consumption as well as more hardware cost. However, HBF is able to save cost in terms of hardware complexity as it exploited less number of RF chains and phase shifters, hence has higher energy efficient and cost-effective. For example, in the case of a massive MIMO system with 128 antennas, DBF usually needs 128 RF chains while HBF probably needs just 8–16 chains, which can bring down the power consumption and hardware deployment by 60–80% or more. Consequently, HBF provides a reasonable trade-off: a bit large SE in exchange for much lower power consumption, and low cost, and simple hardware architecture, which is suitable for the 5G base stations and IoT.

3.3 Bit Error Rate Comparison

As the Signal-to-Noise Ratio (SNR) rises in a digital communication system, the Bit Error Rate (BER) should theoretically fall exponentially, particularly for modulation methods like QPSK. The formula describes this relationship, ½ x erfc (√SNR). This formula functions as a standard for anticipated performance and makes the assumption that the channel is optimal. Numerous bits are created and modulated in the simulation before being delivered over a noisy channel, where various SNR levels correspond to varied noise intensities. The empirical BER for each SNR value is calculated by counting the amount of bit errors that occur after the receiver demodulates the signals as shown Fig. 7.

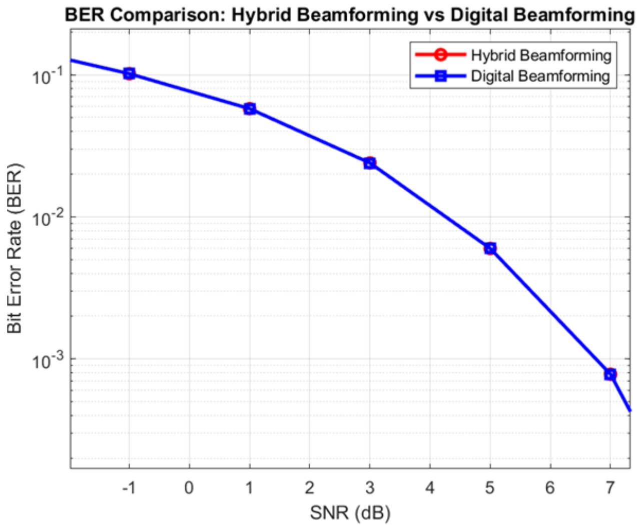

Fig. 7 *BER comparison for HBF and DBF*

Because both HBF and DBF aim to transmit the signal to the receiver as efficiently as possible, their BER curves are extremely similar. Assume that everything runs flawlessly in the simulation, with no errors or hardware issues. This indicates that the phase shifters and other analog components in HBF perform their functions on par with the full digital processing in DBF. Therefore, both approaches are capable of effectively focusing the signal energy, resulting in comparable error rates. In order to save money and power, HBF uses fewer digital chains in conjunction with analog components, whereas DBF uses a single digital chain for every antenna. However, having fewer chains doesn't significantly affect performance in this ideal simulation environment, particularly for simple signals like BPSK. Their BER results appear to be nearly identical as a result. Small hardware issues or noise may make HBF somewhat worse than DBF in real life, but these factors are not present in this simple simulation.

3.4 Equalised Symbol Constellation per Stream for JGP

JSDM-JGP demonstrates the enhanced system performance of the proposed precoding scheme by jointly grouping the users or the antenna elements for obtaining the global precoding designs over the array surface. This technique exploits global channel state information to obtain more efficient beam patterns, which provide higher spectral efficiency and lower bit error rates. It can be seen that JGP is superior to conventional and isolated precoding in particular dense users are placed and there is severe effect of inter-user interference. But with the price of higher complexity and signaling overhead because of centralized control. Generally, JGP has good performance regarding throughput and reliability when system resources are finely distributed.

The equalized symbol constellation of Joint Group Processing (JGP) is based on JGP then adopts equalized symbol constellation to illustrate the influence of JGP in JSDM on signal over multiple user groups of massive MIMO system in detail. Unlike Per-Group Processing (PGP), JGP optimizes beamforming over all groups, which leads more cooperative precoding to suppress inter-group interference. In the Fig. 8, can see that the symbols are well separated where each symbol received by user is matched with ideal QPSK positions. Such close packing explains that JGP can severely suppress the interference to achieve high sensitivity at the receiver. The structured constellation implies that joint beamforming is able to keep spatial separation among groups thus signal quality remains good and distortion is reduced. Therefore, JGP enables smoother transition between the virtual sectors, thereby boosting spectral efficiency and overall system robustness.

