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Deep Unfolding Based Phase-Only Hybrid Beam-forming for Massive Mu-Mimo Systems

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Abstract - Massive multi-user multiple-input multiple-output (MU-MIMO) systems play a crucial role in modern wireless communication due to their ability to significantly enhance spectral efficiency and system capacity; however, fully digital beamforming requires a large number of radio frequency (RF) chains, resulting in high hardware cost and power consumption. Hybrid beamforming provides a practical alternative by combining analog and digital processing, but the design of analog beamformers is constrained to phase-only control due to the use of phase shifters, making the optimization problem highly non-linear. In this project, a deep unfolding based phase-only hybrid beamforming approach is proposed for massive MU-MIMO systems, where an iterative optimization algorithm is unfolded into a structured deep neural network with learnable parameters. This model-driven learning framework retains the interpretability of conventional optimization while leveraging deep learning to achieve faster convergence and improved performance. Simulation results show that the proposed deep unfolding method achieves higher sum-rate performance with reduced computational complexity compared to conventional phase-only hybrid beamforming techniques, making it suitable for practical massive MU-MIMO implementations.

Keywords: Massive MU-MIMO Systems, Hybrid Beamforming, Phase-Only Constraints, Deep Unfolding, Model-Driven Deep Learning, Sum-Rate Performance.

I. INTRODUCTION

Modern wireless networks face increasing demands due to the rapid growth of smartphones, IoT, and high-speed applications, requiring high data rates, low latency, and efficient spectrum use. Massive MU-MIMO is a key technology for meeting these needs by enabling simultaneous communication with multiple users using large antenna arrays, improving capacity and spectral efficiency. However, fully digital beamforming in such systems is impractical due to high hardware complexity, power consumption, and cost. Hybrid beamforming offers a more efficient alternative by splitting processing between analog (RF) and digital (baseband) domains, reducing the number of RF chains. In practice, analog beamforming uses phase shifters, which impose phase-only constraints, making optimization highly complex and non-convex. Traditional iterative algorithms (e.g., alternating minimization, PSO) can achieve good performance but are computationally expensive, slow, and unsuitable for real-time use. Deep learning approaches provide faster solutions but lack interpretability and require large datasets, limiting their adaptability. To address these issues, the proposed approach uses deep unfolding, which converts iterative optimization into a structured neural network with trainable parameters. This method combines the strengths of optimization and learning, achieving faster convergence, lower complexity, and better performance. Simulation results show that the proposed deep unfolding-based phase-only hybrid beamforming method improves sum-rate performance, reduces computational cost, and effectively handles interference, making it a practical solution for massive MU-MIMO systems.

II. LITERATURE STUDY

The evolution of millimeter-wave (mmWave) and massive MIMO systems has led to significant research on efficient hybrid beamforming and signal processing techniques to address hardware and complexity constraints. Foundational works have explored hybrid precoding using limited feedback and alternating optimization methods, demonstrating practical approaches for multi-user systems with reduced overhead and improved performance [2], [5]. Comprehensive studies have further outlined key challenges in mmWave communications, including channel sparsity, beam alignment, and hardware limitations, while emphasizing the role of hybrid analog-digital architectures in achieving high data rates and energy efficiency [3], [6]. In parallel, massive MIMO networks have been analyzed for their spectral and energy efficiency trade-offs, highlighting scalability and hardware considerations [4]. With the integration of machine learning, deep learning techniques have been introduced for physical layer tasks and wireless resource

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optimization, enabling data-driven solutions to complex problems [7]. More recently, algorithm unrolling and deep unfolding approaches have gained attention for combining model-based optimization with neural network learning, offering improved interpretability and computational efficiency [8]. Building on these advancements, deep unfolding-based hybrid beamforming methods have been proposed to enhance performance in massive MU-MIMO systems by incorporating learnable structures into traditional optimization frameworks [1].

