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Optimization and Performance Evaluation of RIS-Integrated Hybrid Precoding in Millimeter Wave Massive MIMO

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Abstract –The evolution toward sixth-generation (6G) wireless systems requires extremely high data rates, massive device connectivity, very low latency, and improved energy efficiency. Millimeter-wave (mmWave) communication is considered a key enabler due to its large available bandwidth and ability to support multi-gigabit transmission. Nevertheless, mmWave signals experience high path loss, vulnerability to blockage, and increased implementation complexity caused by large antenna arrays and multiple RF chains.To overcome these limitations, this thesis explores the integration of Reconfigurable Intelligent Surfaces (RIS) with hybrid analog–digital precoding in mmWave Massive MIMO systems. RIS enables intelligent control of signal propagation by adjusting the phase of reflected waves, while hybrid precoding reduces hardware cost and power consumption without significantly degrading performance. A detailed system model, mathematical analysis, and optimization strategies for precoders and RIS phase shifts are presented. Performance evaluation based on spectral efficiency, energy efficiency, and hardware complexity demonstrates that RIS-assisted hybrid architectures provide notable improvements in coverage, achievable rate, and power utilization.

Keywords-Reconfigurable Intelligent Surfaces, mmWave Massive MIMO systems, Precoders and RIS phase shifters

I. INTRODUCTION

The continuous surge in mobile data demand, fueled by emerging technologies such as immersive multimedia services, large-scale sensor networks, connected transportation systems, and intelligent urban infrastructure, is placing significant pressure on existing wireless communication frameworks [1]. Although fifth-generation networks have introduced improvements in throughput and latency, future sixth-generation systems are expected to support extremely high data rates, ultra-reliable connectivity, minimal communication delay, and the ability to connect an enormous number of devices simultaneously. These ambitious performance targets require innovative transmission techniques and efficient utilization of available spectrum resources.

Millimeter-wave communication has gained considerable attention as a promising solution for high-capacity wireless networks because of its wide bandwidth availability in higher frequency ranges [2]. However, signals operating in these bands are highly sensitive to propagation challenges such as severe path loss, atmospheric attenuation, and obstruction by physical objects. Addressing these issues often requires the deployment of large antenna arrays and sophisticated beamforming strategies, which in turn increase hardware cost, energy consumption, and signal processing complexity. Hybrid precoding has been proposed [3] as a practical alternative to fully digital architectures by combining digital signal processing with analog beam steering, thereby reducing the number of required RF chains while maintaining competitive performance.

In parallel, Reconfigurable Intelligent Surfaces have emerged as an innovative approach to reshape the wireless propagation environment. These surfaces consist of numerous passive reflecting elements capable of adjusting the phase of incoming signals to improve link quality, extend coverage, and mitigate interference. By integrating RIS with hybrid precoding [4], it becomes possible to jointly optimize beamforming efficiency and environmental control[5]. This combined framework offers notable improvements in spectral utilization, power efficiency, and system scalability. Through mathematical modeling, optimization strategies [6], and simulation-based performance evaluation, this thesis demonstrates the potential of RIS-assisted hybrid mmWave communication as a practical and forward-looking solution for next-generation wireless networks and advanced connectivity applications.

The remainder of this paper is organized as follows. Section II presents the literature review and background on mmWave communication and hybrid precoding techniques. Section III describes the system model, including channel modeling and RIS-assisted signal formulation. Section IV discusses the proposed hybrid precoder design and RIS phase optimization methods along with performance analysis. Section V provides simulation results and comparative evaluation based on spectral and energy efficiency metrics. Finally, Section VI concludes the paper and outlines potential future research directions.

