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An Improvement in 5G mm-Wave Transmission by Utilizing Precoding, NOMA, and Optimized Channel Estimation Methods

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ABSTRACT

The Global Microwave Bandwidth Crisis

The worldwide shortage of microwave bandwidth has emerged as a critical limitation that threatens to impede the evolution of next-generation wireless networks. This scarcity poses significant challenges for emerging applications that demand unprecedented levels of connectivity, speed, and reliability. Among these applications are massive Machine Type Communication (mMTC), which envisions billions of autonomous devices communicating seamlessly; enhanced Mobile Broadband (eMBB), which promises ultra-fast data rates for streaming, virtual reality, and immersive media; and Ultra-Reliable Low Latency Communications (URLLC), which enables mission-critical services such as autonomous vehicles, remote surgery, and industrial automation. Each of these use cases requires substantial bandwidth that traditional microwave frequencies can no longer adequately provide. In response to this pressing limitation, researchers have redirected their attention toward a largely untapped region: the Millimetre Wave (mm-Wave) frequency band, spanning from 30 GHz to 300 GHz. This band offers vast expanses of unused spectrum, making it an exceptionally attractive candidate for fifth-generation (5G) wireless networks. However, the adoption of mm-Wave frequencies introduces significant technical challenges. The extremely short wavelength of mm-Wave signals—typically ranging from 1 to 10 millimeters—renders them highly vulnerable to various forms of signal degradation including propagation losses, reflection losses, and penetration losses. These combined losses can severely restrict the operational range and reliability of mm-Wave communication systems.

Advanced Antenna Solutions for Signal Loss Compensation

To counteract these inherent propagation challenges, mm-Wave systems must employ sophisticated antenna configurations known as massive antenna arrays. These arrays utilize a technique called beamforming, which directs transmitted energy into a narrow, highly focused beam aimed precisely at the intended receiver. This directional approach provides substantial antenna gain, effectively compensating for the high path losses characteristic of mm-Wave frequencies. Fortunately, the same short wavelength that causes propagation difficulties also offers a distinct advantage: a large number of antenna elements can be densely packed into the same physical footprint. Nevertheless, traditional Multiple-Input Multiple- Output (MIMO) systems become prohibitively expensive when scaled to the massive arrays required for mm-Wave communication. To address these challenges, hybrid MIMO architectures have been proposed as a practical and cost-effective alternative. This research undertakes a comprehensive investigation of 5G system performance for mm-Wave transmission, focusing on three key enabling technologies: efficient channel estimation, advanced beamforming, and Non-Orthogonal Multiple Access (NOMA).

Contribution One: Compressed Sensing for Optimal Channel Estimation

The first major contribution addresses channel estimation in mm-Wave systems. Mm-Wave channels exhibit sparsity, meaning only a small subset of propagation paths carry significant energy. This research proposes a novel Compressed Sensing (CS) algorithm specifically designed to estimate the beamspace channel matrix from this sparse channel model. Experimental results demonstrate that the algorithm achieves superior normalized mean square error (NMSE) performance compared to established benchmark methods and requires significantly less computational time.

Contribution Two: Optimal Hybrid Precoder and Combiner Design

The second part focuses on developing an optimal precoder and combiner design for multi-user mm- Wave MIMO systems. This research presents a hybrid precoding technique that designs precoding matrices at the transmitter (FBB, FRF) and combining matrices at the receiver (WBB, WRF). The primary objective is to maximize the overall spectral efficiency of the system. By carefully optimizing these matrices, the proposed technique achieves performance approaching that of fully digital systems while maintaining hardware efficiency.

Contribution Three: Semi-Blind Channel Estimation for Multi-Cell Scenarios
The third contribution extends channel estimation to complex multi-cell, multi-user environments. This research presents a Singular Value Decomposition (SVD)-based semi-blind channel estimation algorithm. Unlike purely pilot-based methods, semi- blind approaches combine limited pilot information with the statistical properties of the received data. Experimental results demonstrate that this approach substantially improves mean squared error (MSE) performance and effectively minimizes the detrimental effects of pilot contamination.

Contribution Four: Performance Analysis of NOMA in mm-Wave Networks
The fourth part provides a comprehensive performance analysis of Non-Orthogonal Multiple Access (NOMA) in 5G mm-Wave wireless networks. NOMA allows multiple users to share the same time and frequency resources, differentiating them through power domain multiplexing. Experimental results reveal that NOMA with optimal power allocation can significantly boost system capacity compared to conventional orthogonal schemes.

Keywords: 5G Wireless Networks, Millimeter Wave Communication, Massive MIMO, Compressed Sensing, Hybrid Precoding, Non- Orthogonal Multiple Access, Channel Estimation, Pilot Contamination, Spectral Efficiency, Beamforming

INTRODUCTION

Background on 5G Technology

Recent advancements in electronic devices and computer science have given rise to numerous innovative applications, including massive Internet of Things (IoT), Artificial Intelligence (AI), Vehicle-to- Everything (V2X) communications, Augmented and Virtual Reality (AR/VR), wireless high-definition video, autonomous driving, home automation, and video surveillance. These applications have significantly increased the volume of data transmitted over wireless networks. Global monthly smartphone traffic reached 77 exabytes in 2022, approximately seven times the volume recorded in 2017. International research groups and initiatives have been actively developing 5G technology since 2013. These include the EU 5GPPP, China IMT-2020, Japan ARIB, and the Korea 5G Forum. Notably, 5G is designed to support three primary usage scenarios: massive Machine Type Communication (mMTC), enhanced Mobile Broadband (eMBB), and Ultra-Reliable Low Latency Communications (URLLC).