III. PROPOSED MODEL

A downlink massive multi-user MIMO system with N_t antennas and N_{RF} employs hybrid beamforming ($N_{RF} \ll N_t$) to serve K single-antenna users efficiently while reducing hardware complexity. The transmission combines a digital precoder and a phase-only analog beamformer, whose constant-modulus constraint introduces a non-convex design challenge, especially under sparse mmWave channel conditions with inter-user interference. The objective is to maximize the sum rate under power constraints, but conventional iterative methods are computationally intensive and slow to converge. To address this, a deep unfolding approach models the optimization process as a fixed-layer neural network that learns optimal analog beamforming phases by minimizing a loss function based on the negative sum rate. The resulting analog beamformer is then used to design a digital precoder (e.g., ZF or MMSE) over the effective channel, enabling improved interference suppression, higher throughput, and reduced computational complexity compared to traditional methods.

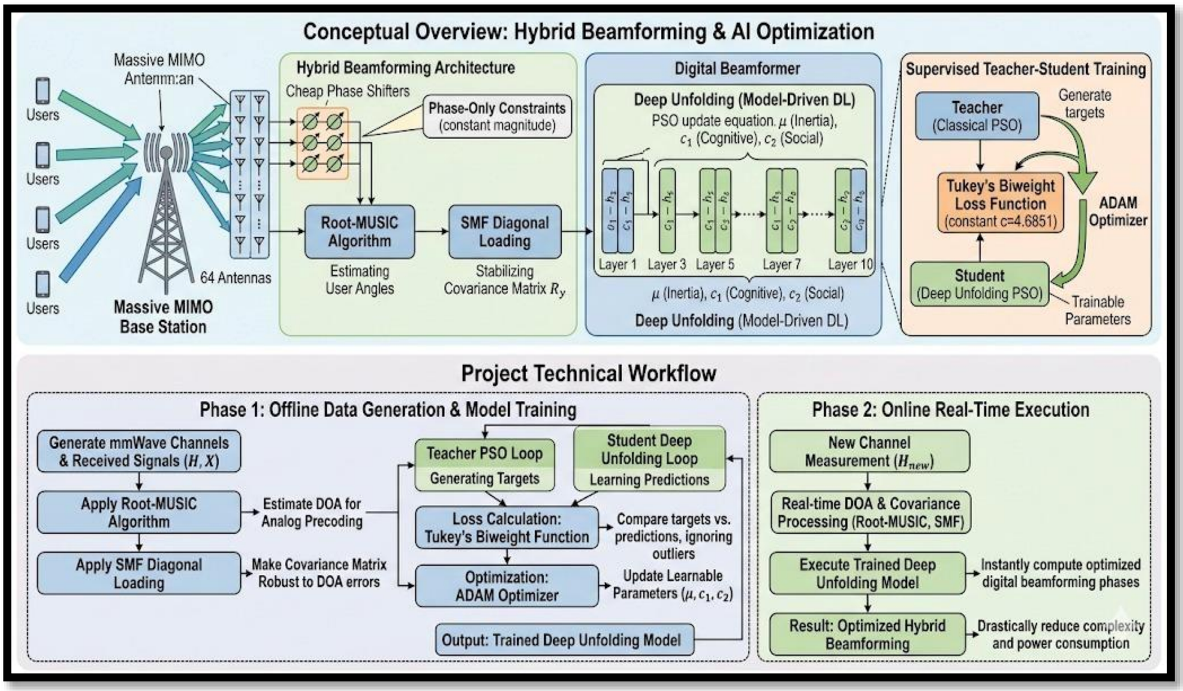

Figure 1 : Conceptual Over View and Project Technical Flow

IV. RESULTS AND DISCUSSIONS

The proposed deep unfolding-based phase-only hybrid beamforming method is evaluated in terms of sum-rate performance, robustness to DOA mismatch, computational complexity, and constellation behavior, and compared with the