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Millimetre-wave Massive MIMO Systems with Optimal Hybrid Precoding

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Abstract- For millimetre-wave (mm-wave) massive-MIMO systems, unrestricted digital precoding is problematic due to the requirement for separate radiofrequency (RF) chains for each antenna, which results in significant costs and power consumption. Hybrid precoding, which enhances data stream adaptability and permits large MIMO transmission in mm-wave communications, is introduced as a workable approach in this study. Our study focuses on capacity analysis and hybrid precoding optimization in mm-wave massive MIMO systems, opening the path for next-generation wireless communication technologies that are more effective, affordable and have high throughput and low energy consumption.

Keywords: *Massive MIMO, Hybrid precoding, Millimetre wave, RF Chain*

1. Introduction

Throughout wireless communication setups, spectral efficiency and output power consumption stand out as critical performance measures [1,2]. In particular, the fifth generation (5G) has brought about notable improvements in terms of fast transmission and low latency. The development of new physical layer technologies, network densification strategies, and other methods [3-6] is largely responsible for these advancements. However, the current issue of spectrum scarcity continues to be crucial to the development of communication networks. Millimeter-wave (mm-wave) technology offers a solution to this problem by providing more spectrum resources to meet the bandwidth requirements of 5G services [7].

By employing shorter wavelengths, the mm-wave massive MIMO technology allows multiple large-scale antennas to be aggregated into confined physical locations. In the millimeter-wave spectrum, massive MIMO technology enables the efficient use of gigahertz-level capacity. By employing massive arrays of antennas, this invention increases data rates and broadens coverage, making it a crucial tactic in the developing field of wireless communications [8]. But a problem occurs when every antenna has its own radio frequency network, which raises the cost of hardware and energy consumption and makes it unfeasible from an economic standpoint. Hybrid beamforming technology [9] provides a solution to this issue by lowering the large route losses that are a part of millimeter-wave transmission and increasing connection dependability.

Due to significant signal propagation losses, traditional MIMO transceiver setups have difficulty obtaining effective signal identification in millimeter-wave (mm-wave) environments. In order to improve the received signal strength, a large number of antennas must be added to the transmitting and receiving ends in order to solve this problem. Acknowledging this requirement, future 5G wireless communication systems are driving the use of huge MIMO transceiver designs [10].

MM-wave communication is a promising technique in the context of fifth-generation networks [11]. Hybrid precoding techniques are used in mm-wave communication systems to balance energy consumption and system performance [12]. By fusing excellent digital precoding with affordable analogue beamforming techniques, hybrid precoding seeks to strike the best possible compromise [13]. This is swapping out a huge digital precoder for a smaller one and adding a larger analogue precoder that maintains magnitude by using cheap phase shifters. Baseband and RF precoding are the terms used to describe the digital and analogue precoding algorithms that function in the corresponding baseband and RF domains. Non-convex optimisation is a challenging task because of the fixed magnitude constraints on phase shifters, which complicate the design of hybrid precoders and combiners.

Moreover, the intricacy of a successful design is increased by the interaction complexity between hybrid precoders and combiners, whether on the transmitter or receiver side [14]. Notwithstanding these obstacles, the efficacy of ideal hybrid precoding methods in the context of millimeter-wave technology has been confirmed by successful demonstrations. This work's second portion compares

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different precoding techniques and discusses the importance of massive MIMO technology in the context of hybrid precoding for millimeter-wave applications. Section 4 covers the technicalities of simulation and performance evaluations, whereas Section 3 explores the mathematical analysis of hybrid precoding in millimeter-wave MIMO systems. In conclusion, Section 5 offers suggestions for additional study.

2. Hybrid Architectures with Massive MIMO Technology

Massive MIMO is one of the most successful wireless communication systems because of its unique benefits, which include high user capacity, enhanced spectral density, and diversity. These characteristics are especially important for the current 5G-IoT age and the networks of the future. Large-scale MIMO systems use more antennas to enhance the advantages of classic MIMO, serving more users concurrently with the same time and frequency resources.

