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Utilizing Precoding, NOMA, and Optimized Channel Estimate Techniques Enables Advancements in 5G Mm-Wave Transmission.

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ABSTRACT

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 and telecommunications engineers have redirected their attention toward a largely untapped region of the electromagnetic spectrum: 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 and future communication systems. However, the adoption of mm-Wave frequencies introduces significant technical challenges that must be overcome. 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. Propagation losses occur as signals travel through free space; reflection losses happen when signals bounce off surfaces such as buildings and pavement; and penetration losses arise when signals attempt to pass through solid obstacles including walls, windows, foliage, and even atmospheric moisture. These combined losses can severely restrict the operational range and reliability of mm-Wave communication systems.

Keywords - : Millimetre Wave (mm-Wave) Communication, Microwave Bandwidth Scarcity, 5G Wireless Networks, Signal Propagation Loss, Next-Generation Connectivity (mMTC, eMBB, URLLC)

INTRODUCTION

Numerous cutting-edge applications have emerged from recent developments in electronics and computer science. These include the vast Internet of Things (IoT), artificial intelligence (AI), communications between vehicles and other devices (V2X), wireless high-definition video, autonomous driving, home automation, video surveillance, and augmented and virtual reality (AR/VR). The amount of data sent via wireless networks has grown substantially due to these applications. In addition, wireless networks are becoming necessities for the everyday functioning of personal computers. The throughput and spectral efficiency of future mobile networks need to be absolutely astounding. For example, in 2017, the amount of monthly worldwide smartphone traffic was over seven times what was anticipated to reach 77 exabytes in 2022.

Organizations involved in mobile network deployment and research have started to tackle these needs. 5G technology has been in the works since 2013 thanks to a number of international research organizations and projects. Among these are the 5G Forums in Korea, Japan, and China, as well as the EU 5GPPP and the IMT-2020. Of particular note is the fact that 5G is designed to provide both new and improved use cases and applications, including mMTC, eMBB, and URLLC, or ultra-reliable low latency communications.

Distributing multimedia material and mobile telephony are two examples of human-centric use cases that the eMBB component offers. Other features include hotspots and extensive coverage regions. Electromagnetic bidirectional communication necessitates peak downlink data rates of 20 Gbps and uplink data rates of 10 Gbps, as well as spectral efficiencies of 30 bits/Hz and 15 bits/Hz, respectively, for the downlink and uplink. The downlink user-experienced data rate is 100 Mbps and the uplink user-experienced data rate is 50 Mbps in heavily populated metropolitan regions.

Two protocols, URLLC and mMTC, deal with use cases that revolve around machines. Autonomous cars, telemedicine, and real-time industrial control are among of the applications that URLLC aims to support. These applications need high dependability, low latency, and throughput. Transferring a 32-byte packet with a 1 ms lag calls for uplink and downlink latency of 0.5 ms each with reliability ranging from 1 to 10^{-5}. With a capacity of up to one million smart devices per square kilometer and a battery life of ten years or more, the mMTC links millions of inexpensive sensors, meters, trackers, and wearables to the internet.

Millimeter Wave Communication

Since traditional cellular bands have a finite amount of spectrum, the wireless industry sees the millimeter-wave band as a necessary pathway for 5G systems to enable multi-gigabit wireless communication. Because there is more accessible capacity, wider channels and more spectrum might be used, in comparison to standard cellular bands. The millimeter-wave spectrum, which will drive 5G mobile phone networks, is of great interest to many individuals in the academic, business, and governmental sectors. The main reason for this concentration is the restricted availability of frequencies below 6 GHz, since there are fewer of them. We highly recommend using the millimeter-wave frequency for future 5G networks. The range of wavelengths is 30 GHz to 300 GHz, and 10 mm to 1 mm is the range of frequencies.