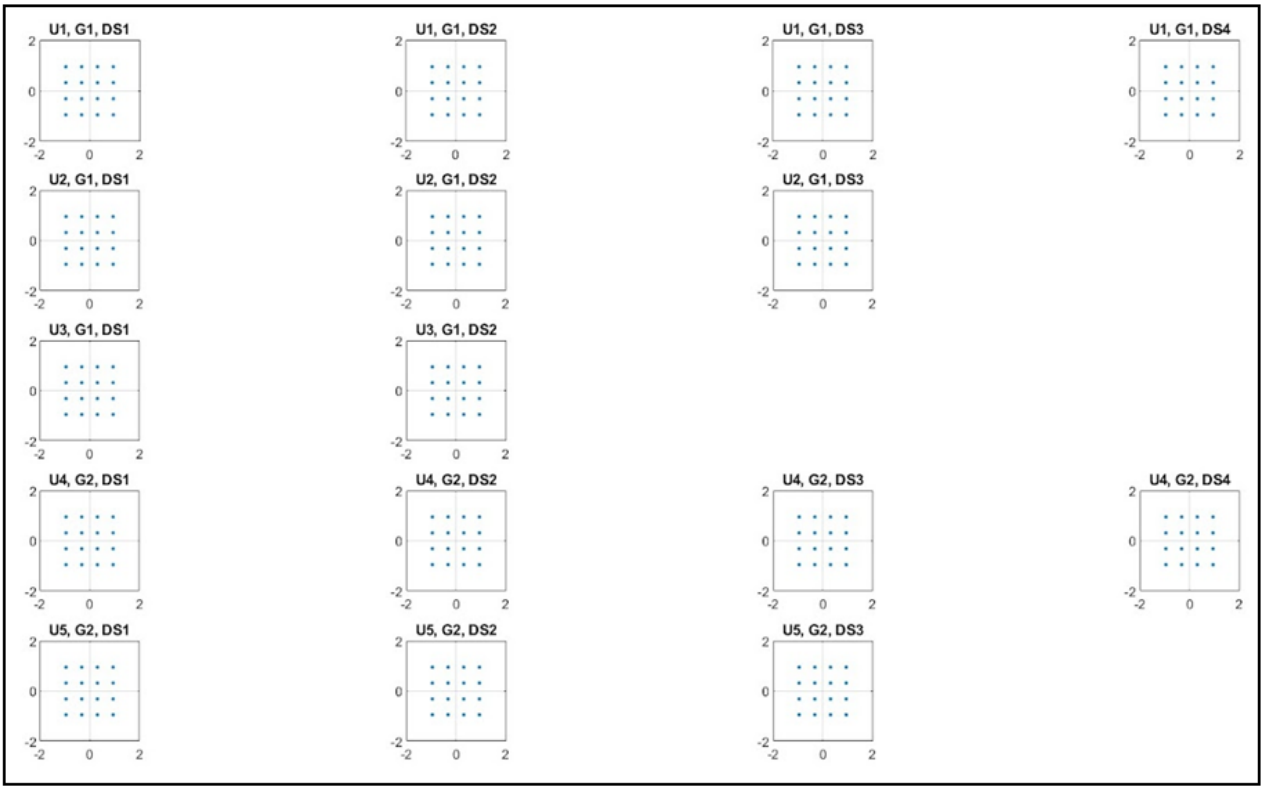

Fig. 8 *Symbol constellation per stream for JGP*

Group 1 is composed of users U1, U2, and U3, all members from Group 1 (G1) as illustrated in Fig. 8. If we look at their channel distributions over two data sets (DS1 and DS4), we can observe a clear similarity of the shape, the orientation and the concentration of the beamspace patterns. The signal energy of every user concentrates predominantly in the center, and has the same ranges along both axes, which indicates that they are sharing common or almost common angular domain channel characteristics. Such steadiness means that the users possibly have similar physical position or space spreading condition (in the same sector of base station coverage area). Due to their aforementioned similarity, one can process the group of users jointly, which is exactly what Joint Group Processing (JGP) tries to optimize, to jointly design beamforming across a group of users with correlated channels for the purpose of enhancing signal strength and interference rejection.

