I.J. Wireless and Microwave Technologies, **2025, 1, 51-65**
Published Online on February 8, 2025 by MECS Press (http://www.mecs-press.org/)
DOI: 10.5815/ijwmt.2025.01.04

Performance Analysis of Optimal and Hybrid Beamforming Techniques and Spectral Efficiency Enhancement for 5G Millimeter-Wave Systems

Padmasree Ramineni*
Department of ECE, Rajiv Gandhi University of Knowledge and Technologies, Basar, Telangana, 504107, India
E-mail: r.padmasree3@gmail.com
ORCID ID: https://orcid.org/0009-0006-2351-7274
*Corresponding Author

Pranaya Pasula
Department of ECE, Rajiv Gandhi University of Knowledge and Technologies, Basar, Telangana, 504107, India
E-mail: pranaya@rgukt.ac.in
ORCID ID: https://orcid.org/0009-0006-9639-499X

Tejasvey Panchareddy
Department of ECE, Rajiv Gandhi University of Knowledge and Technologies, Basar, Telangana, 504107, India
E-mail: tejasvey@rgukt.ac.in
ORCID ID: https://orcid.org/0009-0007-0824-7867

Received: 28 September, 2024; Revised: 15 November, 2024; Accepted: 12 December, 2024; Published: 08 February, 2025

Abstract: Millimeter-wave (mm-wave) communication stands as a vital technology for future wireless networks, necessitating efficient beamforming techniques to mitigate significant path loss and harness the extensive mm-wave spectrum. Traditional fully digital beamforming methods are often deemed unfeasible due to the substantial costs and energy requirements, which stem from the need for individual radio frequency (RF) chains for each antenna element particularly in Massive MIMO systems. Hybrid beamforming emerges as a more economical solution, reducing both hardware expenses and energy consumption by utilizing a limited number of RF chains. This paper offers an in-depth evaluation of hybrid beamforming in 5G and beyond mm-wave systems, proposing a new classification framework for various hardware configurations. The research employs a practical approach to compare different strategies, focusing on two main factors: the beam patterns produced with optimal and hybrid weights, and the resulting spectral efficiency, which is a key performance metric. The findings indicate that the beam patterns generated with both optimal and hybrid weights display comparable characteristics, especially for dominant beams. Additionally, the study shows that increasing the number of data streams leads to a significant boost in spectral efficiency, an essential element for enhancing 5G network performance. The systematic comparisons delve into the interactions and trade-offs between these design aspects, highlighting promising candidates for hybrid beamforming in the wireless communication systems of the future.

Index Terms: 5G Networks, Hybrid Beamforming, Millimeter-Wave Communication, Optimal Weights, Radio Frequency Chains, Spectral Efficiency

1. Introduction

The rapid advancement of wireless communication technologies has significantly increased demands on network capacity, data speeds, and overall performance. As 5G and subsequent technologies progress, millimeter-wave (mm-wave) communication [1] has emerged as a key solution to meet these demands. Operating at frequencies that provide extensive unused spectrum, mm-wave communication is well-positioned to offer the high-speed data rates necessary for emerging applications such as augmented reality, autonomous vehicles, and the Internet of Things (IoT). Despite its potential, mm-wave signals face considerable path loss and attenuation challenges, which require advanced methods to preserve signal quality and network efficiency.

Beamforming is a crucial signal processing technique in wireless communication systems that directs the transmission or reception of signals toward specific directions by employing multiple antennas [2]. Unlike conventional methods that disperse signals in all directions, beamforming concentrates energy on a particular area or user. This focused signal power is especially beneficial in high-frequency communication systems like millimeter-wave (mm-wave) and 5G, where maintaining signal strength over distance is a major challenge. By precisely controlling the phase and amplitude of signals at each antenna, beamforming creates a narrow beam that can be steered toward the intended direction, thereby improving both the quality and efficiency of communication.

The advantages of beamforming make it indispensable for modern wireless communication. It significantly boosts signal strength at the receiver by directing energy where it is most needed, which is particularly important in environments with substantial path loss, such as dense urban areas. This increased signal strength results in improved spectral efficiency, enabling multiple users to share the same frequency spectrum with minimal interference. Additionally, beamforming extends the range and coverage of communication systems by increasing the effective signal reach, which is crucial for applications like 5G [3] that require extensive and reliable coverage. The technique also minimizes interference with other users by reducing signal spillover, leading to a more stable and cleaner connection. Moreover, beamforming optimizes energy usage by focusing power precisely where it is required, resulting in lower energy consumption and greater operational efficiency. Finally, by accurately directing signals, beamforming enhances the security of wireless communications, making it more difficult for unauthorized receivers to intercept transmissions.

Beamforming methods are generally categorized into three types: analog, digital, and hybrid. Analog beamforming [4] utilizes phase shifters and other analog devices to direct signal energy. It is noted for its simplicity and lower power usage but is limited by reduced flexibility, fixed beam patterns, and challenges with scalability. Digital beamforming, on the other hand, uses digital signal processing to achieve highly adjustable and precise beam patterns. While it provides superior performance in terms of adaptability and precision, it incurs higher costs, increased power consumption, complexity, and potential latency issues. Traditional fully digital beamforming [5], despite its effectiveness, necessitates a separate radio frequency (RF) chain for each antenna element, which leads to substantial expenses and high energy consumption, making it impractical for extensive 5G networks. This highlights the need for more efficient approaches, such as hybrid beamforming.

Hybrid beamforming integrates both analog and digital techniques [6], enhancing flexibility and precision while mitigating the high costs and energy inefficiencies of fully digital systems. By utilizing fewer RF chains, hybrid beamforming reduces hardware expenses and power consumption, yet maintains effective beamforming performance [7]. The method optimizes performance through the strategic selection and application of beamforming weights, with both optimal and hybrid weights contributing distinct advantages.

This paper addresses the challenge of optimizing hybrid beamforming configurations for 5G and upcoming mm-wave systems, specifically focusing on achieving an effective balance between spectral efficiency and hardware complexity. Although hybrid beamforming has the potential to reduce both costs and power consumption, there remain significant uncertainties regarding the best configuration of beamforming weights and their effects on performance metrics such as spectral efficiency. To resolve these issues, the study examines the design and evaluation of beam patterns using both optimal and hybrid weight configurations. The objectives of this research are to:

1. Examine the impact of beam pattern characteristics on spectral efficiency.
2. Compare the performance of hybrid beamforming and optimal beamforming configurations.
3. Identify scalable and practical solutions for hybrid beamforming in future wireless networks.

Through detailed comparisons, this study aims to bridge the gap between theoretical research and practical application, providing key insights into the development of efficient hybrid beamforming techniques for next-generation communication systems.

2. Literature Review

Beamforming is a crucial technology in wireless communication, especially in systems with multiple antennas. It works by creating constructive interference in specific directions and minimizing interference in others, which boosts the Signal-to-Noise Ratio (SNR) and improves system performance. This technique is key for enhancing energy efficiency and lowering costs in today's communication networks. Beamforming is particularly beneficial in high-frequency applications like millimeter-wave (mm Wave) communications, where managing interference and directing signals is becoming increasingly critical [8].

Analog beamforming is one of the earliest and most widely implemented techniques in Multiple Input Multiple Output (MIMO) systems. It uses a single radio frequency (RF) chain to manage all the antennas, which simplifies the system design and enhances the Signal-to-Noise Ratio (SNR) [9]. However, its primary limitation is that it can only generate one beam at a time, which constrains its ability to handle multiple users simultaneously. Despite its straightforward design and efficiency, analog beamforming is not well-suited for scenarios requiring multiple beams. To mitigate these limitations, On-Off analog beamforming has been developed, which involves selectively activating certain antennas for beamforming. While this method decreases complexity and power usage, it also reduces flexibility [10].