Although present wireless systems work in the sub-6 GHz band (frequency range below 6 GHz) [15], it is expected that the next generation of wireless networks will use the mm-wave spectrum. The incredibly low wavelength (λ) of the mm-wave spectrum results in reduced power received by the square of the wavelength (λ^2), making it an ideal choice for propagation. When additional antenna components are crammed into the same physical area, the directional antenna gains increase by 1/^2. This increased antenna gain compensates for the higher propagation losses at mm-wave frequencies. Consequently, in order to fully use mm-wave MIMO (mm-wave massive MIMO) benefits, beamforming from a sizable antenna array becomes essential [16].

Appropriate beamforming, precoder/combiner design strategies, and MIMO architecture at mm-wave frequencies differ greatly from sub-6 GHz in the implementation of mm-wave systems [17]. Fig. 1 shows fully digital precoding, which is digital baseband signal processing below 6 GHz, with each antenna having its own RF chain and ADC/DAC.

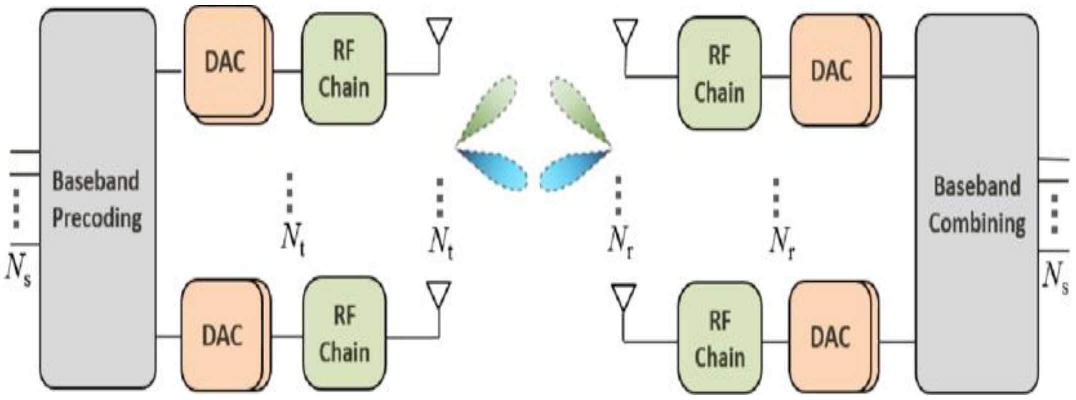

Fig. 1 Fully digital precoding [18]

Due to various hardware limitations, separate Radio Frequency (RF) chains and data converters for every antenna in mm-wave MIMO systems become impractical:

- **Implementation Challenges:** It is difficult to implement distinct RF chains for every antenna at mm-wave frequencies because each RF chain needs a low-noise amplifier and a power amplifier.
- **Fast-Sampling Rate and Power Usage:** Power consumption in the millimeter-wave range is made worse by the high sampling rate, particularly when each antenna has a large number of DACs and ADCs working at giga samples per second [19].
- **Physical Space Constraint:** The practicality of utilising an entire RF chain for every antenna is limited by the physical closeness of antennas because of spatial limitations.

Modern designs for mm-wave MIMO systems must use hybrid analog-digital signal processing due to these significant hardware constraints. To overcome the difficulties brought on by hardware limitations, this method combines the analogue and digital worlds.

Analogue beamforming (RF beamforming) is a basic technique that can be used at both the transmitter and the receiver in mm-wave MIMO systems [20]. The IEEE 802.11ad standard recognises this method as a workable fix. In analogue beamforming, RF beamforming is made possible by digitally controlled phase shifters that connect every antenna element to a single RF chain. But it's crucial to remember that, as Fig. 2 illustrates, only one user can be serviced at a time with single-symbol transmission, which limits the simultaneous advantages of MIMO.