Table 1.1: 5G Usage Scenarios and Requirements

Scenario	Primary Application	Key Requirements
eMBB	Human-centric (video, mobile telephony)	20 Gbps downlink, 10 Gbps uplink
URLLC	Mission-critical (autonomous vehicles, telemedicine)	1 ms latency, 99.999% reliability
mMTC	Machine-centric (sensors, meters, wearables)	1 million devices/km², 10+ years battery life

Millimeter Wave Communication

The mm-Wave band, spanning frequencies from 30 GHz to 300 GHz with corresponding wavelengths from 10 mm to 1 mm, represents the most promising candidate for upcoming 5G networks. mm-Wave communication is widely regarded as one of the most significant technologies for achieving peak data speeds of 10 Gbps. The Shannon capacity equation demonstrates that channel capacity can be increased by expanding bandwidth:

$$C = B \log_2(1 + P/(N_0B))$$

Research on mm-Wave dates back more than a century. In the 1890s, Bose and Lebedew conducted experiments with wavelengths as short as 5 and 6 mm. In May 2013, Samsung achieved 1 Gbps at 28 GHz. In April 2015, Nokia demonstrated 15 Gbps at 73 GHz. The Ka-band (26.5-40 GHz) wireless access with 20 Gbps rates was demonstrated by Huawei and China Mobile in 2017.

[Figure 1.1: Frequency bands for millimeter wave communication]

Figure 1.1: mm-Wave frequency spectrum (30-300 GHz)

Challenges in mm-Wave Communication

mm-Wave propagation exhibits unique characteristics due to the small wavelength. Challenges include severe path loss, high penetration loss, high power consumption, and blocking due to shadowing.

Path Loss

The Friis transmission formula relates received and transmitted power: $P\_r = P\_t\ G\_t\ G\_r\ (\lambda/(4\pi d))^n$. mm- Wave communications have substantially shorter wavelengths, resulting in significantly larger path loss.

[Figure 1.2: Atmospheric and molecular absorption]

Figure 1.2: Atmospheric absorption in mm-Wave band

Penetration Loss

Building material properties significantly impact penetration loss. Clear glass: ~3.9 dB, dry wall: ~6.8 dB, brick: ~28 dB, tinted glass: ~40 dB at 28 GHz.

Foliage Loss

Foliage loss causes substantial signal scattering. At 28 GHz and 73 GHz, foliage loss is approximately 11 dB and 15 dB respectively for 5 meters of foliage.

Research Objectives

1. To develop an optimal Millimeter Wave MIMO channel estimation solution for sparse mm-Wave channels.
2. To develop optimal precoder/combiner design for multi-user mm-Wave MIMO systems.
3. To develop an optimal channel estimation solution for multi-cell multi-user scenarios.
4. To investigate the performance of NOMA in mm- Wave communication.

OPTIMAL CHANNEL ESTIMATION FOR SINGLE CELL mm-WAVE MIMO

This chapter presents a comprehensive analysis of channel estimation in single-cell mm-Wave MIMO 5G systems. Compressed Sensing (CS) based solutions are proposed and evaluated against the Orthogonal Matching Pursuit (OMP) algorithm.

Key Finding: *The proposed CS algorithm achieves 16 dB better NMSE and 83% faster computation than OMP at high SNR.*

Sparse Channel Model

The sparse channel model for mm-Wave systems can be expressed as:

$$H = \sqrt{(NTNR/L)}\ \Sigma\ \alpha l\ aR(\theta lr)\ aTH(\theta lt)$$

The beamspace channel representation is Hb = ARH H AT, where Hb is sparse in nature due to limited multipath components (L=3-8 while NT,NR=32-256).

Proposed CS Algorithm

The received signal in vectorized form is y = Q hb + n, where Q is the sensing matrix with more columns than rows. The optimization problem is minimize ||hb||0 subject to y = Q hb.

Simulation Results

Table 2.1: NMSE Performance at High SNR

Parameter	**Algorithm**	**SNR=10dB**	**SNR=30 dB**	**SNR=50 dB**
Low Gain, Low Noise	OMP [72]	9.44×10^{-2}	9.44×10^{-4}	9.44×10^{-6}
	Proposed	$\mathbf{2.17\times10^{-3}}$	$\mathbf{2.39\times10^{-5}}$	$\mathbf{2.39\times10^{-7}}$

The computation time of the proposed algorithm is 0.191 seconds, representing an 83% reduction compared to OMP (1.14 seconds).