Conversely, digital beamforming provides significant flexibility by assigning a dedicated radio frequency (RF) chain to each antenna, which allows for the simultaneous creation of multiple beams [11]. This improves the Signal-to-Noise Ratio (SNR) and enhances performance in environments with a high density of users. However, this advantage comes with substantial drawbacks, including increased power consumption and greater system complexity. The necessity of having a separate RF chain for each antenna element makes digital beamforming less feasible for large antenna arrays due to its high energy demands and elevated hardware costs [12].

To reconcile the trade-offs between analog and digital beamforming, hybrid beamforming has emerged as a promising solution. This technique connects a group of antennas to fewer radio frequency (RF) chains, enabling the creation of multiple beams with fewer RF chains compared to fully digital systems [13]. It combines flexibility and Signal-to-Noise Ratio (SNR) performance similar to digital beamforming, but with lower power consumption and reduced complexity. Hybrid beamforming is particularly advantageous for massive MIMO systems, where the high costs and energy demands of fully digital beamforming can be prohibitive.

Hybrid beamforming can be categorized into two main types: fully connected and partially connected configurations. In the fully connected setup, each radio frequency (RF) chain is connected to all antenna elements, which maximizes flexibility but increases the complexity of signal processing. On the other hand, partially connected hybrid beamforming involves connecting certain groups of antennas to each RF chain, which lowers both system costs and processing requirements, though it provides slightly less flexibility. Hybrid beamforming, with its ability to balance performance, cost, and complexity, is expected to be a significant technology in the advancement of 5G and future communication systems.

Although the existing literature offers important insights into beamforming techniques, there is a need for a more concentrated exploration of the comparative performance of various beamforming methods, especially optimal weight and hybrid weight beamforming. Much of the research tends to focus on theoretical aspects under idealized conditions, often neglecting the performance of these methods across different system configurations and the trade-offs involved in spectral efficiency, complexity, and power consumption. This study seeks to fill this gap by providing an in-depth assessment of optimal weight and hybrid weight beamforming, specifically examining their effects on spectral efficiency in large-scale communication systems.

3. Methodology

Multiple-Input Multiple-Output (MIMO) Systems and Massive MIMO are fundamental technologies in contemporary wireless communication. MIMO boosts performance by utilizing multiple antennas at both the transmitter and receiver ends, allowing for the simultaneous transmission of several data streams over the same frequency band. This setup enhances system capacity, improves reliability through spatial diversity, and refines signal quality.

Massive MIMO, an advanced variant of MIMO, employs a large number of antennas at the base station. This technology further augments capacity and throughput, allows for precise beamforming to direct signals to specific users, and enhances energy efficiency by spreading power across many antennas. It also offers improved interference management and supports high-density user environments, making it crucial for 5G and future wireless systems.

3.1 Massive MIMO and Beam forming

In a Massive MIMO system [14], the transmitter and receiver each play crucial roles in enhancing wireless communication performance.

Massive MIMO Transmitter: Massive MIMO systems employ transmitters equipped with large antenna arrays, often comprising hundreds or thousands of elements, enabling the simultaneous transmission of multiple data streams. These systems leverage spatial multiplexing to significantly enhance data rates by transmitting distinct signals over the same frequency band, as shown in Figure 1.

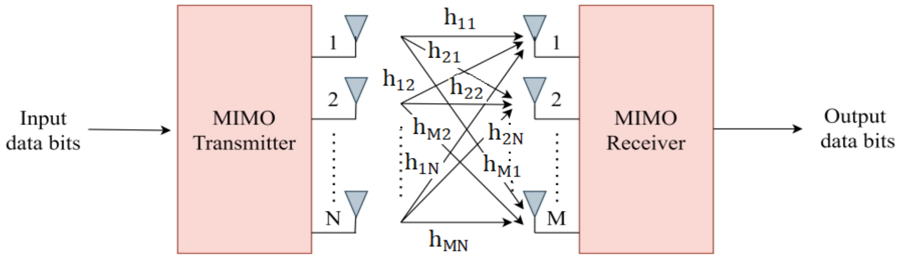

Fig. 1. Massive MIMO System Model

Beamforming techniques focus energy in the direction of specific users, improving the signal-to-noise ratio (SNR) while reducing interference. This is achieved by adjusting the amplitude and phase of signals across antenna elements, ensuring constructive signal combination in desired directions. The transmit precoder is integral to forming beam patterns, calculating appropriate antenna weights based on Channel State Information (CSI) to adapt dynamically to channel conditions. This ensures optimal energy distribution across antennas, balancing high data rates with efficient power management.

Massive MIMO Receiver: on the receiver side, large antenna arrays capture signals from multiple directions, efficiently handling multipath propagation. Advanced signal processing algorithms, such as interference cancellation and multi-user detection (MUD**)**, decode and separate these signals [15], even in dense user environments. Accurate channel estimation helps the receiver adapt to varying channel conditions in real-time, directly influencing overall system performance.

Beamforming at the receiver enhances the desired signals while suppressing interference, resulting in improved capacity and reliability. After signals are captured by the antenna array, they undergo combination using beamforming algorithms. These algorithms amplify desired signals and reduce interference, allowing efficient downstream processing in the RF chains and baseband unit.

Beamforming in Massive MIMO: It directs transmitted signals toward target users, enhancing communication efficiency and reducing interference. By concentrating energy into narrow beams rather than dispersing it in all directions, this technique improves signal strength and range while minimizing power wastage. Such focused signal transmission is particularly valuable in mm-wave communication, where signals are more susceptible to path loss and blockage.

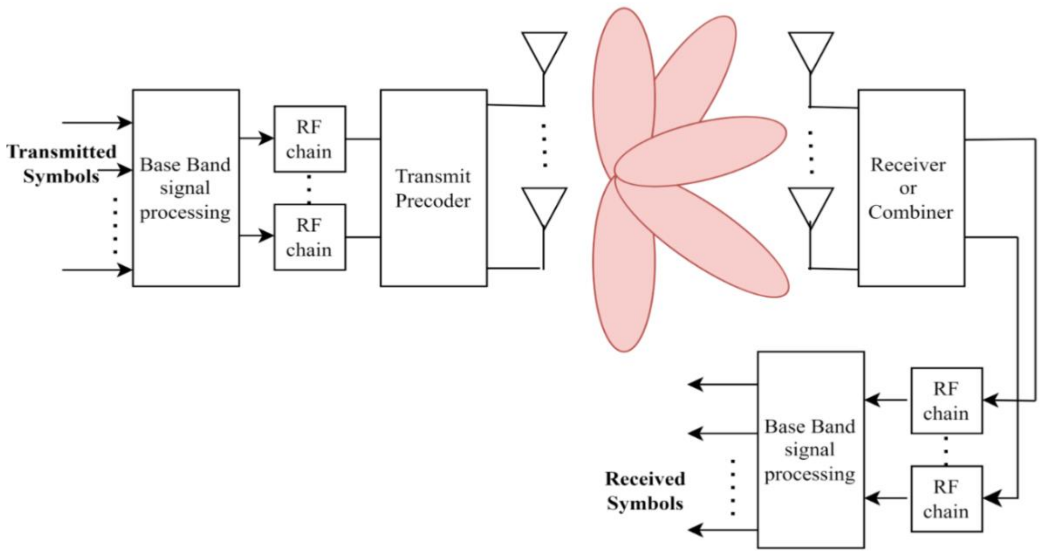

Fig. 2. Massive MIMO Beam forming System model

As shown in Figure 2, beamforming [16] begins with baseband signal processing**,** where data streams are modulated and encoded. The signals are then passed through multiple RF chains connected to a precoder**.** The precoder adjusts the beamforming weights to focus the signal energy toward specific directions, optimizing transmission. At the receiver, signals are captured by the antenna array, combined using beamforming techniques, and processed through RF chains and the baseband unit for decoding.