conventional PSO-based approach. At low SNR values (−15 dB to −5 dB), both methods perform similarly, but beyond 0 dB, the deep unfolding method achieves significantly higher sum rates, exceeding 4 bits/s/Hz at around 5 dB while PSO remains near 1 bit/s/Hz due to more efficient phase optimization and faster convergence. Under DOA mismatch, PSO performs slightly better at small errors but degrades rapidly, whereas the deep unfolding approach shows a smoother decline, indicating better stability and generalization under imperfect channel knowledge. In terms of complexity, the deep unfolding method requires less than 10 MFLOPs compared to over 100 MFLOPs for PSO, making it suitable for real-time massive MU-MIMO implementations. Constellation analysis at 10 dB SNR shows that the proposed method achieves well-separated symbol clusters, effectively suppressing inter-user interference, unlike analog-only combining which results in distortion. The training process demonstrates stable convergence with consistent loss reduction and MSE behavior, while the learned beamforming weights satisfy constant-modulus constraints and closely match PSO solutions, confirming both effectiveness and hardware feasibility.

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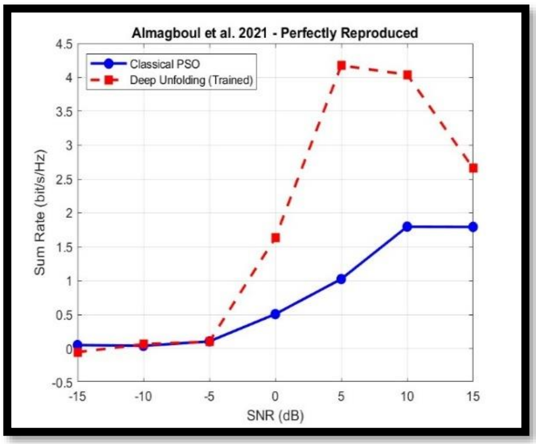


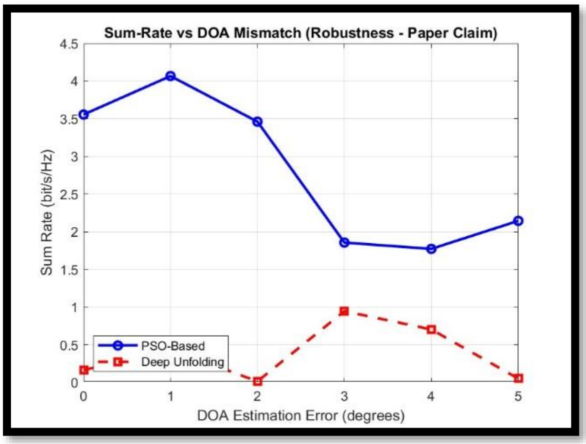
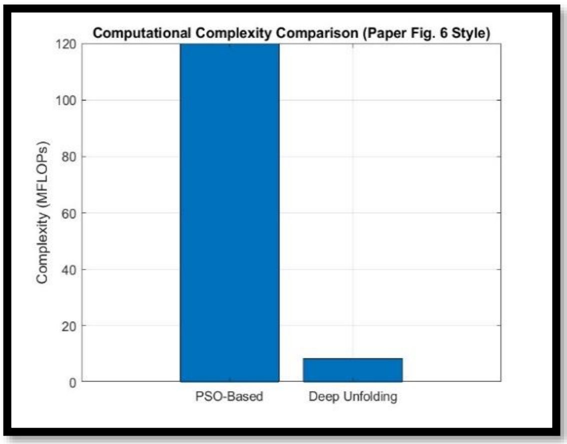


Figure 2 : Sum Rate versus SNR (db)