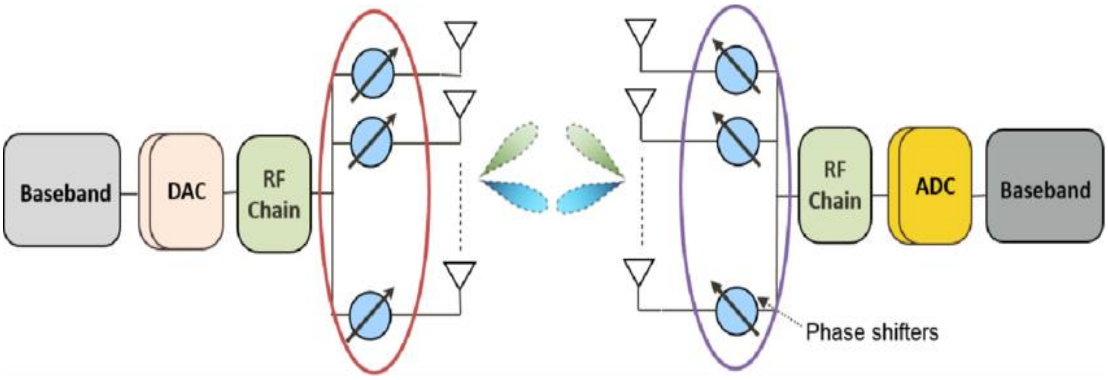

Fig. 2 Analog-only beamforming [18]

In the first scenario, where distinct signals are created for each antenna in the digital domain, analogue phase shifters modify the array's signal to guide it in the desired direction. Digital beamforming, sometimes referred to as precoding, is the process of multiplexing numerous data streams by generating several beams, choosing the direction of travel (steering), and allocating power to transmit the data. Hybrid precoding, also known as hybrid beamforming, is a signal processing technique that uses both the analogue and digital domains. Reduced transceiver power and radio frequency (RF) chains are the result of this hybrid architecture.

The number of radio frequency chains utilised on the transmitter and reception sides, respectively, is indicated by the parameters N_t^RF and N_r^RF in the context of hybrid precoding for millimeter-wave communication. Proper utilisation is ensured by the constraints N_s ≤ N_t^RF < N_t and N_s ≤ N_r^RF < N_r, where N_s is the number of streams and N_r and N_t are the transmitter and receiver antennas, respectively.

Hybrid design enables spatial multiplexing and multiuser Multiple Input Multiple Output (MIMO) in mm-wave settings, which are not possible with analogue beamforming alone. Two structural types of hybrid precoders are available for single-user systems: (i) the spatially sparse hybrid precoder, which has a fully integrated design with phase shifters connecting every Base Station (BS) antenna to every RF chain; and (ii) the sequential interference cancellation hybrid precoder, which has a subarray of BS antennas linked to each RF chain in a sub-connected design. These structures are shown in Figures 3(a) and (b), respectively. The latter architecture sacrifices flexibility in order to reduce hardware complexity.