II. MM WAVE CHANNEL MODEL

mmWave channels exhibit sparse multipath characteristics. Unlike rich scattering in sub-6 GHz bands, mmWave propagation consists of a limited number of dominant paths.
The widely used Saleh-Valenzuela channel model represents the mmWave channel as:

$$H=\sqrt{\frac{N_tN_r}{L}}\sum_{l=1}^{L}\alpha_l a_r\left(\theta_l\right)\mathrm{a}_t^H\left(\phi_l\right) \tag{1}$$

Where N_tN_r denotes the number of transmitand receive antennas at the user side. The parameter L indicates the total number of dominant propagation paths, reflecting [7] the sparse multipath nature of high-frequency wireless communication environments.The term α_l represents the complex gain. The ULA Array Response can be expressed as

$$a_t\left(\theta\right)=\frac{1}{\sqrt{Nt}}\begin{bmatrix}1\\ e^{j\frac{2\pi}{\lambda}d\sin\theta}\\ \vdots\\ e^{j\frac{2\pi}{\lambda}(Nt-1)d\sin\theta}\end{bmatrix} \tag{2}$$

III. HYBRID PRECODING METHODOLOGY

Hybrid beamforming architectures include fully connected and partially connected structures. In the fully connected architecture, each RF chain is linked to all antennas, offering high performance and flexible beamforming but increasing hardware complexity and power consumption. In the partially connected architecture, each RF chain serves only a subset of antennas, reducing the number of phase shifters and overall system cost.

The objective of hybrid precoding is to approximate the optimal fully digital precoder:

$\min\limits_{\mathrm{F}_{RF},\mathrm{F}_{BB}}\left\|\mathrm{F}_{FD}-\mathrm{F}_{RF}\mathrm{F}_{BB}\right\|_F$ Subject to $\left|\left[\mathrm{F}_{RF}\right]_{i,j}\right|=\frac{1}{\sqrt{N_t}}$. This is a non-convex optimization problem due to constant modulus constraints.

A. *SVD-Based Fully Digital Precoder*

First, compute optimal fully digital precoder using Singular Value Decomposition (SVD) with

$$\mathrm{H}=\mathrm{U}\Sigma\mathrm{V}^H \tag{3}$$

The optimal precoder is:

$$\mathrm{F}_{FD}=\mathrm{V}_{(:,1:N_s)} \tag{4}$$

Where N_s = Number of data streams.
Fully digital optimal precoder: $\mathrm{F}_{opt}=\mathrm{V}_1$ (from SVD of channel).
The Hybrid precoding approximates: $\mathbf{F}_{opt}\approx\mathbf{F}_{RF}\mathbf{F}_{BB}$

Optimization: $\frac{min}{F_{RF},F_{BB}}\|F_{opt}-F_{\mathrm{RF}}F_{BB}\|_2^F$ Subject to

$|[\mathrm{F}_{RF}]_{i,j}|=\frac{1}{\sqrt{Nt}}$ (Phase-only constraint)

B. *Orthogonal Matching Pursuit (OMP) Algorithm*

A widely used method for hybrid precoding is the OMP algorithm, proposed by Ahmed Alkhateeb. The mmWave channels are sparse, meaning only a few dominant propagation paths exist. This sparsity can be exploited using compressed sensing techniques.
OMP selects dominant steering vectors that best approximate the optimal precoder.

OMP Algorithm Steps

Step 1: Initialize Residual matrix $R=F_{FD}$
Step2: Select column from dictionary A that maximizesprojection: $k=\arg\max\limits_i\left\|A_i^H R\right\|$
Step 3: Update RF precoder is $\mathrm{F}_{RF}=\left[\mathrm{F}_{RF},A_k\right]$
Step 4: Compute baseband precoder is $F_{BB}=\left(F_{RF}^HF_{RF}\right)^{-1}F_{RF}^HF_{FD}$
Step 5: Update residual: $R=F_{FD}-F_{RF}F_{BB}$
Repeat until number of RF chains is reached.

IV. PROPOSED RIS METHOD

An RIS is made up of a large number of passive[8] reflecting elements integrated with phase shifters to intelligently control the propagation of wireless signals [9]. It also includes a controller unit and low-power electronic circuits to dynamically adjust reflection characteristics and improve communication performance.