While Massive MIMO provides significant benefits [17], it also encounters challenges in beamforming methods. Analog beamforming, reliant on phase shifters, is less flexible and limits spectral efficiency. In contrast, digital beamforming offers greater precision and adaptability but comes with high power consumption and computational complexity. Hybrid beamforming emerges as a promising alternative, combining the advantages of both analog and digital techniques to achieve efficient and flexible beamforming with reduced hardware requirements.

3.2 Hybrid Beam forming

The Massive MIMO hybrid beamforming system model at the transmitter, which employs a mix of digital and analog beamforming techniques is illustrated in Figure 3. The Baseband Signal Processing block prepares the transmitted symbols through modulation and coding. In this hybrid model, the signal is split between Digital Precoding and Analog Precoding, minimizing the number of required RF chains. The Digital Precoder operates in the digital domain, optimizing beamforming and signal management before the signal reaches the RF chains, handling fewer data streams due to the limited number of RF chains available.

Following digital processing, the signal is passed through a smaller number of RF chains, which significantly lowers hardware costs. The signal then undergoes further processing through Analog Precoding, where phase shifts are applied to the signals in the RF domain. This technique directs the beams toward specific angles, compensating for the reduced number of RF chains. The Analog Precoder modifies the phase for each antenna, creating directional beams that, although less precise than those produced by fully digital systems, remain effective for large-scale applications. Ultimately, the Antenna Array transmits these directional beams to the receiver.

Integrating digital and analog processing allows this hybrid system to improve both performance and cost efficiency. The Hybrid Beamforming [18] block achieves a balance between the precision of digital beamforming and the reduced hardware demands of analog beamforming. This approach is especially beneficial for systems such as 5G, where the deployment of numerous RF chains in large antenna arrays can be excessively costly. This combination enables effective beamforming while maintaining manageable hardware expenses.

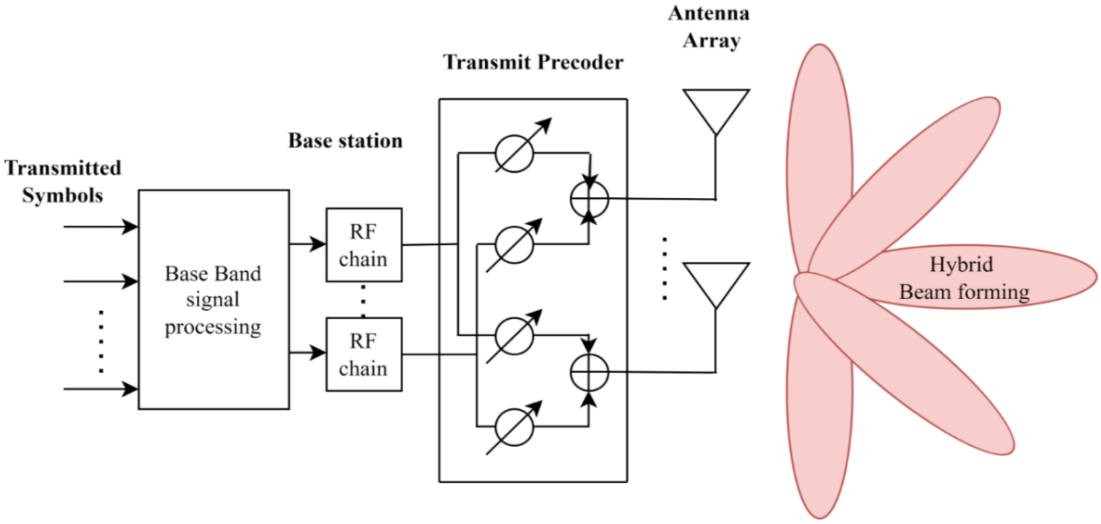

Fig. 3. Massive MIMO Hybrid Beam forming System model at the transmitter

The Massive MIMO hybrid beamforming system model at the receiver is depicted in Figure 4, it initiates with hybrid beamforming, which merges signals from multiple antennas to optimize reception. This approach enhances signal quality by utilizing both digital and analog processing, concentrating on the most pertinent signals while minimizing interference. The antenna array captures incoming signals from various directions and prepares them for processing, establishing the system's overall gain and directivity to improve the signal-to-noise ratio.

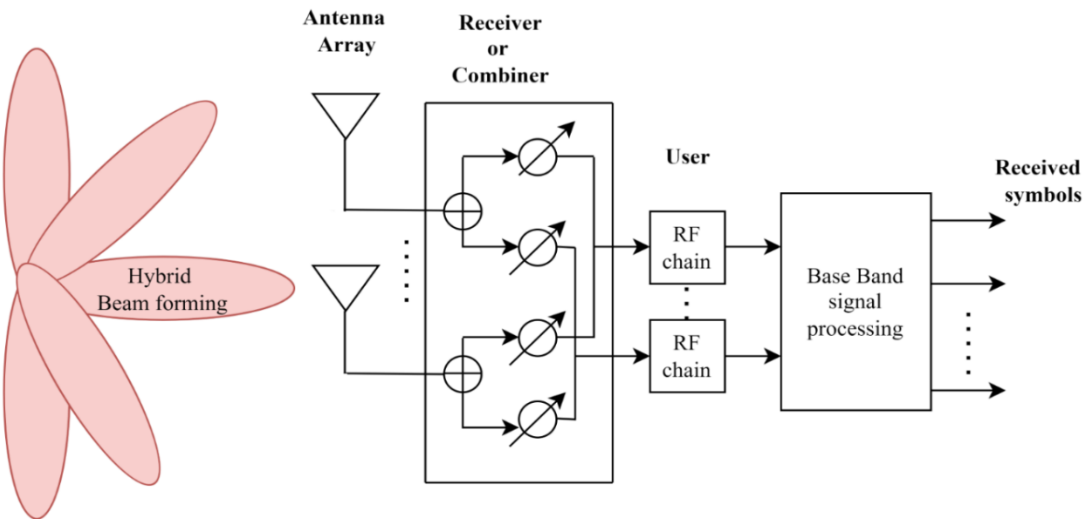

Fig. 4. Massive MIMO Hybrid Beam forming System model at the Receiver

The combined signals are then directed to the combiner, which merges them into a single stream, a critical step for preserving data integrity while simplifying system complexity. After this, the signals advance to the RF chains, where they are amplified and undergo additional processing, including filtering and frequency conversion. This stage is essential for ensuring the signals are adequately prepared for baseband processing and meet the required quality standards. Subsequently, the processed signals reach the baseband signal processing block, where received symbols are extracted through demodulation and decoding. This step reconstructs the original transmitted information, allowing for accurate interpretation by the receiver. This process from hybrid beamforming [19] to extracting received symbols ensures effective signal reception and improves overall system performance.

Analog beamforming, digital beamforming, and hybrid beamforming each offer distinct benefits and challenges. The following Table 1 provides a detailed analysis of these methods.