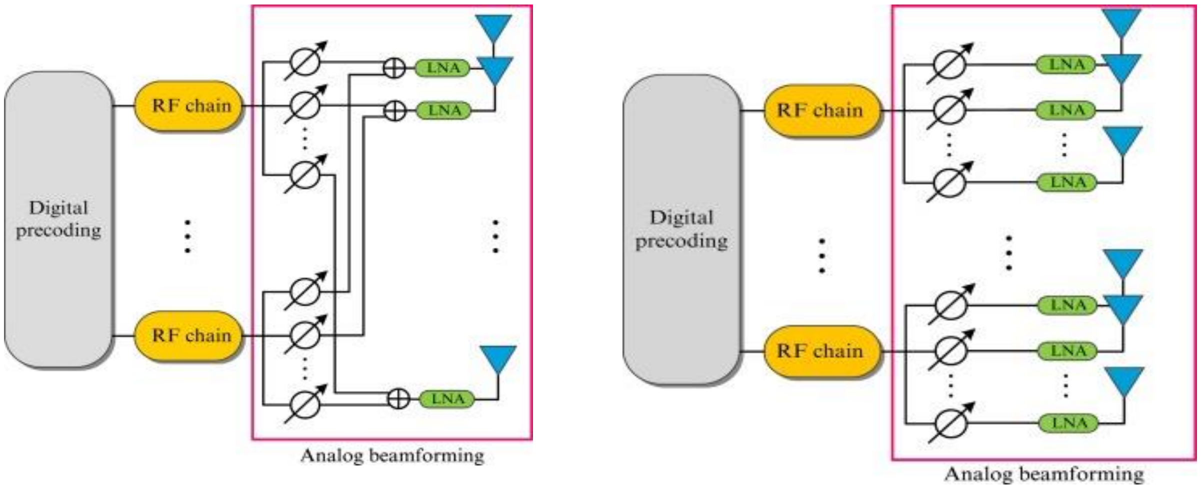

Fig. 3 BS antenna linked with RF chain in different configuration [**23**]

Table 1: Comparison of various Precoding Methods

Attributes	**Analog only Beamforming**	**Fully Digital (Baseband) Precoding**	**Hybrid - Precoding**
Quantity of streams	One stream only	Multiple streams	Multiple streams
Total number of users	One user only	Multiple users	Multiple users
Capability for signal control	Control only phases	Control both phases as well as the amplitude	Both phase and amplitude can be controlled
Required hardware	Minimum: Only a single Radio Frequency chain is used.	Maximum: Dedicated RF chain per antenna element	Moderate: Radio Frequency chains are fewer compared to transmit antennas.
Energy dissipation	Minimum	Maximum	Moderate
Cost	Minimum	Maximum	Moderate
Performance	Minimum	Optimal	Close to Optimal
Suitability for large MIMO at mm-wave	Unsuitable since there is no control on amplitude and not support multi-user	Excessive cost, space constraints along excessive power use make it impractical.	Realistic and practical

3. Millimeter Wave Massive Mimo

Millimeter-wave technology minimises diffraction effects by having a smaller Fresnel zone and larger penetration losses than sub-6 GHz technology, which results in fewer multipath components. In millimeter-wave systems, massive MIMO improves channel sparsity. The expression for the millimeter-wave channel model is:

$$\mathbf{H}=\sum_{l=1}^{L}\alpha_l\,\mathbf{a}_R(\theta_l^r)\,\mathbf{a}_T^H(\theta_l^t)=\overline{\mathbf{A}}_R\,\mathbf{H}_b\overline{\mathbf{A}}_T^H$$

L is the number of scatters or multipaths. The transmitting end's array steering vector is a_T, while the receiving end's is a_R. The lth path's complicated gain is _l. There are Angles of Arrival (AoA) (_lr) and Angles of Departure (_lt) for each path. The dictionaries for the transmit and receive array responses are AT and AR [**17**].

$$\theta_i\in\Phi=\{\theta_1,\theta_2,\ldots,\theta_G\},\ \text{where }\Phi\text{ denotes the angular grid.}$$

Beam space channel representation is given by: $-\mathbf{H}=\mathbf{A}_\mathrm{R}\,\mathbf{H}_b\mathbf{A}_T^H$

$\mathbf{H}_b$, the beam space has a channel matrix many zero elements, indicating sparsity. The challenge of channel estimation is to minimize the ‖h_b‖_0 norm, commonly known as compressive sensing. This problem is non-convex, making direct solutions challenging. Sparse signal estimation and refinement are possible with the Orthogonal Matching Pursuit algorithm.