Each RIS element applies a phase shift ϕ_n to the incident signal.The reflection coefficient of the n^{th} element is:

$$\beta_n=\alpha_n e^{j\phi n} \tag{5}$$

Where α_n = Reflection amplitude (usually ≈ 1) and ϕ_n = Adjustable phase shift. The RIS phase shift matrix is expressed as:

$$\Phi=diag(e^{j\phi 1},e^{j\phi 2},\ldots,e^{j\phi N}) \tag{6}$$

Where N = Number of RIS elements

A. *RIS-Assisted System Model*

First, we derive the basic hybrid precoding model without RIS [10-12].Let the transmitted Signal

$$\begin{aligned} &\mathbf{s} \in \mathbb{C}^{K\times 1} \rightarrow \text{data symbol vector} \\ &\mathbb{E}[\mathbf{s}\mathbf{s}^H] = \mathbf{I}_K \end{aligned} \tag{7}$$

The Hybrid precoding is applied as $x = \mathrm{F}_{RF}\mathrm{F}_{BB}\mathrm{s}$ Where

$$\mathbf{F}_{RF} \in \mathbb{C}^{N_t \times N_{RF}} \rightarrow \text{Analog precoder}$$

$$\mathbf{F}_{BB} \in \mathbb{C}^{N_{RF} \times K} \rightarrow \text{Digital precoder}$$

Total power constraint can be given by $\| F_{RF}F_{BB}\|_F^2 = K$

Let the Received Signal at User k, $\mathbf{h}_k \in \mathbb{C}^{1\times N_t}$ be channel from BS to user k.

$$y_k = \mathrm{h}_k \mathrm{F}_{RF}\mathrm{F}_{BB}\mathrm{s} + n_k \tag{8}$$

Where $n_k \sim \mathcal{CN}(0, \sigma^2)$

Now, consider the two propagation paths such as Direct channel, $\mathbf{H}_d$ and Reflected channel: $\mathbf{H}_{ru}\Phi\,\mathbf{H}_{br}$. The effective channel becomes:

$$\mathrm{H}_{eff} = \mathrm{H}_d + \mathrm{H}_{ru}\Phi\,\mathrm{H}_{br} \tag{9}$$

The received signal can expressed by $y = \mathrm{H}_{eff}\mathrm{Fs} + \mathrm{n}$. RIS enhances the effective channel by intelligently aligning phase shifts [14].

The cascaded channel consists of BS to RIS channel: $\mathbf{H}_{br}$, and the RIS to User channel: $\mathbf{H}_{ru}$

Assuming narrowband flat fading:

$$\begin{aligned} \mathbf{H}_{br} &= \sqrt{\frac{N_t N}{L_1}} \sum_{l=1}^{L_1} \alpha_l \mathbf{a}_{RIS}(\theta_l)\mathbf{a}_t^H(\phi_l) \\ \mathbf{H}_{ru} &= \sqrt{\frac{NN_r}{L_2}} \sum_{k=1}^{L_2} \beta_k \mathbf{a}_r(\theta_k)\mathbf{a}_{RIS}^H(\phi_k) \end{aligned} \tag{10}$$

Where L_1, L_2= Number of paths, N = RIS elements, N_t = Transmit antennas, N_r = Receive antennas

The reflected channel gain increases proportionally to N^2 under ideal phase alignment.

The maximize received signal power of RIS Phase Optimization is

$$\underset{\Phi}{\Phi max} \| H_{ru}\Phi\, H_{br}\| \tag{11}$$

To achieve constructive interference Optimal Phase Alignment from

$$\phi_n = -\angle(h_{ru,n}h_{br,n}) \tag{12}$$

However, theRandom Phase Configuration $\phi_n \sim U(0, 2\pi)$. For baseline comparison, phase shifts can be randomly generated [15-17].

The Received Signal with RIS can be expressed as

$$y_k = \underbrace{\mathrm{h}_k \mathrm{F}_{RF}\mathrm{F}_{BB}\mathrm{s}}_{Direct\ path} + \underbrace{\mathrm{h}_{r,k}\Phi \mathrm{G}\mathrm{F}_{RF}\mathrm{F}_{BB}\mathrm{s}}_{Reflected\ path} + n_k \tag{13}$$

The effective channel expressed in $\mathrm{h}_k^{eff} = \mathrm{h}_k + \mathrm{h}_{r,k}\Phi\mathrm{G}$ then

$$y_k = \mathrm{h}_k^{eff}\mathrm{F}_{RF}\mathrm{F}_{BB}\mathrm{s} + n_k \tag{14}$$