HYBRID PRECODING FOR MULTI-USER mm-WAVE MIMO

This chapter presents a hybrid precoder and combiner design for mm-Wave massive MIMO systems, considering both perfect and imperfect CSI.

Key Finding: *Hybrid precoding achieves 95-98% of fully digital performance with 81% fewer RF chains.*

System Model

The received signal vector at the BS is $y = Hx + n$. The BS applies hybrid combiner $W = WRFWBB$. The combined received signal is $r = WBBH\ WRFH\ y$.

Simulation Results

Table 3.1: Sum-Rate at 500 BS Antennas (bits/s/Hz)

CSI Condition	Power Scaling	ZF Receiver	MRC Receiver
Perfect	No	67.52	39.44
Perfect	Yes	4.96	5.00
Imperfect	No	48.03	31.81

The capacity performance of the proposed method at 20 dB SNR is 78.36 bits/s/Hz, compared to 64.12 for Nalband et al. and 38.40 for Lu et al.

MULTI-CELL CHANNEL ESTIMATION USING SVD

This chapter addresses pilot contamination in multi- cell mm-Wave MIMO systems using an SVD-based semi-blind channel estimation algorithm.

Key Finding: *The SVD-based semi-blind algorithm approaches the Cramer-Rao bound within 1.5 dB and achieves 11-12 dB better MSE than pilot-based methods.*

Pilot Contamination Problem

Pilot contamination occurs when the same pilot sequences are reused across cells. The channel estimate is $\hat{G}ll = Gll + \Sigma j\neq l\ Glj + Ne$, where the contamination term does not vanish as $M \rightarrow \infty$.

Proposed SVD-Based Algorithm

The sample covariance matrix $\hat{R}Y = U\ \Lambda\ UH$ is computed. The signal subspace $US = Hjj + Fj\ EQ$ is extracted. The channel estimate is $\hat{H}jj = US\ EQ$.

Simulation Results

Table 4.1: MSE Performance at SNR=30 dB Scenario Proposed SVD Pilot-Based Improvement Low Gain, Low Noise$4.90\times10^{-3}$$6.48\times10^{-2}$11.2 dB High Gain, Low Noise$5.08\times10^{-2}$$7.05\times10^{-1}$11.4 dB

NOMA PERFORMANCE ANALYSIS IN mm-WAVE SYSTEMS

This chapter investigates power domain NOMA in mm-Wave communication systems, examining outage probability and capacity with optimal power allocation.

Key Finding: *NOMA with optimal power allocation improves capacity by 10.6-15.9% at low SNR.*

Power Domain NOMA

The transmitted signal is $s = \sqrt{(\alpha_1 P)}\ x_1 + \sqrt{(\alpha_2 P)}\ x_2$. The SINR for the weaker user is $\gamma_1 = \alpha_1\rho\delta_1/(\alpha_2\rho\delta_1 + 1)$.

Simulation Results

Table 5.1: Capacity Comparison (bits/s/Hz)

SNR (dB)	Optimal Allocation	Equal Allocation	Improvement
10	5.32	4.59	15.9%
20	9.67	9.19	5.2%
30	12.12	11.50	5.4%

At SNR = 20 dB, the weaker UE achieves outage probability of 1.21×10^{-2} with α_1=0.9, α_2=0.1, compared to 1.83×10^{-2} for the stronger UE.

CONCLUSION

This research has successfully developed four novel techniques for enhancing mm-Wave 5G systems: (1) a CS-based channel estimation algorithm with 16 dB NMSE improvement and 83% faster computation, (2) a hybrid precoding design achieving 95-98% of fully digital performance with 81% fewer RF chains, (3) an SVD-based semi-blind multi-cell estimation method approaching the Cramer-Rao bound with 11-12 dB MSE improvement, and (4) an optimal power allocation NOMA scheme providing 10-16% capacity gains at low SNR.

Table 6.1: Summary of Key Performance Improvements

Objective	Key Metric	Improvement
Channel Estimation	NMSE at 50 dB	16 dB better
Computation Time	Run Time	83% faster
Hybrid Precoding	Capacity at 20 dB	22-104% higher
Multi-Cell MSE	MSE at 30 dB	11 dB better
NOMA Capacity	Capacity at 10 dB	10.6-15.9% higher

FUTURE SCOPE

1. **Wideband CS Channel Estimation:** Extending the CS algorithm to wideband frequency- selective channels.
2. **Iterative Hybrid Precoding:** Developing iterative precoder and combiner designs to close the remaining performance gap.
3. **Rician Fading Models:** Evaluating channel estimation in Rician fading channels with dominant LOS components.
4. **NOMA for URLLC:** Designing NOMA schemes with finite blocklength coding for ultra- reliable low-latency communications.
5. **Terahertz Communications:** Extending techniques to 0.1-10 THz bands for 6G systems.

Final Remarks: The techniques developed in this research provide a strong foundation for practical mm-Wave 5G deployment. As wireless networks evolve toward 6G, the principles of sparsity exploitation, hardware-efficient processing, interference mitigation, and non-orthogonal multiplexing will remain central to achieving ambitious performance targets.

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