Table 1. Comparison of Analog, Digital and Hybrid beamforming with key features

Characteristics	Analog Beamforming	Digital Beamforming	Hybrid Beamforming
Definition	Adjusts signal phase and amplitude using phase shifters.	Uses digital signal processing to control beamforming weights.	Combines analog and digital techniques for beamforming.
Beamforming Flexibility	Limited to single-beam per RF chain.	Supports multi-beam per RF chain.	Can generate multiple beams with reduced RF chains.
Hardware Complexity	Low: Requires fewer RF chains but relies on phase shifters.	High: Requires one RF chain per antenna and complex processors.	Moderate: Reduces the number of RF chains compared to digital.
Cost	Low: Cheaper due to fewer RF chains and simpler components.	High: Expensive due to many RF chains and high computational needs.	Moderate: Balances cost between analog and digital systems.
Power Consumption	Low: Operates in the RF domain without extensive processing.	High: Digital processing and RF chains consume significant power.	Moderate: Fewer RF chains reduce power demands compared to digital.
Spectral Efficiency	Low: Limited by single beam and lack of flexibility.	High: Optimizes performance for multi-user scenarios.	Moderate to High: Improves efficiency with fewer resources.
Challenges	1. Phase shifter accuracy and scalability. 2. Limited adaptability to dynamic environments.	1. High power consumption. 2. Complexity in processing. 3. Latency in real-time applications.	1. Requires coordination between analog and digital blocks. 2. Algorithmic complexity for beam allocation.
Use Cases	Suitable for scenarios with static or low-density users.	Ideal for dynamic, multi-user environments with high throughput demands.	Effective for large-scale, cost-sensitive deployments like 5G and mm wave systems.
Practicality for Massive MIMO	Limited scalability for dense environments.	Highly effective but costly and power-intensive.	Strikes a balance, making it the most practical choice for 5G.

3.3 Optimal Weights and Hybrid weights in Beamforming

In beamforming, optimal and hybrid weights are essential for effective signal transmission. Optimal weights in beamforming are a set of parameters that optimize transmission by steering signals in the desired direction while reducing interference. These weights aim to boost the signal-to-noise ratio (SNR) and improve communication quality by concentrating transmitted energy on the intended user or target area. The use of optimal weights is especially important in multi-user systems, where it ensures that each user receives the strongest possible signal with minimal interference from other users. Several algorithms are employed to determine optimal weights, among which the most commonly used are Maximum Ratio Transmission (MRT) and Minimum Mean Square Error (MMSE) [20].

Maximum Ratio Transmission: It aims to maximize the power of the received signal at the intended receiver by aligning the transmitted signal with the strongest part of the channel. This approach is particularly beneficial in scenarios where enhancing signal strength and reducing noise is crucial.

MRT calculates beamforming weights by taking the conjugate of the channel matrix (CSI), allowing the transmitted signal to align with the direction of the strongest path. This alignment ensures that the phases of the signals are matched with the channel phases, leading to constructive interference at the receiver. As a result, the signal strength and signal-to-noise ratio (SNR) at the intended receiver are maximized. The optimal weights in MRT are determined using the formula provided in Equation 1.

$$W_{MRT} = \frac{h^H}{|h|} \quad (1)$$

where,
h^H is the conjugate transpose (Hermitian transpose) of the channel matrix,
$|h|$ is the norm (magnitude) of the channel matrix, used for normalizing the weight vector.

The calculation of the optimal weights using MRT is explained through the following steps:

Consider a simple 2x1 MIMO system with a channel vector

$$h = (2 + 3i \quad 1 + 4i)^T$$

Step 1: Compute the conjugate transpose h^H:

$$h^H = (2 - 3i \quad 1 - 4i)$$

Step 2: Compute the norm $|h|$:

$$|h| = \sqrt{|2+3i|^2 + |1+4i|^2}$$
$$|h| = 5.477$$

Step 3: Compute the beamforming weights W_{MRT} using Equation 1 as:

$$W_{MRT} = \frac{(2-3i \quad 1-4i)}{5.477}$$
$$W_{MRT} = (0.365 - 0.5477i \quad 0.182 - 0.730i)$$

These weights are used to direct the transmitted signal towards the receiver in the direction of the strongest channel path, maximizing the received signal strength.

MRT maximizes the received signal strength by aligning the transmitted signal with the strongest path, making it particularly effective in high signal-to-noise ratio (SNR) environments. This method does not consider interference from other users, which can lead to increased interference in multi-user scenarios, as it focuses solely on enhancing signal strength for the intended receiver. While MRT is straightforward and computationally efficient, excelling in low-interference or single-user situations, it may inadvertently create interference for other users in multi-user settings. For this reason, the Minimum Mean Square Error (MMSE) approach is often preferred, as it balances signal enhancement with interference management, providing a more robust solution in complex environments.

Minimum Mean Square Error: This algorithm aims to minimize the error between the transmitted and received signals, considering both interference from other users and noise present in the system. Unlike MRT, MMSE effectively balances the maximization of signal power for the intended user with the minimization of interference for others.

In wireless communication, transmitted signals are often affected by noise and interference from multiple users. MMSE beamforming determines optimal weights to minimize the mean square error (MSE) between the transmitted and received signals, quantifying the deviation of the received signal from the desired one by incorporating both noise and interference. To achieve this, MMSE utilizes the channel matrix (Channel State Information or CSI) along with the noise-plus-interference covariance matrix. This information allows the algorithm to calculate beamforming weights that optimize the trade-off between minimizing interference and maximizing signal quality. The optimal weights are calculated by using MMSE algorithm using the formula provided in Equation 2.

$$W_{MMSE} = (H^H H + \sigma^2 I)^{-1} H^H \tag{2}$$

where,
H^H the conjugate transpose of the channel matrix,
$H^H H$ represents the channel correlation,
σ^2 denotes the noise variance (or power), accounting for noise's effect on the signal,
I is the identity matrix.

The calculation of the optimal weights using MMSE is explained through the following steps:
Consider a 2x2 MIMO system with the channel matrix H given as:

$$H = \begin{pmatrix} 2+3i & 1+2i \\ 1+4i & 2+5i \end{pmatrix}$$

Assume the noise variance σ^2 = 0.01
Step 1: Compute the conjugate transpose H^H:

$$H^H = \begin{pmatrix} 2-3i & 1-4i \\ 1-2i & 2-5i \end{pmatrix}$$

Step 2: Compute $H^H H$:

$$H^H H = \begin{pmatrix} 2-3i & 1-4i \\ 1-2i & 2-5i \end{pmatrix} * \begin{pmatrix} 2+3i & 1+2i \\ 1+4i & 2+5i \end{pmatrix}$$

Upon multiplication of H^H with H, the resulting matrix is given as:

$$H^H H = \begin{pmatrix} 30 & 10+22i \\ 10-22i & 68 \end{pmatrix}$$

Step 3: Add the noise variance term $\sigma^2 I$

$$H^H H + \sigma^2 I = \begin{pmatrix} 30.01 & 10+22i \\ 10-22i & 68.01 \end{pmatrix}$$

Step 4: Invert the $H^H H + \sigma^2 I$ matrix and multiply by H^H to get W_{MMSE}.

The inversion of the matrix and multiplication by H^H yields the MMSE beamforming weights, this typically requires numerical computation.

The weights for MMSE beamforming are particularly effective in multi-user environments because they account for both interference and noise, ensuring that each user receives a clear signal with minimal disruption. Compared to MRT, MMSE has greater computational complexity due to the need for matrix inversions and more comprehensive information regarding noise. MMSE beamforming is well-suited for scenarios where minimizing interference is essential. While it requires more computational resources, it surpasses simpler methods like MRT in effectively balancing noise and interference. MMSE is commonly utilized in practical applications, such as multi-user MIMO systems, where managing interference is critical for maintaining overall system capacity.

Hybrid weights are a combination of digital and analog beamforming weights used in hybrid beamforming systems. They enable efficient beam steering while reducing the complexity and costs associated with fully digital systems. By leveraging both digital and analog processing, hybrid weights provide flexibility to adapt to varying channel conditions and facilitate the use of large-scale antenna arrays, making them ideal for modern applications like 5G and beyond. By utilizing the Orthogonal Matching Pursuit (OMP) algorithm to calculate hybrid weights, the system can effectively direct beams while ensuring high spectral efficiency.