However, the SINR can be expressed as
For user k:

$$\mathrm{SINR}_k = \frac{\left|\mathrm{h}_k^{eff}\mathrm{F}_{RF}\mathrm{f}_{BB,k}\right|^2}{\sum_{i\neq k}\left|\mathrm{h}_k^{eff}\mathrm{F}_{RF}\mathrm{f}_{BB,i}\right|^2 + \sigma^2} \tag{15}$$

Where $\mathrm{f}_{BB,k}$ = k-th column of F_{BB}

And the Spectral Efficiency derived in $R_k = \log_2(1 + \mathrm{SINR}_k)$

$$\text{Total sum-rate is } R_{sum} = \sum_{k=1}^{K} \log_2(1 + \mathrm{SINR}_k) \tag{16}$$

The Optimization Problemcan be expressed as

$$\max_{\mathrm{F}_{RF}\mathrm{F}_{BB},\Phi} = \sum_{k=1}^{K} \log_2(1 + \mathrm{SINR}_k) \text{ subject to}$$

$$\begin{aligned} &|[\mathbf{F}_{RF}]_{i,j}| = \frac{1}{\sqrt{N_t}} \\ &|e^{j\phi n}| = 1 \end{aligned} \tag{17}$$

Power constraint can give by $\| \mathrm{F}_{RF}\mathrm{F}_{BB}\|_F^2 \leq P$. The Joint problem of Hybrid Precoder + RIS Optimization [18] is

$$\max_{\mathrm{F}_{RF},\mathrm{F}_{BB},\Phi} R_{sum} \text{ Subject toPower and Unit modulus constraints}$$

V. RESULTS AND DISCUSSIONS

Figure 1 shows how energy efficiency changes with the number of RIS elements for Hybrid + RIS and conventional Hybrid schemes. In the conventional Hybrid case, energy efficiency remains almost constant because the system hardware and power usage do not vary with the number of reflecting elements. When RIS is introduced, energy efficiency improves significantly at first due to the additional passive beamforming gain that strengthens the wireless channel. This enhancement increases the achievable data rate while adding only minimal extra power consumption from the RIS circuitry. As a result, the overall system becomes more power-efficient with the initial increase in RIS elements.

Figure 2 compares the energy efficiency of OMP Hybrid Precoding, OMP + RIS-assisted Hybrid Precoding, and Fully Digital ZF across different SNR values. At low SNR, all schemes show poor energy efficiency due to noise-limited spectral efficiency, although the RIS-assisted method performs slightly better because of passive beamforming gain. As SNR increases, energy efficiency improves since achievable data rates grow faster than power consumption, with hybrid precoding outperforming fully digital ZF due to reduced RF hardware usage. Among all schemes, the OMP + RIS architecture consistently achieves the highest efficiency because it strengthens channel gain through phase-controlled reflections with minimal additional power. At high SNR levels, this advantage becomes more pronounced, highlighting the superior balance between throughput and energy consumption offered by RIS-assisted hybrid designs.