Fig. 8 shows that Users U4 and U5 are both members of G2 under group 2. Moreover, their channel responses between these two datasets are also stably similar to one another. As in the case of Group 1, the beamspace patterns U4 and U5 have nearly identical angular support and energy distributions, and are also clearly different from Group 1. This implies that, U4 and U5 see the channel from different spatial locations that may belong to a different cluster of users located somewhere else in the cell. The important thing to note here is that the data sets change, and yet U4 and U5 exhibit this common structure showing that the way they're grouped isn't random, or based on some non-physical channel properties. Similarity between the classes motivates us to group them under JGP so that a smarter and more coordinated beamforming can be imposed to jointly serve them but efficiently.

3.5 Equalised Symbol Constellation per Stream for PGP

A key concept in Joint Spatial Division and Multiplexing Per-Group Processing (JSDM-PGP) divides users into spatial groups according to their channel characteristics, allowing for effective multi-user MIMO (MU-MIMO) transmission. Pre-beamforming and PGP are the two stages of the beamforming process that make up the core concept of JSDM. During the initial phase, pre-beamforming uses the long-term channel covariance matrices of the users to construct semi-orthogonal or orthogonal spatial beams that divide various user groups. This makes it possible to treat each group as functioning in a nearly distinct spatial subspace by greatly reducing inter-group interference. Following group separation, the second stage, Per-Group Processing (PGP), manages multi-user interference and short-term channel fluctuations within each group as shown in Fig. 9.

During the PGP stage, the base station only uses standard MU-MIMO methods (such Dirty Paper Coding, MMSE, or Zero-Forcing) within the group and not for all system users. Because only a few users are processed at a time, this lowers the total computational complexity and channel feedback needs. PGP assumes that each group's users have comparable angular channel characteristics, but they may still interfere with one another. For this reason, accurate beamforming inside the group is required to isolate each group's distinct data streams. To conclude, we can see that the PGP approach can significantly enhance the spectrum efficiency and the system scalability while the high-dimensionality MIMO systems can serve a large number of users in parallel without losing system complexity. The DMMVSC partitions the problem into group-wise processing jobs based on channel statistics enabling practical systems such as 5G mmWave communications having massive MIMO.