Orthogonal Matching Pursuit: This algorithm is commonly utilized in hybrid beamforming, especially in mm wave communication systems, to identify sparse solutions for beamforming challenges when the number of RF chains is limited. OMP reduces system complexity and hardware costs by approximating fully digital beamforming weights. It calculates hybrid beamforming weights by optimizing both the digital baseband and analog RF precoders.

The flowchart depicted in Figure 5 illustrates the process for computing hybrid beamforming weights with the OMP algorithm, outlining each step of the procedure involved, as follows:

1. *Initialization*: The process begins by setting up the channel matrix (H), residual vector, and necessary system parameters, including RF chains, frequency, and scattering characteristics.
2. *Iterative Process:*
    - In each iteration, the algorithm calculates the correlation between the residual vector and available basis functions.
    - The basis function that best matches the residual is selected and added to the set of chosen functions.
    - The residual vector is then updated by subtracting the contribution from the selected basis function.
3. *Stopping Criteria:* The iterations continue until one of the following conditions is met:
    - The magnitude of the residual vector drops below a defined threshold, indicating adequate signal capture.
    - A preset maximum number of iterations is reached.
4. *Finalization:* Once the stopping condition is satisfied, the final beamforming weights are determined by combining the selected basis functions, which are used in the hybrid beamforming system to improve communication performance.
5. This flowchart effectively illustrates the iterative nature of the OMP algorithm, highlighting the significance of systematic basis function selection and residual management in optimizing hybrid beamforming weights.
6. *Simulation Parameters:* These parameters, along with their specific values used in the simulation, are presented in Table 2. Proper initialization of these parameters is vital for the successful execution of the OMP algorithm, enabling accurate computation of beamforming weights and the optimization of both digital baseband and analog RF precoders to achieve the desired performance.

Total Number of Transmitter Antennas (64): The selection of 64 antennas aligns with modern Massive MIMO systems, where large antenna arrays enhance capacity and spectral efficiency. This configuration is standard for mm wave systems in 5G and beyond, supporting high data rates and improved spatial multiplexing.

Number of RF Chains at Transmitter (4): A total of 4 RF chains reflects practical system limitations where the number of RF chains is much smaller than the number of antennas due to constraints such as cost and power consumption. This setup demonstrates the application of hybrid beamforming, where fewer RF chains are used to achieve efficient beamforming.

Total Number of Receiver Antennas (16): With 16 receiver antennas, the configuration supports enhanced multipath resolution and diversity. This number represents a typical deployment in mm wave systems, where robust signal reception in complex environments, such as urban areas, is critical.

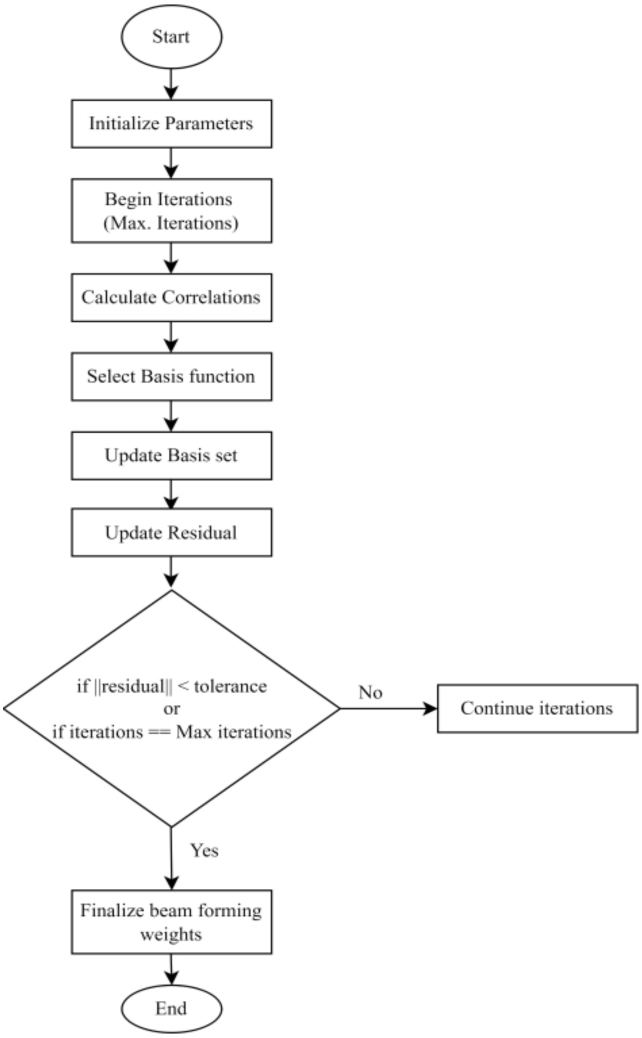

Fig. 5. Flowchart for Hybrid Beamforming Weights Calculation Using OMP

Table 2. Simulation Parameters for Hybrid Beamforming

Parameter	Value
Total Number of Transmitter Antennas	64
Number of RF Chains at Transmitter	4
Total Number of Receiver Antennas	16
Number of RF Chains at Receiver	4
Carrier Frequency (fc)	28 GHz
Wavelength (λ)	0.0107 meters
Number of Scattering Clusters	6
Number of Rays per Cluster	8
Total Number of Scatterers	48
Angular Spread	5 degrees
SNR Range	- 40 dB to 0 dB
Number of SNR Points	9
Number of Data Streams	1,2
Number of Data Stream Points	2
Number of Iterations	50

Number of RF Chains at Receiver (4): Similar to the transmitter, 4 RF chains are used at the receiver, consistent with hybrid beamforming architectures. This approach balances system complexity with performance, enabling efficient signal processing while addressing hardware limitations.

Carrier Frequency (28 GHz): The carrier frequency of 28 GHz is widely adopted in 5G mm wave communication, offering large bandwidths for high-speed data transmission. This choice reflects the real-world frequency allocation for mm wave systems, where challenges like path loss and blockage are prevalent.

Wavelength (λ = 0.0107 meters): The wavelength, derived from the carrier frequency, is used to model propagation characteristics and antenna design. A wavelength of approximately 1.07 cm corresponds to 28 GHz, essential for calculating beamforming gains and understanding signal interaction with the environment.

Number of Scattering Clusters (6): The presence of 6 scattering clusters represents the typical multipath propagation scenario in urban environments. This parameter influences the channel model, enabling realistic simulations of fading and signal propagation.

Number of Rays per Cluster (8): The 8 rays per cluster simulate the individual paths within each scattering cluster, accounting for reflections, refractions, and diffractions. This value provides adequate diversity in the channel model, ensuring realistic evaluation of beamforming techniques.

Total Number of Scatterers (48): A total of 48 scatterers captures the complexity of urban environments, with multiple objects contributing to signal scattering. This parameter ensures that the simulation accounts for multipath effects, critical for assessing system performance.

Angular Spread (5 degrees): An angular spread of 5 degrees' models focused signal paths, typical of urban environments with limited scattering angles. This value strikes a balance between computational feasibility and realistic propagation conditions.

SNR Range (-40 dB to 0 dB): The selected SNR range represents a wide spectrum of conditions, from poor signal quality (low SNR) to ideal scenarios (high SNR). This range enables thorough evaluation of system performance across varying operating conditions.

Number of SNR Points (9): Using 9 SNR points ensures a detailed analysis of the system under different signal quality levels. This allows for a comprehensive assessment of beamforming algorithms over a range of communication scenarios.