3.1 Hybrid Precoding for Millimeter-Wave MIMO

Hybrid precoding in a millimeter-wave massive MIMO system is shown in Fig. 4. Precoding determines the transmission directions for transmission, and the combiner inversely reconstructs the precoding for reception to precisely collect signals from the desired directions.

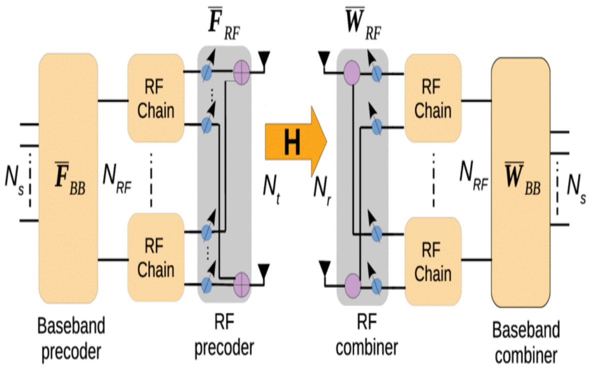

Fig4. Millimetre-Wave Massive-MIMO with Hybrid Precoding [24]

3.1.1 Optimal Precoder

For conventional MIMO systems, the optimal precoder is $\mathbf{F}=\overline{\mathbf{V}}$, also known as an ideal fully digital precoder for millimeter-wave (mm-wave) MIMO. The mm-wave MIMO precoding model is given by:

$$\tilde{y}=\mathbf{Hx}+\mathbf{n}=\mathbf{H}\boldsymbol{F}_{RF}\boldsymbol{F}_{BB}\mathbf{s}+\mathbf{n}=\mathbf{HFs}+\mathbf{n}$$

Here, the sizes of the precoding matrices are

$\mathbf{F}_{RF} \sim N_t \times N_{RF}$

$\mathbf{F}_{BB} \sim N_{RF} \times N_S$

3.1.2 mm-Wave Precoder

Ideally, we aim for $\overline{\mathbf{V}} = \mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}$ The baseband precoder ($\mathbf{F}_{\mathrm{BB}}$) is normalized to meet the overall transmit power restriction:

$\|\mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}\|_{\mathrm{F}}^2 = \mathrm{N_s}$

Entries of $\mathbf{F}_{RF}$ have to be unit- magnitude phase -shifters $e^{j\Phi}$

From the channel for mm-Wave given in (1) it can be observed that basis for the column space $\mathbf{H}^H$ is formed by response vectors of transmit array in $\overline{\mathbf{A}}_{\mathrm{T}}$, As a result, in the MIMO channel for mmWave, $\overline{\mathbf{V}}$ may be represented in the form of a linear combination of $\overline{\mathbf{A}}_{\mathrm{T}}$ columns are shown below.

$$\overline{\boldsymbol{V}} = \overline{\boldsymbol{A}_T}\ \overline{\boldsymbol{F}} \tag{5}$$

3.1.3 Ideal RF/BB precoders

Ideally $\overline{\mathbf{A}}_{\mathrm{T}}$ can be made of RF precoder, because entries of $\overline{\mathbf{A}}_{\mathrm{T}}$ are unit magnitude

$$\mathbf{a}_{T}(\theta_l^t) = \begin{bmatrix} \mathbf{1} \\ \boldsymbol{e}^{-j\frac{2\pi}{\lambda}} d_t \cos\theta_l^t \\ \vdots \\ \boldsymbol{e}^{-j\frac{2\pi}{\lambda}} (N_t - 1) d_t \cos\theta_l^t \end{bmatrix} \tag{6}$$

and $\overline{\mathbf{F}}$ can be the baseband precoder.

3.1.4 Precoder optimization

Since $\overline{\mathbf{A}}_{\mathrm{T}}$ is unknown, one can use the dictionary matrix.

$$\mathbf{A}_{\mathrm{T}} = [\,\mathbf{a}_T(\theta_1) \quad \mathbf{a}_T(\theta_2) \ \ldots \ \mathbf{a}_T(\theta_G)] \tag{7}$$

$\overline{\mathbf{F}}$ can only contain N_{RF} non-zero rows. it is simultaneously sparse.