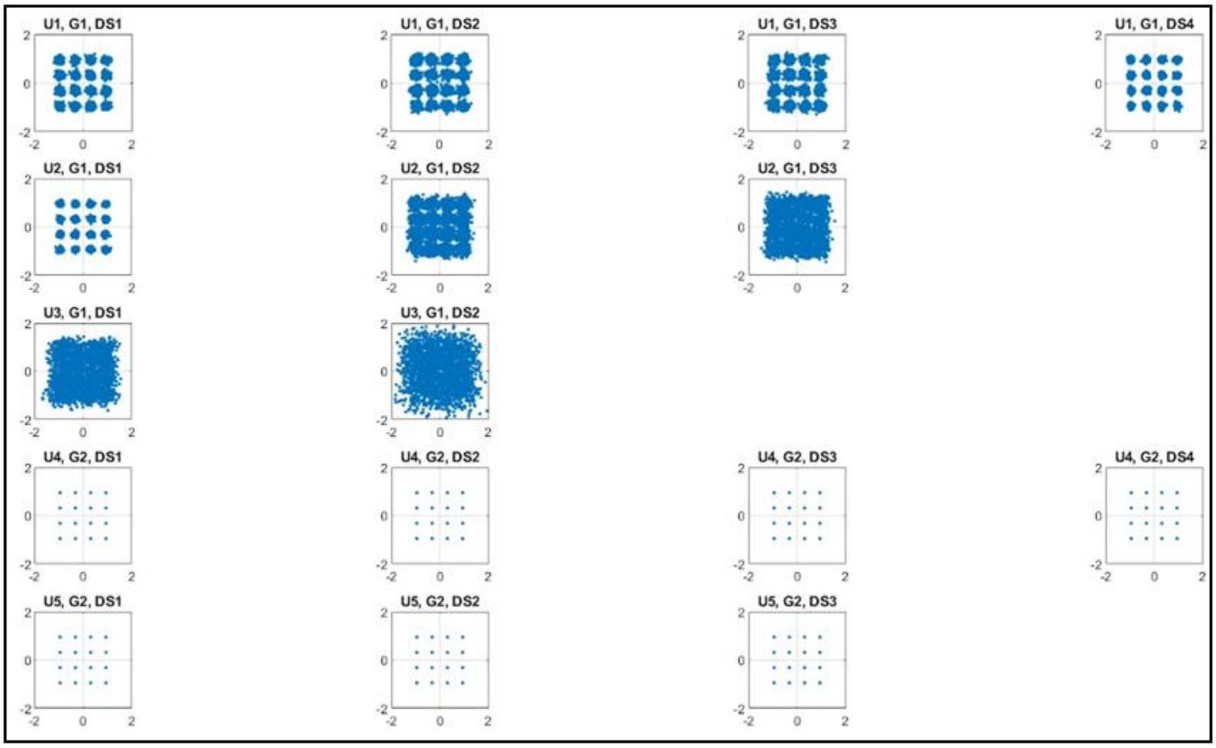

Fig. 9 *Symbol constellation per stream for PGP*

From Fig. 9, Group 1 (G1) has U1 to U3 and multiple data streams (DS1 to DS4) and the scatter plot exhibits tight constellation points clustered, especially for U3. It can be implied that G1 serves in the high-mobility or interference-limited scenario where the users suffer from challenging channel environment. The possibility of clattering and overlaying constellations is probably produced by increasing spatial correlation and decreasing orthogonality between users, and making the separation among data streams becomes more complicated accordingly. Under JSDM with PGP, Group 1 would need more complex intra-group processing (such as ZF or MMSE beamforming) to cancel the inter-user interference afterwards due to pre-beamforming. The work in U3 is denser that results in higher spatial multiplexing or simultaneous users, lead to higher computation of per-group signal separation. This complication reflects a practical situation in massive MIMO systems when the group belongs to the same angular domain and the streams need accurate separating in the group.

In addition, Group 2 (G2) including users U4 and U5 experiences clear and differentiated constellation points on all data streams on the other hand, for G2 suggesting a very good and low interference environment. These users are presumably in different angular sectors from Group 1 and the pre-beamformer is able to suppress them to a greater extent. In Group 2 the intra-group user channels are orthogonal or have extremely low correlation so that per-group processing is simple. It is also observed that in all the DS (DS1–DS4) the regular grid-like structures facilitate the readability and differentiate between modulation symbols as compared to Group 1, which is noisy and inter-user contaminated. This indicates a smaller number of users or lower spatial multiplexing requirements; in which case the PGP stage can operate effectively with a low computational complexity. The comparison between G1 and G2 indicates that the JSDM is effective in dealing with user heterogeneity: G1 corresponds to high-density and interference user scenario, G2 corresponds to the sparse and separate user scenario with transmission condition is superior in reality.

4. Conclusion

The study is concluded in which summarizes the main conclusions drawn from the design, simulation, and performance analysis of a 5G mmWave Massive MIMO system utilizing Joint Spatial Division Multiplexing (JSDM) and hybrid beamforming (HBF). The study showed that combining HBF and JSDM allows for efficient virtual sectorization and user grouping, which lowers interference and channel estimation overhead while preserving usable performance. The study assessed how system design decisions affect overall 5G network performance by concentrating on three key metrics: bit error rate (BER), energy efficiency (EE), and spectrum efficiency (SE)..

Results have demonstrated that the usage of complete RF chains per antenna in digital beamforming (DBF) results in a marginally higher SE. This performance boost, however, comes at the expense of far higher energy and device complexity. On the other hand, hybrid beamforming achieved near-optimal SE with significantly higher power usage efficiency, even though it used fewer RF chains. Because of this, HBF is a more economical and sustainable option, particularly for dense 5G installations where hardware scaling is a major concern.