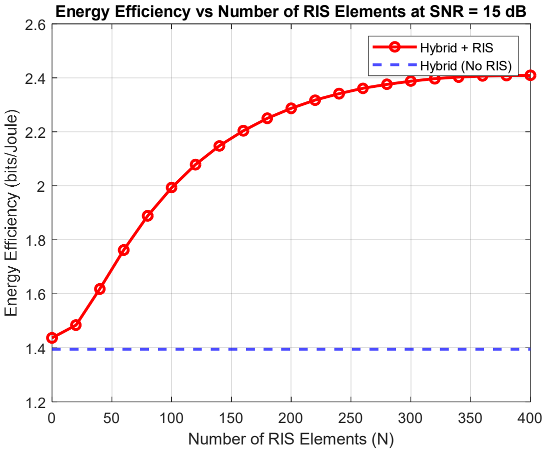

Figure 1: Comparison of Energy Efficiency and Number of RIS Elements

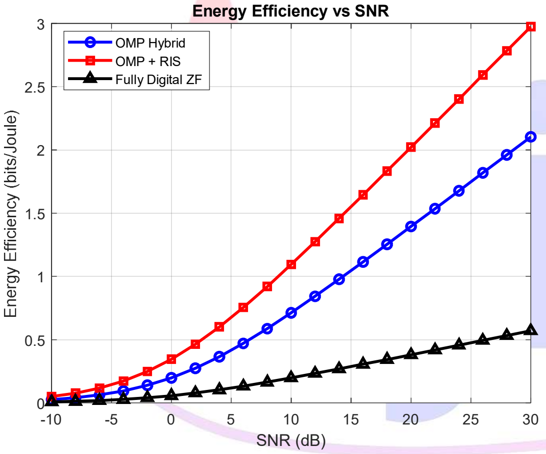

Figure 2:Comparison of Energy Efficiency and SNR

At low SNR levels, all schemes experience high BER because noise strongly affects signal detection, though Fully Digital ZF performs better due to its superior interference suppression and spatial processing capability.

As SNR increases, BER decreases rapidly, with RIS-assisted hybrid precoding showing clear improvement over conventional OMP Hybrid by enhancing the effective channel through constructive signal reflection. At high SNR, the OMP + RIS scheme achieves very low BER, significantly reducing the gap with Fully Digital ZF while maintaining lower hardware complexity. In mmWave environments where blockage is common, RIS helps reconstruct the signal by creating alternative reflected paths. This leads to improved coverage, reliable NLOS communication, higher SINR, and overall more stable system performance.

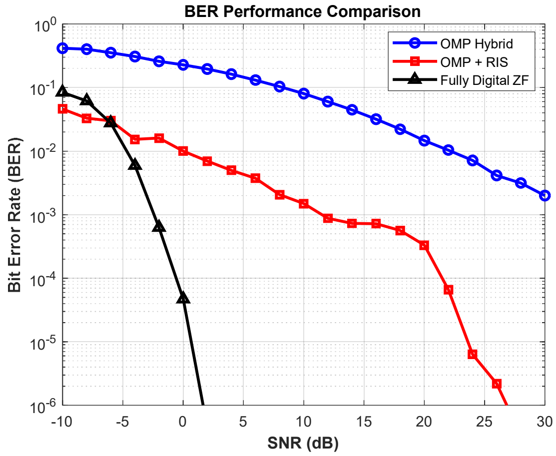

Figure 3: Comparison of BER and SNR Performance

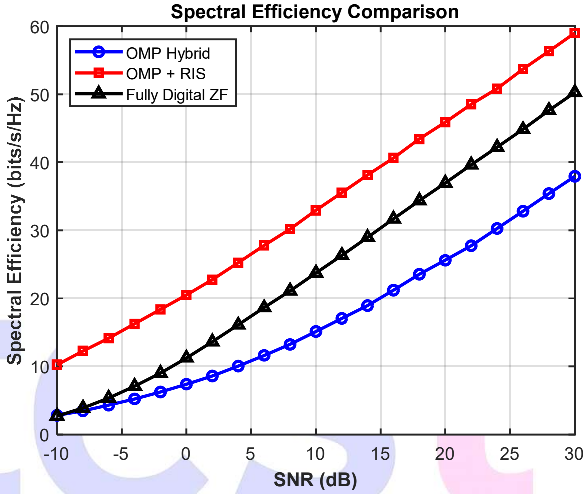

Figure 4: Comparison of Spectral Efficiency and SNR

Figure 4, Spectral efficiency increases steadily with SNR for all precoding schemes, as higher signal strength improves data transmission capability. At low SNR, the difference among methods is small because system performance is mainly limited by noise. Fully Digital ZF achieves better spectral efficiency than conventional OMP-based hybrid precoding due to its higher beamforming flexibility and effective interference suppression. The OMP + RIS scheme provides the highest performance by adding passive beamforming gain that strengthens the effective channel. This advantage becomes more noticeable at high SNR, showing that RIS can significantly enhance hybrid precoding efficiency.