Number of Data Streams (1, 2): The system supports 1 and 2 data streams to evaluate both single-user and multi-user scenarios. This parameter is crucial for assessing multiplexing capabilities and system performance in hybrid beamforming setups.

Number of Data Stream Points (2): The evaluation of system performance at two points, corresponding to 1 and 2 data streams, provides insights into how the system handles multiple streams effectively.

Number of Iterations (50): Conducting 50 iterations ensures convergence of algorithms like Orthogonal Matching Pursuit (OMP) and provides stable results. This number balances computational efficiency with reliable performance evaluation.

These simulation parameters are carefully chosen to reflect realistic system configurations, particularly for 5G mm wave technologies

3.4 Spectral Efficiency

Evaluating spectral efficiency in hybrid beamforming using optimal and hybrid weights involves determining the received signal power, calculating the noise power, computing the achievable data rate, and deriving the spectral efficiency as detailed below:

Received Signal Power (P_r): The received signal power measures the signal's strength after it has passed through the channel and the beamforming weights. It can be represented by the Equation 3 as:

$$P_r = w^H H P_s H^H w \tag{3}$$

where,
w is the vector of beamforming weights (optimal or hybrid),
w^H is the conjugate transpose of beamforming weight vector,
P_s is the transmit power, indicating the strength of the signal sent by the transmitter,
H is the channel matrix,
H^H is the conjugate transpose of channel matrix

This equation effectively calculates the efficiency with which the transmitted signal power, modified by the channel conditions (represented by (H)), is directed towards the receiver using the chosen beamforming weights.

Noise Power (P_n): Noise power plays a crucial role in evaluating the quality of the received signal and is represented by Equation 4 as :

$$P_n = N_o B \tag{4}$$

where,
N_o is the noise power spectral density,
B is the bandwidth of the communication channel.

This equation shows that the total noise power depends on the bandwidth, implying that a broader channel can result in higher total noise power.

Achievable Data Rate (R): The achievable data rate signifies the maximum information transmission rate that can be reliably maintained over the channel. It is calculated using the Shannon capacity formula given by Equation 5 as:

$$R = B\, log_2\left(1 + \frac{P_r}{P_n}\right) \tag{5}$$

The term $\frac{P_r}{P_n}$ represents the signal-to-noise ratio (SNR), which indicates the quality of the received signal relative to the noise level. A higher SNR signifies better transmission quality, allowing for a higher data rate. The logarithmic function reflects the nonlinear relationship between SNR and achievable data rate, showing that increases in SNR lead to diminishing returns in data rate improvements.

Spectral Efficiency (SE): Spectral efficiency is a key performance metric that measures the effectiveness of the available bandwidth utilization, calculated as given by Equation 6 as:

$$SE = \frac{R}{B} \tag{6}$$

where,
R is the achievable data rate,
B is the bandwidth of the communication channel

This equation normalizes the achievable data rate in relation to the channel bandwidth. The outcome is represented in bits per second per hertz (bps/Hz), providing a clear illustration of the data rate achieved for every unit of bandwidth used.

The spectral efficiency for both optimal and hybrid weights are calculated using Equations (7) and (8) as follows:

$$SE_{optimal} = \frac{R_{optimal}}{B} \tag{7}$$

$$SE_{hybrid} = \frac{R_{hybrid}}{B} \tag{8}$$

The comparison of the spectral efficiency of optimal and hybrid weights enables an evaluation of the performance trade-offs associated with the two beamforming techniques. By analyzing spectral efficiency, it is possible to determine which method provides superior bandwidth utilization under specific channel conditions.

These assessments provide meaningful insights into the efficacy of hybrid beamforming systems, especially within high-frequency contexts like millimeter-wave communications. Comprehending these aspects is crucial for optimizing communication systems, particularly in light of the escalating demand for increased data throughput in modern wireless networks.

4. Results and Discussions

The beam patterns and spectral efficiency measurements obtained with both optimal and hybrid weights reveal the performance differences between these methods. Optimal beamforming requires more computational power to achieve precise beam formation, while hybrid beamforming is more efficient in terms of hardware but may come with reduced performance. Analyzing these methods provides important insights into their practical effectiveness.

The beam pattern obtained with optimal weights is depicted in Figure 6, featuring a well-defined and prominent main lobe that is accurately aimed at the intended target. This demonstrates the capability of optimal beamforming to direct most of the energy toward the desired direction, thereby improving signal strength and reducing potential losses.

The pattern shows a notable reduction in side lobes, indicating minimal interference in other directions. This characteristic of optimal beamforming is crucial for reducing interference and achieving high signal-to-noise ratios (SNR), especially in millimeter-wave (mm Wave) communications where signal attenuation is a significant issue. These outcomes are particularly advantageous for situations that demand precise beam steering, such as high-frequency mm Wave systems that experience path loss from obstacles. By applying optimal weights, power transmission is efficiently managed, thereby enhancing coverage while preserving signal quality.

Computational Complexity of Beamforming with optimal weight configuration: It involves complex computations, such as matrix inversions, which require significant processing power, especially with large antenna arrays. This increases the computational burden, making it less suitable for large-scale systems. Optimal Beamforming requires a larger number of RF chains, which significantly drives up hardware costs, particularly in systems with many antennas and multiple data streams. This can be impractical for large deployments.

The 3D beam response pattern using hybrid beamforming at azimuth 0 ° and elevation 90 ° displays a well-focused main lobe with suppressed side lobes, closely matching the expected performance in hybrid beamforming systems. Although specific quantitative metrics such as beamwidth and side lobe levels are not provided in this Figure 6, the visual alignment of the main lobe with the desired direction suggests that hybrid beamforming performs similarly to optimal beamforming. Further analysis will include detailed numerical metrics to enhance the validation of this observation.

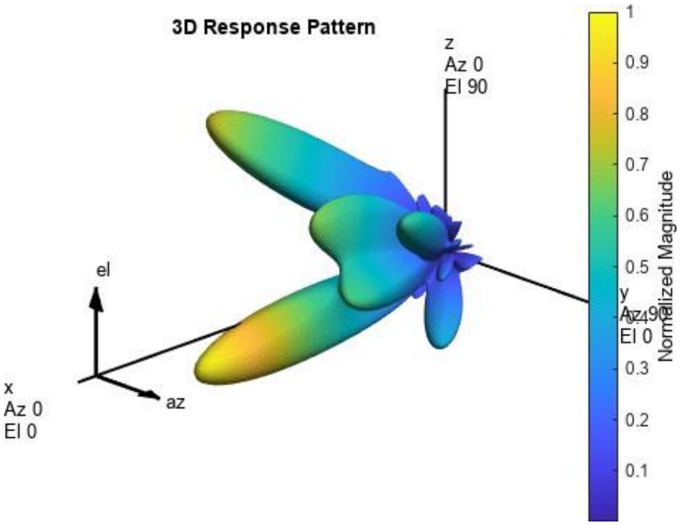

Fig. 6. Three-Dimensional Beam Patten with Optimal Weight Configuration

The three-dimensional beam pattern with hybrid weight configuration, as depicted in Figure 7, shows that the main lobe remains robust but is slightly broader compared to the optimal beamforming pattern, indicating some dispersion of energy into nearby directions. This is due to the use of fewer RF chains in hybrid beamforming, which results in a trade-off between performance and hardware efficiency.