The optimization problem for precoder design is.

$$\arg \quad \min \quad \left\|\overline{\mathbf{V}} - \mathbf{A}_T\,\tilde{\mathbf{F}}_{BB}\ \right\|_F^2 \tag{8}$$

$$\text{s.t.} \quad \left\|\operatorname{diag}\left(\tilde{\mathbf{F}}_{BB}\ \tilde{\mathbf{F}}_{BB}^H\right)\right\|_0 = \quad N_{RF} \tag{9}$$

Simultaneous Orthogonal Matching Pursuit (SOMP), an extension of OMP for sparse signal recovery, can solve this. $\mathbf{F}_{RF}^{(0)} = []$, $\mathbf{F}_{res}^{(0)} = \overline{\mathbf{V}}$

For $1 \le k \le N_{RF}$

$\Psi = \mathbf{A}_T^H\,\mathbf{F}_{res}^{(k-1)}$

$\mathrm{i}(k) = \arg\max[\Psi\Psi^{\boldsymbol{H}}]_{l,l}$

$\mathbf{F}_{RF}^{(k)} = \left[\mathbf{F}_{RF}^{(k-1)}\ \middle|\,\mathbf{a}_T\ (\theta_{i(k)}\right]$

$\mathbf{F}_{BB}^{(k)} = \left(\left(\mathbf{F}_{RF}^{(k)}\right)^H \mathbf{F}_{RF}^{(k)}\right)^{-1} \left(\mathbf{F}_{RF}^{(k)}\right)^H \overline{\mathbf{V}}$

$\mathbf{F}_{\mathrm{res}}^{(\mathrm{k})} = \dfrac{\overline{\mathbf{V}} - \mathbf{F}_{RF}^{(k)}\ \mathbf{F}_{BB}^{(k)}}{\left\|\overline{\mathbf{V}} - \mathbf{F}_{RF}^{(k)}\mathbf{F}_{BB}^{(k)}\right\|_F}$

end for

Algorithm 1: Precoder Optimization using SOMP.

3.1.5 Combiner optimization

At the receiver, the optimal fully digital combiner is the MMSE combiner which is given as

$$\mathrm{W_{mmse\_opt}} = \mathrm{HF_{opt}}\left(\mathrm{F_{opt}^H H^H H F_{opt}} + \mathrm{N_S}\sigma^2\mathrm{I}\right)^{-1} \tag{10}$$

Hybrid MMSE combiner is given as

$$\mathrm{W_{mmse\_Hyb}} = \mathrm{HF_{RF}}F_{BB}\left(\mathrm{F_{BB}^H}F_{RF}^H\mathrm{H^H H F_{RF}}F_{BB} + \mathrm{N_S}\sigma^2\mathrm{I}\right)^{-1} \tag{11}$$

MSE minimization is equivalent to min

$$\left\|R_{yy}^{\frac{1}{2}}\left(\overline{W}_{mmse\_Hyb} - W_{RF}\,W_{BB}\ \right)\right\|_F^2 \tag{12}$$

$$R_{yy} = HF_{RF}F_{BB\_norm}F_{BB\_norm}^H F_{RF}^H H^H + N_S\sigma^2 \tag{13}$$

3.1.6 MMSE minimization

$\mathbf{W}_{RF}$ can be formed from the receive array response vector $\mathbf{a}_R(\theta_l^r)$.However, these are unknown, Start with the dictionary matrix

$$\mathbf{A}_{\mathrm{R}} = [\,\mathbf{a}_R(\theta_1) \quad \mathbf{a}_R(\theta_2) \ \ldots \ \mathbf{a}_R(\theta_G)] \tag{14}$$