VI. CONCLUSION

Thispaper analyzes RIS-assisted mmWave communication systems using hybrid precoding to meet the growing demand for high data rates and reliable low-latency connectivity. While mmWave offers wide bandwidth, it suffers from severe path loss, blockage, and hardware complexity. RIS helps overcome these issues by intelligently controlling signal reflections through programmable passive elements. Optimized phase tuning enhances coverage, link reliability, and spectral efficiency without increasing transmit power.

Hybrid precoding reduces RF chain requirements while still providing effective beamforming capability. System modeling and simulations demonstrate improved achievable rate and energy efficiency compared to conventional approaches. Overall, RIS-enabled hybrid architectures offer a scalable and energy-efficient solution for future 6G wireless networks.

REFERENCES

[1] T. S. Rappaport *et al.*, “Millimeter Wave Mobile Communications for 5G Cellular: It Will Work,” IEEE Access, 2013.

[2] R. W. Heath Jr., N. González-Prelcic, S. Rangan, W. Roh, and A. M. Sayeed, “An Overview of Signal Processing Techniques for Millimeter Wave MIMO Systems,” IEEE Journal of Selected Topics in Signal Processing, 2016.

[3] O. E. Ayach*et al.*, “Spatially Sparse Precoding in Millimeter Wave MIMO Systems,” IEEE Transactions on Wireless Communications, 2014.

[4] A. Alkhateeb, O. E. Ayach, G. Leus, and R. W. Heath Jr., “Channel Estimation and Hybrid Precoding for Millimeter Wave Cellular Systems,” IEEE Journal of Selected Topics in Signal Processing, 2014.

[5] A. F. Molisch *et al.*, “Hybrid Beamforming for Massive MIMO: A Survey,” IEEE Communications Magazine, 2017.

[6] X. Gao, L. Dai, Z. Chen, Z. Wang, and Z. Zhang, “Near-Optimal Beam Selection for BeamspacemmWave Massive MIMO Systems,” IEEE Communications Letters, 2016.

[7] E. Björnson, L. Sanguinetti, “Making Intelligent Reflecting Surfaces Practical,” IEEE Wireless Communications, 2020.

[8] Q. Wu and R. Zhang, “Intelligent Reflecting Surface Enhanced Wireless Network via Joint Active and Passive Beamforming,” IEEE Transactions on Wireless Communications, 2019.

[9] C. Huang *et al.*, “Reconfigurable Intelligent Surfaces for Energy Efficiency in Wireless Communication,” IEEE Transactions on Wireless Communications, 2019.

[10] M. Di Renzo *et al.*, “Smart Radio Environments Empowered by Reconfigurable Intelligent Surfaces,” IEEE Journal on Selected Areas in Communications, 2020.

[11] S. Gong *et al.*, “Towards Smart Wireless Communications via Intelligent Reflecting Surfaces,” IEEE Communications Magazine, 2020.

[12] E. Basar*et al.*, “Wireless Communications Through Reconfigurable Intelligent Surfaces,” IEEE Access, 2019.

[13] L. Dai *et al.*, “Reconfigurable Intelligent Surface-Based Wireless Communications: Antenna Design, Prototyping, and Experimental Results,” IEEE Access, 2020.

[14] Y. Han, W. Tang, S. Jin, C.-K. Wen, X. Ma, “Large Intelligent Surface-Assisted Wireless Communication Exploiting Statistical CSI,” IEEE Transactions on Vehicular Technology, 2019.

[15] Q. Wu and R. Zhang, “Beamforming Optimization for Intelligent Reflecting Surface with Discrete Phase Shifts,” IEEE Transactions on Communications, 2020.

[16] H. Yang, C.-K. Wen, S. Jin, F. Gao, “Channel Estimation for RIS-Assisted Multiuser Communications,” IEEE Journal of Selected Topics in Signal Processing, 2020.

[17] S. Abeywickrama, R. Zhang, Q. Wu, C. Yuen, “Intelligent Reflecting Surface: Practical Phase Shift Model and Beamforming Optimization,” IEEE Transactions on Communications, 2020.

[18] C. Pan *et al.*, “Multicell MIMO Communications Relying on Intelligent Reflecting Surfaces,” IEEE Transactions on Wireless Communications, 2020.

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