The benefit of hybrid beamforming in reducing power consumption and providing competitive throughput was brought to light by energy efficiency studies. By grouping users into spatially correlated groups, JSDM improved this benefit and made beamforming more effective and focused. Furthermore, the system's robustness and dependability were confirmed by the BER performance under varied SNR settings, with the simulated outcomes nearly matching theoretical predictions. This shown that in real-world settings, hybrid beamforming systems can sustain low error rates.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Muhammad Zulfiqri Razali, Norshidah binti Katiran;* ***data collection:*** *Muhammad Zulfiqri Razali;* ***analysis and interpretation of results:*** *Norshidah Katiran, Nurulhuda Ismail;* ***draft manuscript preparation:*** *Muhammad Zulfiqri Razali, Norshidah Katiran. All authors reviewed the results and approved the final version of the manuscript.*

References

[1] T. Kebede, Y. Wondie, J. Steinbrunn, H. B. Kassa and K. T. Kornegay, "Precoding and Beamforming Techniques in mmWave-Massive MIMO: Performance Assessment," in IEEE Access, vol. 10, pp. 16365-16387, 2022, doi: 10.1109/ACCESS.2022.3149301.

[2] Adedoyin, M. A., & Falowo, O. E. (2020). Combination of ultra-dense networks and other 5G enabling technologies: A survey. In *IEEE Access* (Vol. 8, pp. 22893– 22932). Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/ACCESS.2020.2969980.

[3] Adhikary, A., Al Safadi, E., Samimi, M. K., Wang, R., Caire, G., Rappaport, T. S., & Molisch, A. F. (2014). Joint spatial division and multiplexing for mm-Wave channels. *IEEE Journal on Selected Areas in Communications*, *32*(6), 1239– 1255. https://doi.org/10.1109/JSAC.2014.2328173.

[4] Busari, S. A., Huq, K. M. S., Mumtaz, S., Dai, L., & Rodriguez, J. (2018). Millimeter- Wave Massive MIMO Communication for Future Wireless Systems: A Survey. In *IEEE Communications Surveys and Tutorials* (Vol. 20, Issue 2, pp. 836–869). Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/COMST.2017.2787460.

[5] Hamid, S., Chopra, S. R., Gupta, A., Tanwar, S., Florea, B. C., Taralunga, D. D., Alfarraj, O., & Shehata, A. M. (2023). Hybrid Beamforming in Massive MIMO for Next-Generation Communication Technology. *Sensors*, *23*(16). https://doi.org/10.3390/s23167294

[6] Sohal, R. S., Grewal, V., Kaur, J., & Singh, M. L. (2022). Deep Learning Based Analog Beamforming Design for Millimetre Wave Massive MIMO System. *Wireless Personal Communications*, *126*(1), 701–717. https://doi.org/10.1007/s11277- 022-09766-z.

[7] G. Liu, B. Cai and W. Xie, "Research on 5G Wireless Networks and Evolution," 2021 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), Chengdu, China, 2021, pp. 1-5, doi: 10.1109/BMSB53066.2021.9547155.

[8] T. Kebede, Y. Wondie and J. Steinbrunn, "Performance Evaluation of MillimeterWave-Massive MIMO with Beamforming Techniques," 2021 International Symposium on Networks, Computers and Communications (ISNCC), Dubai, United Arab Emirates, 2021, pp. 1-8, doi: 10.1109/ISNCC52172.2021.9615728.

[9] Altamirano, C. D., Altamirano, C. D., Carvajal, H., & de Almeida, C. (2021). BER of Massive MIMO in time-variant channels using multiplexed, superimposed and hybrid channel estimation techniques. Aeu-International Journal of Electronics and Communications, 131, 153594. https://doi.org/10.1016/J.AEUE.2020.153594.

[10] A. Alkhateeb, G. Leus, and R. W. Heath Jr., "Limited feedback hybrid precoding for multi-user millimeter wave systems," IEEE Transactions on Wireless Communications, vol. 14, no. 11, pp. 6481–6494, Nov. 2015. [Online]. Available: https://doi.org/10.1109/TWC.2015.2454521