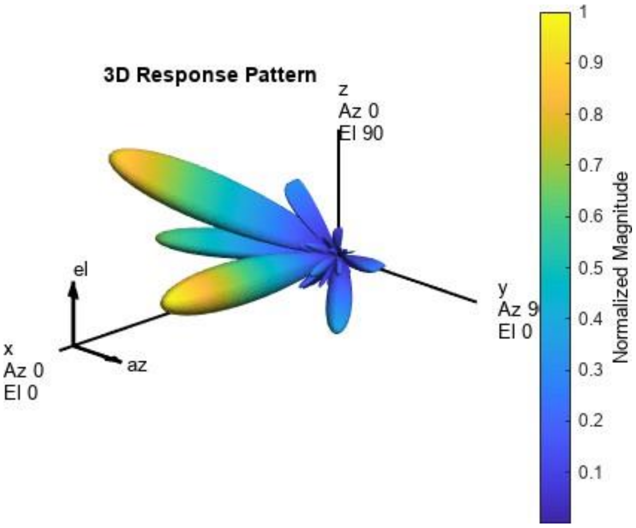

Fig. 7. Three-Dimensional Beam Patten with Hybrid Weight Configuration

The 3D beam response pattern using hybrid beamforming at azimuth 90° and elevation 0° reveals a main lobe shifted toward the desired angle, accompanied by well-controlled side lobes. Although metrics such as beam gain and beamwidth are not shown, the qualitative similarity to optimal beamforming underscores the effectiveness of hybrid beamforming in preserving the desired beam characteristics. Further quantitative analysis is recommended to expand on this study.

In this pattern, the side lobes are more prominent than those observed with optimal weights. This increase is due to the approximations and fewer degrees of freedom in hybrid beamforming. Despite a reduction in precision, hybrid beamforming still offers commendable performance at a lower hardware cost. By reducing the number of RF chains while approximating the optimal beam pattern, hybrid beamforming strikes a balance between cost and performance. This makes it particularly suitable for large antenna arrays where fully digital systems would be too costly, such as in practical 5G deployments and massive MIMO setups.

Computational Complexity of Beamforming with hybrid weight configuration: By using fewer RF chains, simplifies the computational process. It employs more efficient algorithms, reducing the time and resources needed for processing, and is better suited for real-time operations. Hybrid Beamforming lowers hardware costs by reducing the number of RF chains needed, making it a more cost-effective option. This is especially beneficial for large-scale applications like 5G small cells, where cost efficiency and scalability are essential.

The spectral efficiency of beam patterns for single and two data streams with both optimal and hybrid weights are depicted in Figure 8. For a single data stream (Ns = 1), both optimal and hybrid weights show similar trends in spectral efficiency, with performance improving as the SNR increases. At lower SNR levels (below -20 dB), the difference between the two methods is minimal, suggesting that hybrid beamforming is effective in low-SNR situations where cost efficiency is crucial. As the SNR increases, optimal beamforming begins to exhibit a clear advantage over hybrid beamforming, benefiting from its precise control over beam pattern and power distribution.

When using two data streams (Ns = 2), both optimal and hybrid weights result in a noticeable improvement in spectral efficiency compared to a single stream, as the system can handle more data simultaneously, thereby boosting throughput. The disparity in performance between hybrid and optimal beamforming becomes more pronounced with two data streams, particularly at higher SNR values (above -15 dB). Optimal beamforming achieves significantly higher spectral efficiency due to its enhanced capability to manage multiple streams, while hybrid beamforming experiences greater performance degradation due to its inherent approximations. As the number of streams increases, optimal beamforming demonstrates greater benefits in managing signal directionality and separation, although hybrid beamforming still offers acceptable performance at a lower cost, making it suitable for multi-stream scenarios where budget and energy efficiency are important.

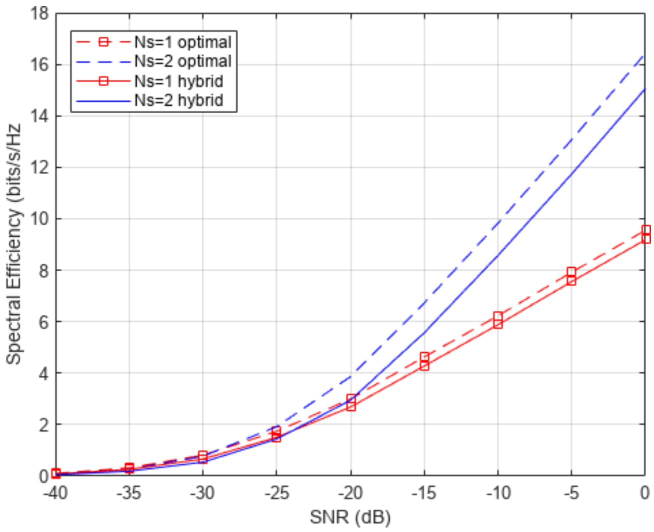

Fig. 8. Spectral Efficiency Comparison of Optimal and Hybrid Beamforming for Single and Dual Data Streams

Beamforming with optimal weights achieves remarkable accuracy in defining the beam pattern, notably enhancing the main lobe and minimizing side lobes. This method optimizes spectral efficiency, particularly in high SNR conditions and with multiple data streams, by leveraging all available degrees of freedom to direct the signal. It is especially effective in scenarios where maintaining high signal quality and reducing interference are essential, such as in mm Wave and 5G applications.

Beamforming with hybrid weights provides a cost-efficient solution by utilizing fewer RF chains, while still delivering satisfactory beam patterns and spectral efficiency, particularly in low-SNR or single-stream scenarios. This approach generally leads to more noticeable side lobes and slightly reduced spectral efficiency, especially at higher SNR levels and with multiple data streams. Despite these trade-offs, hybrid beamforming proves practical when budget constraints, power consumption, and scalability are important factors. It is particularly suitable for practical 5G deployments, massive MIMO setups, and extensive antenna arrays where fully digital beamforming would be too costly.

The simulation results demonstrate that optimal beamforming performs best in high-SNR environments with multiple data streams, as it enhances spectral efficiency and reduces interference, making it well-suited for demanding applications like mm wave and 5G backhaul. However, this comes at the cost of increased hardware complexity and power consumption, which may limit scalability. In contrast, hybrid beamforming lowers the number of RF chains, providing a more cost-effective and scalable solution, particularly for large antenna arrays in 5G small cells. While it offers slightly reduced beamforming precision and spectral efficiency, the balance between performance and reduced hardware demands makes hybrid beamforming a more viable option for large-scale deployments.

Beamforming with optimal weights is best suited for high-performance systems where power and cost constraints are less of an issue, such as in base stations or mm Wave backhaul links. On the other hand, beamforming with hybrid weights is more appropriate for large-scale deployments like 5G small cells, where it is crucial to reduce hardware complexity and power consumption while maintaining competitive performance.

The findings indicate that both optimal and hybrid beamforming have distinct advantages depending on the specific system requirements and constraints. Optimal weights deliver superior performance, particularly in high-SNR and multi-stream environments, but at the cost of higher expenses and complexity. Hybrid weights offer a balanced approach, providing a practical compromise between performance and hardware efficiency, making them well-suited for scalable and cost-sensitive applications such as 5G deployments.

5. Conclusion

This study examines beamforming techniques using both optimal and hybrid weights, with an emphasis on their performance, cost-effectiveness, and suitability for various applications. Optimal beamforming achieves higher accuracy, featuring sharp main lobes and minimal side lobes, which significantly enhances spectral efficiency, particularly in high SNR and multi-stream scenarios. It is well-suited for high-performance applications like mm wave and 5G systems, where maintaining signal integrity and minimizing interference are crucial. In contrast, hybrid beamforming provides a more cost-effective solution by using fewer RF chains, offering adequate performance in low-SNR or single-stream environments. While it produces more pronounced side lobes and slightly lower efficiency, it remains a viable choice for large-scale deployments focused on cost and power savings. The study concludes that optimal beamforming is preferable in settings with fewer budget and power limitations, whereas hybrid beamforming is a practical solution for cost-sensitive applications. Further research could aim to optimize hybrid beamforming, particularly to reduce side lobes and improve efficiency in real-world settings. Additionally, a more detailed investigation into hybrid beamforming’s potential in mm wave and 5G systems would offer useful insights into its deployment in next-generation wireless networks.