The problem of optimization can be written as

$$\min \quad \left\|\mathbf{R}_{yy}^{\frac{1}{2}}\left(\overline{\boldsymbol{W}}_{\boldsymbol{mmse\_Hyb}} - \mathbf{A}_R\,\widetilde{\mathbf{W}}_{BB}\ \right)\right\|_F^2 \tag{15}$$

SOMP can once again be used to design $\widetilde{\mathrm{W}}_{BB}$

$\mathbf{W}_{RF}^{(0)} = []$, $\mathbf{W}_{res}^{(0)} = \overline{\mathbf{W}}$

For $1 \le k \le \mathrm{N}_{RF}$

$\Psi = \mathbf{A}_{\mathrm{R}}^H\mathbf{R}_{yy}\,\mathbf{W}_{res}^{(k-1)}$

$\mathrm{i}(k) = \arg\max[\Psi\Psi^{\boldsymbol{H}}]_{l,l}$

$\mathbf{W}_{RF}^{(k)} = \left[\mathbf{W}_{RF}^{(k-1)}\ \middle|\,\mathbf{a}_R\ (\theta_{i(k)}\right]$

$\mathbf{W}_{BB}^{(k)} = \left(\left(\mathbf{W}_{RF}^{(k)}\right)^H \mathbf{R}_{yy}\mathbf{W}_{RF}^{(k)}\right)^{-1} \left(\mathbf{W}_{RF}^{(k)}\right)^H \mathbf{R}_{yy}\ \overline{\mathbf{W}}$

$$\mathbf{W}_{\mathrm{res}}^{(\mathrm{k})} = \frac{\bar{\mathbf{W}} - \mathbf{W}_{RF}^{(k)} \; \mathbf{W}_{BB}^{(k)}}{\left\| \bar{\mathbf{W}} - \mathbf{W}_{RF}^{(k)} \mathbf{W}_{BB}^{(k)} \right\|_F}$$

end for

Algorithm 2: Combiner Optimization using SOMP.

4 Simulation Result and Discussion

With an emphasis on sum rate and energy efficiency, this section discusses and displays the findings of simulations on hybrid precoding in massive MIMO technology. The parameters listed in Table 2 were used for the simulations.

Table 2. Simulation Parameters

Parameters	Value
Number of Transmit (Tx) & Receive (Rx) antennas	t = 32, r = 32
Number of Radio Frequency (RF) Chains	numRF = 6, 8
Gride size (size of Dictionaries)	G = 32, 64
Number of Multipath Components	L = 5,8
Number of Symbols	Ns = 6
Number of Iterations	ITER=1000
Signal to Noise Ratio (SNR) from 10 to 50 at the step size of 5	SNR = 10:5:50
SNR from -5 to 5 at the step size of 1	SNR = -5:1:5

The OMP technique reduces mean square error (MSE) in predicting mmWave channel parameters compared to the reference ORACLE model. Additionally, the SOMP technique is utilized to compare the capacity of an mm-wave hybrid precoding system to a standard MIMO model. In Fig. 5, the mmWave MIMO channel estimation performance is demonstrated using OMP, where the transmitter and receiver are equipped with 32 antennas each, and the base station (BS) has 8 RF chains. Angles of departure ranging from 0 to 180 degrees are calculated using 32-grid dictionary matrices. OMP initialization maintains a threshold of 1, and channel sparsity is assumed to be 5.

Fig. 6 illustrates the capacity vs SNR analysis for a model of the mm-wave system with 32 Rx/Tx, equipped with 6 RF chains. The sparsity level is assumed to be eight for a sparse mm-wave channel with six streams of data being broadcast concurrently. The SOMP method, an optimal hybrid precoding algorithm, is employed for capacity analysis. It is noteworthy that the performance of the suggested scheme (SOMP algorithm) is comparable to that of a traditional digital precoder, which is an optimal fully digital precoder with the number of Radio Frequency chains equal to the antenna count.

