

# Abstract

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The rising demand for high-speed, low-latency, and reliable wireless communication has accelerated the adoption of Millimeter Wave (mmWave) technology, a key enabler of next-generation networks. While mmWave offers abundant bandwidth, it faces critical challenges such as high path loss, beam misalignment, and complex channel estimation (CE), particularly under Non-Line of Sight (NLoS) conditions. Relay-assisted communication—especially Full-Duplex Two-Way Relay (FDTWR)—improves spectral efficiency (SE) through simultaneous transmission and reception, but residual self-interference (RSI) remains a limiting factor.

Use cases like smart infrastructure, autonomous mobility, and telemedicine further increase network demands. Unmanned Aerial Vehicles (UAVs) are being deployed as mobile relays for dynamic and critical operations. Beyond-5G networks will rely on narrow-beam mmWave links to address spectrum scarcity, but hardware imperfections and CE errors lead to imperfect beam alignment (IBA), significantly degrading link quality. Although beam misalignment has been studied in backhaul and access networks, its impact on FDTWR remains underexplored. Conventional models using flat-top antenna patterns oversimplify realistic behavior. In contrast, Gaussian directional antenna models more accurately capture gain variation under IBA, yet their role in FDTWR mmWave systems is not well studied.

This thesis tackles key challenges in CE and beamforming for relay-based mmWave MIMO systems. An iterative variational Bayesian inference (IVBI)-based CE algorithm is developed to enhance estimation accuracy by addressing sparse Bayesian learning under NLoS and high-dimensional conditions. The joint impact of IBA and RSI on the SE of FDTWR systems is analyzed using a realistic Gaussian antenna model, with intra-cluster angular spread included to evaluate robustness against multipath-induced misalignment.

A Deep Reinforcement Learning (DRL)-based Hybrid Beamforming (HBF) method is also proposed for IRS-assisted mmWave MU-MIMO systems. Within

a Multi-Agent Reinforcement Learning (MARL) framework, a novel Multi-Agent Deep Deterministic Policy Gradient (MADDPG)-based algorithm enables coordinated multi-agent learning (e.g., among base stations or subarrays), optimizing beamformers under practical constraints like limited RF chains and IBA. This ensures synchronized policy updates and improved system-wide performance.

Extensive analysis and simulations demonstrate the effectiveness of the proposed methods in enhancing CE, beamforming robustness, and scalability. Overall, this work advances the design of intelligent, resilient, and high-throughput mmWave systems for next-generation wireless networks.

**Keywords:** mmWave, FDTWR, CE, Multi-Input Multi-Output (MIMO), IBA, MARL, Intelligent Reflecting Surface (IRS), HBF.