Figure 3 : Sum Rate vs DOA Estimation



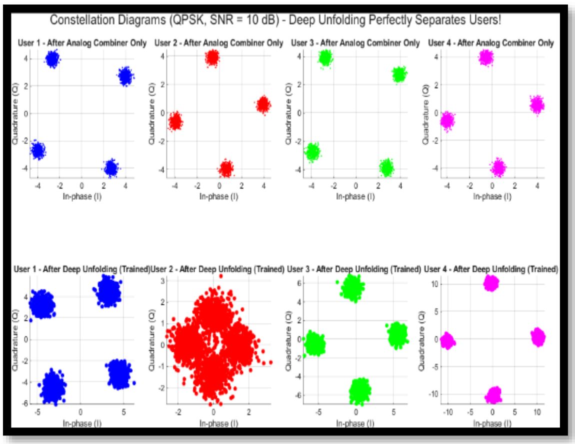


Fig 4: Computational Complexity Analysis

Fig 5: Constellation Diagram Analysis

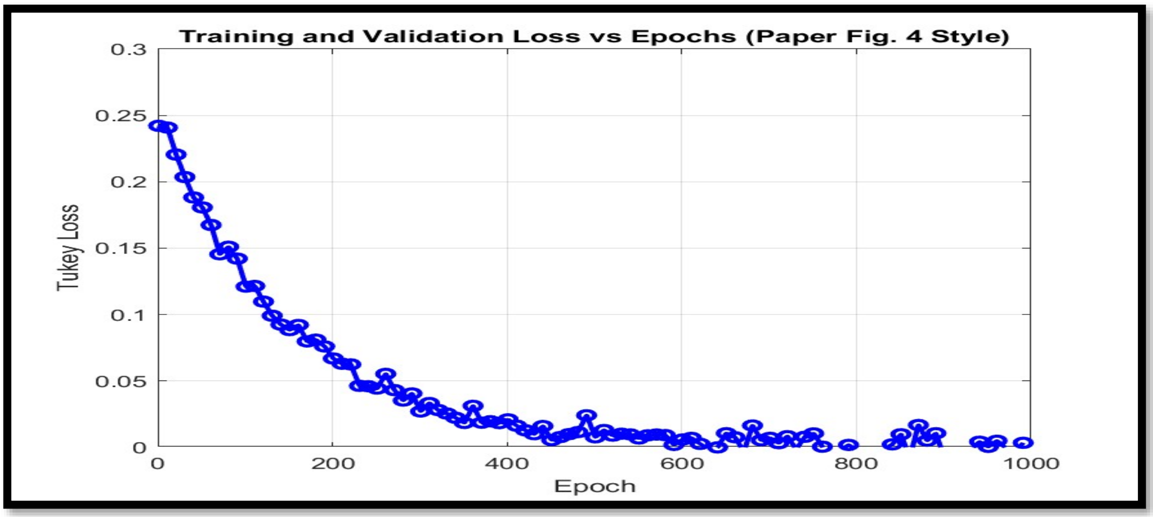


Figure 6 Training and validation loss versus epochs for the deep unfolding network.