As depicted in Fig. 7, when the number of Radio Frequency chains is further increased and set equal to the number of multipath or sparsity levels of the channel (i.e., number of RF chains = 8 and L = 8), the performance gap is significantly reduced. Hybrid precoding approaches closer to fully digital optimal precoding. The suggested scheme's capacity is nearly identical to that of completely digital precoding, with a much lower requirement of RF chains compared to fully digital precoding. Additionally, the system functions optimally when Ns is less than or equal to the channel's sparsity.

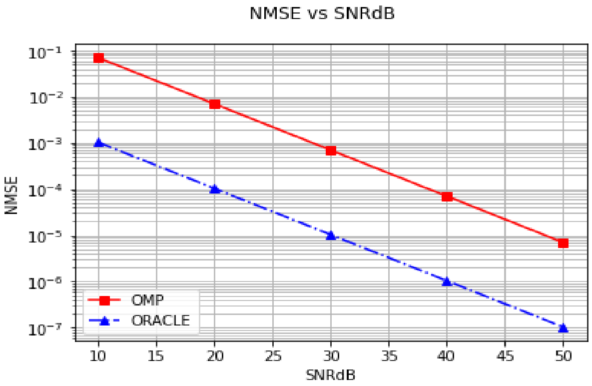

Fig. 5: Millimeter Wave MIMO Channel Estimation Performance using OMP

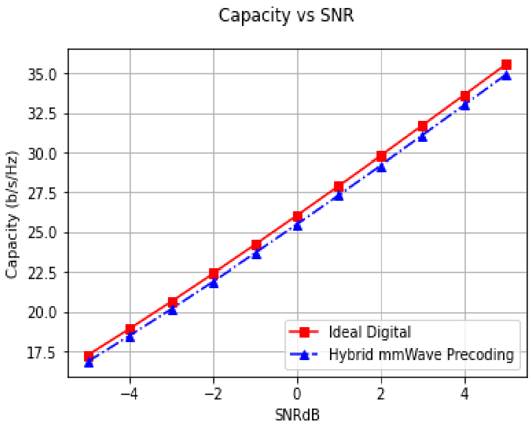

Fig. 6: Capacity vs SNR Investigation for an mm-wave system.

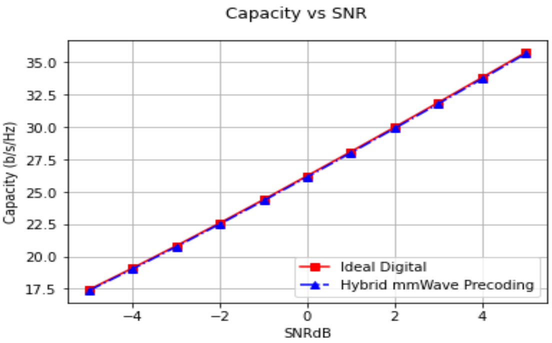

Fig. 7: Capacity Analysis for Proposed Scheme.

5. Conclusion and Future Work

With an emphasis on energy efficiency, this study assesses the sum rate of hybrid precoding methods in large MIMO systems running at mm-wave frequencies. The Sequential Orthogonal Matching Pursuit (SOMP) technique is used for hybrid precoding optimisation, and the sum rate and power reduction results are compared to typical baseband precoding techniques. When compared to ordinary MIMO systems, the hybrid precoding technique achieves a system capacity that is nearly optimum. In order to solve multi-cell interference, future work could broaden this research to cover multi-cell and user scenarios.

Credit authorship contribution statement

Shailender: Methodology, Conceptualization of Original draft, data curation, software. **Shelej Khera:** Conceptualization, Supervision, Data curation, Funding acquisition. **Sajjan Singh:** Supervision, Writing-review & editing, Software, Proofreading.

Declaration of competing interest

The author discloses no competing interests.

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Data availability

This study's data is available upon reasonable request.

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