References

[1] M. H. Alsharif and R. Nordin, "Evolution towards fifth generation (5G) wireless networks: Current trends and challenges in the deployment of millimetre wave, massive MIMO, and small cells," *Telecommunication Systems*, vol. 64, pp. 617-637, 2017.

[2] Q. Xu, C. Jiang, Y. Han, B. Wang, and K. J. R. Liu, "Waveforming: An overview with beamforming," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 1, pp. 132-149, 2017.

[3] W. Roh et al., "Millimeter-wave beamforming as an enabling technology for 5G cellular communications: Theoretical feasibility and prototype results," *IEEE Communications Magazine*, vol. 52, pp. 106-113, 2014.

[4] S. Zhang, C. Guo, T. Wang, and W. Zhang, "ON–OFF analog beamforming for massive MIMO," *IEEE Transactions on Vehicular Technology*, vol. 67, no. 5, pp. 4113-4123, 2018.

[5] S. Ioushua and Y. C. Eldar, "A family of hybrid analog–digital beamforming methods for massive MIMO systems,” *IEEE Transactions on Signal Processing*, vol. 67, no. 12, pp. 3243-3257, 2019.

[6] A. F. Molisch et al., "Hybrid beamforming for massive MIMO: A survey," *IEEE Communications Magazine*, vol. 55, no. 9, pp. 134-141, 2017.

[7] I. Ahmed et al., "A survey on hybrid beamforming techniques in 5G: Architecture and system model perspectives," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 4, pp. 3060-3097, 2018.

[8] S. A. Khwandah, J. P. Cosmas, P. I. Lazaridis, Z. D. Zaharis, and I. P. Chochliouros, "Massive MIMO systems for 5G communications," *Wireless Personal Communications*, vol. 120, pp. 2101-2115, 2021.

[9] X. Gao, L. Dai, S. Han, C.-L. I, and R. W. Heath, "Energy-efficient hybrid analog and digital precoding for mmWave MIMO systems with large antenna arrays," *IEEE Journal on Selected Areas in Communications*, vol. 34, pp. 998-1009, 2016.

[10] X. Yu, J. C. Shen, J. Zhang, and K. B. Letaief, "Hybrid precoding design in millimeter wave MIMO systems: An alternating minimization approach," in *Proceedings of the IEEE Global Communications Conference (GLOBECOM)*, San Diego, CA, USA, 2015, pp. 1-6.

[11] F. Khan, Z. Pi, and S. Rajagopal, "Millimeter-wave mobile broadband with large scale spatial processing for 5G mobile communication," in *Proceedings of the 50th Annual Allerton Conference on Communication, Control, and Computing*, Monticello, IL, USA, 2012, pp. 1517-1523.

[12] Z. Xu, S. Han, Z. Pan, and C.-L. I, "Alternating beamforming methods for hybrid analog and digital MIMO transmission," in *Proceedings of the IEEE International Conference on Communications (ICC)*, London, UK, 2015, pp. 1595-1600.

[13] O. El Ayach, R. W. Heath, S. Rajagopal, and Z. Pi, "Multimode precoding in millimeter wave MIMO transmitters with multiple antenna sub-arrays," in *Proceedings of the IEEE Global Communications Conference*. *(GLOBECOM)*, Atlanta, GA, USA, 2013, pp. 3476-3480.

[14] E. G. Larsson, O. Edfors, F. Tufvesson, and T. L. Marzetta, "Massive MIMO for next generation wireless systems," *IEEE Communications Magazine*, vol. 52, no. 2, pp. 186-195, 2014.

[15] D. Borges, P. Montezuma, R. Dinis, and M. Beko, "Massive MIMO techniques for 5G and beyond—opportunities and challenges," *Electronics*, vol. 10, no. 14, p. 1667, 2021.

[16] T. Kebede et al., "Precoding and beamforming techniques in mmWave-massive MIMO: Performance assessment," *IEEE Access*, vol. 10, pp. 16365-16387, 2022.

[17] S. Han, C.-L. I, Z. Xu, and C. Rowell, "Large-scale antenna systems with hybrid analog and digital beamforming for millimeter wave 5G," *IEEE Communications Magazine*, vol. 53, no. 1, pp. 186-194, 2015.

[18] K. Ying, Z. Gao, S. Lyu, Y. Wu, H. Wang, and M.-S. Alouini, "GMD-based hybrid beamforming for large reconfigurable intelligent surface assisted millimeter-wave massive MIMO," *IEEE Access*, vol. 8, pp. 19530-19539, 2020.

[19] S. Hamid et al., "Hybrid beamforming in massive MIMO for next-generation communication technology," *Sensors*, vol. 23, no. 16, p. 7294, 2023.

[20] M. A. Albreem, M. Juntti, and S. Shahabuddin, "Massive MIMO detection techniques: A survey," *IEEE Communications Surveys & Tutorials*, vol. 21, pp. 3109-3132, 2021.

Authors' Profiles

Padmasree Ramineni is currently serving as an Assistant Professor in the Department of Electronics and Communication Engineering (ECE) at Rajiv Gandhi University of Knowledge and Technologies, Basar. Alongside her teaching responsibilities, she has completed her Ph.D. in Wireless Communications from Osmania University, Hyderabad. She obtained her M. Tech degree in Digital Electronics and Communication Systems (DECS) from Jawaharlal Nehru Technological University (JNTU) Hyderabad, following her undergraduate studies in Electronics and Communications Engineering (ECE) from the same institution. She has contributed significantly to her field and has published several papers internationally. Her research interests lie in the interdisciplinary fields of Wireless Communication, Advanced Microcontrollers-Embedded Systems, Wireless Sensor Networks, Antenna Designs, and Machine Learning. She is actively engaged in both teaching and research, contributing to the advancement of knowledge in her areas of expertise.

Pranaya Pasula is currently serving as an Assistant Professor in the Department of Electronics and Communication Engineering (ECE) at Rajiv Gandhi University of Knowledge and Technologies, Basar. She obtained her M. Tech degree in VLSI from Jawaharlal Nehru Technological University (JNTU) Hyderabad, following her undergraduate studies in Electronics and Communications Engineering (ECE) from the same institution. Her research interests lie in the interdisciplinary fields of VLSI, Advanced Microcontrollers-Embedded Systems and Machine Learning.

Tejasvey Panchareddy is currently serving as an Assistant Professor in the Department of Electronics and Communication Engineering (ECE) at Rajiv Gandhi University of Knowledge and Technologies, Basar. Alongside her teaching responsibilities, she is pursuing a part-time Ph.D. in IOT and Embedded systems at Gitam's University, Hyderabad. She obtained her M. Tech degree in VLSI from Jawaharlal Nehru Technological University (JNTU) Hyderabad, following her undergraduate studies in Electronics and Communications Engineering (ECE) from the same institution. Her research interests lie in the interdisciplinary fields of Advanced Microcontrollers-Embedded Systems, IOT Networks, and Machine Learning.

How to cite this paper: Padmasree Ramineni, Pranaya Pasula, Tejasvey Panchareddy, "Performance Analysis of Optimal and Hybrid Beamforming Techniques and Spectral Efficiency Enhancement for 5G Millimeter-Wave Systems", International Journal of Wireless and Microwave Technologies(IJWMT), Vol.15, No.1, pp. 51-65, 2025. DOI:10.5815/ijwmt.2025.01.04