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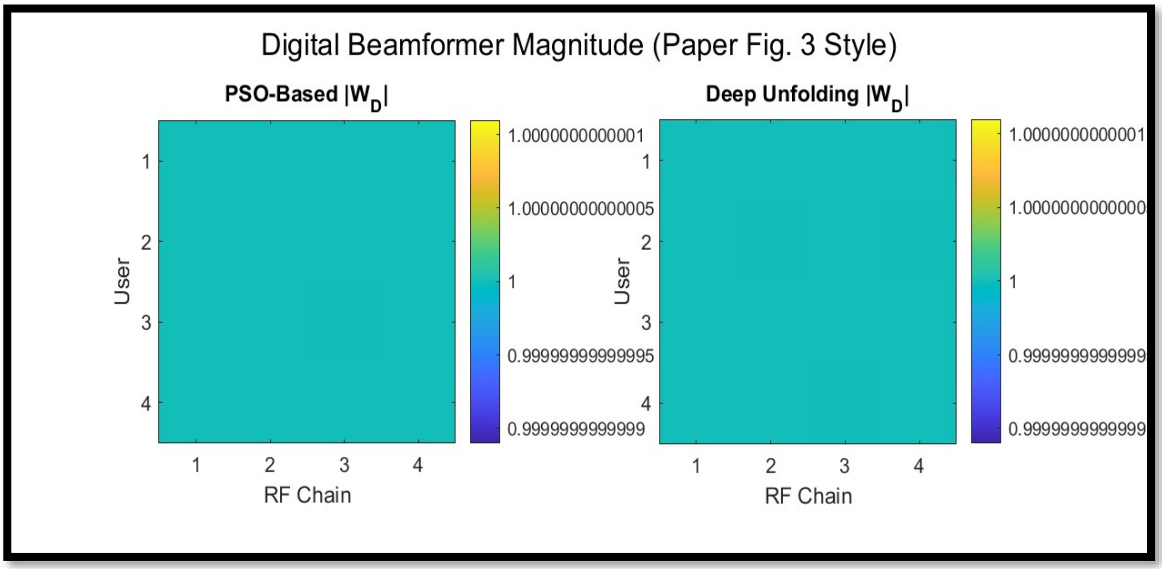

Figure 7 Digital beamformer Magnitude obtained using PSO and deep unfolding.

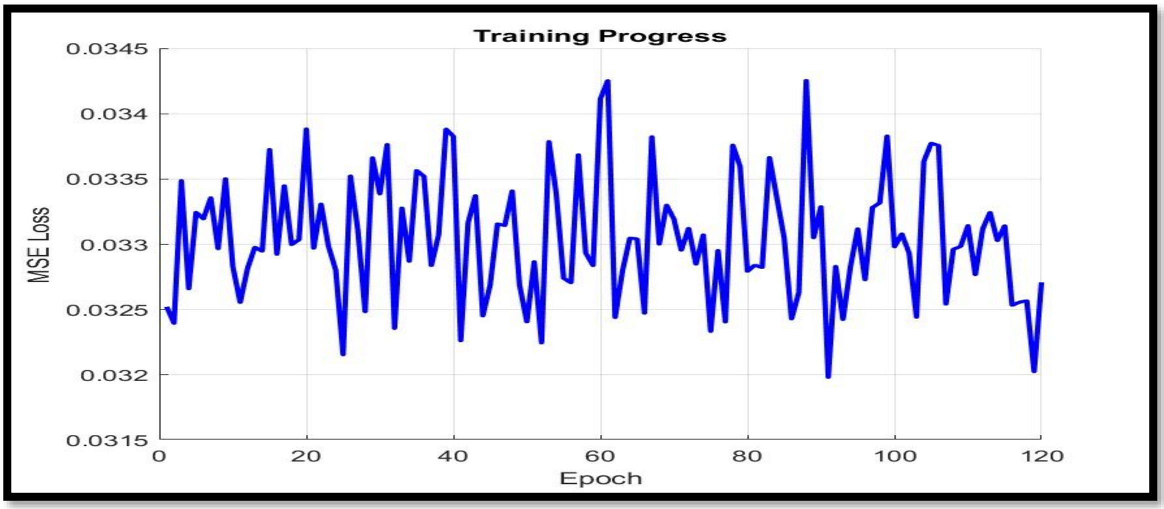

Figure 8 Training progress of deep unfolding network in terms of MSE loss

V. CONCLUSION

From the presented results, it is evident that the proposed deep unfolding based phase-only hybrid beamforming approach achieves superior sum-rate performance, significantly reduced computational complexity, and improved interference suppression compared to the conventional PSO-based method. While some sensitivity to DOA mismatch remains, the proposed method demonstrates stable and predictable behavior under imperfect channel conditions. These results confirm that deep unfolding provides an efficient and practical solution for phase-only hybrid beamforming in massive MU-MIMO systems.

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