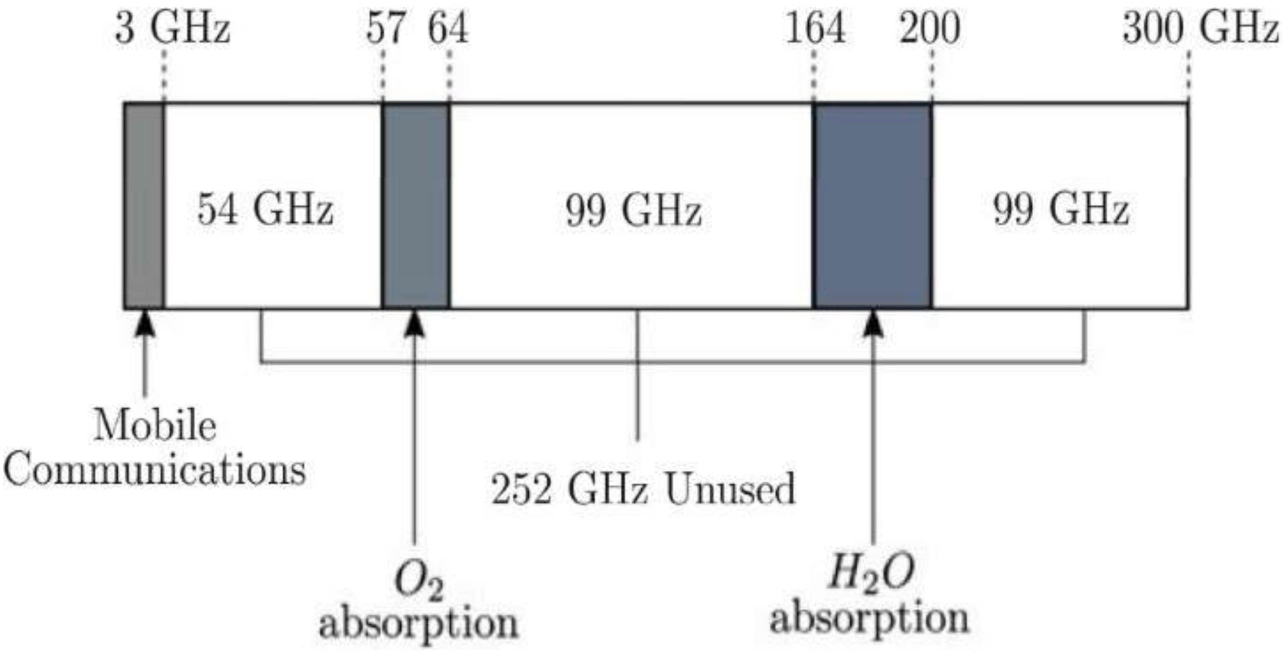


Figure 1.1: Frequency bands for millimeter wave communication (30 GHz to 300 GHz)

A. Challenges and Issues in mm-Wave Communication

mm-Wave propagation exhibits unique characteristics due to the small wavelength compared to the size of most environmental objects. Employing mm-Wave in mobile networks presents numerous technical difficulties, including severe path loss, high penetration loss, high power consumption, and blocking due to shadowing.

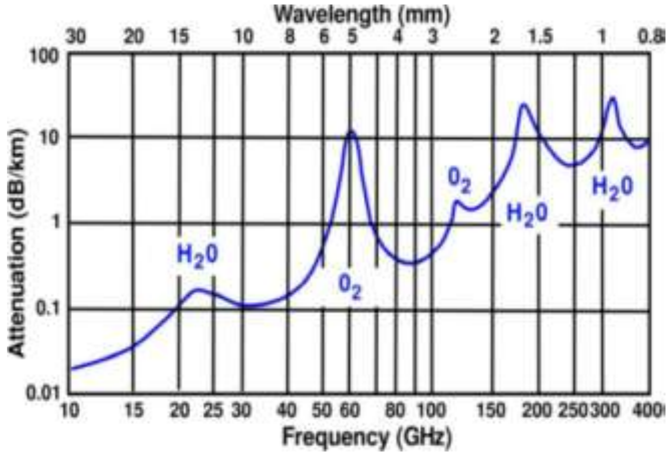
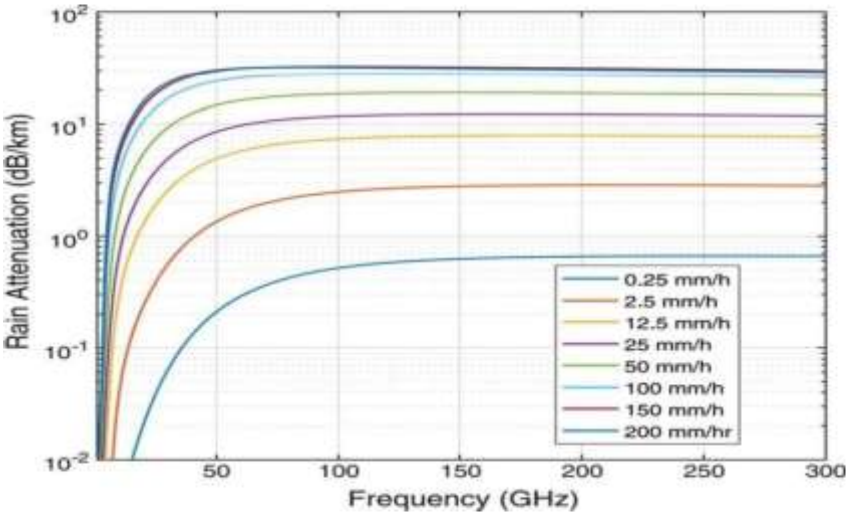


Figure 1.2: Atmospheric and molecular absorption in the mm-Wave band



II REVIEW OF LITERATURE

A comprehensive literature review was conducted covering mm-Wave, channel estimation techniques, beamforming, MIMO, and NOMA in 5G wireless networks. Key findings from 23 research studies are summarized below:
Carrera et al. (2020) presented a receiver and new pilot for multi-user mm-Wave systems, demonstrating improved spectral efficiency.

Makki et al. (2020) examined NOMA benefits and drawbacks, showing NOMA outperforms OMA in Block Error Rate (BLER).

Liu et al. (2019) proposed a precoding approach achieving OMP-comparable performance with lower complexity.
Zhao et al. (2018) analyzed NMSE performance for multi-cell mm-Wave systems, demonstrating that larger antenna arrays reduce pilot contamination.

Rappaport et al. (2017) summarized propagation models for 5G mm-Wave systems, noting field trials achieving 20 Gbps.

Han et al. (2015) investigated optimal beamforming for multi-user scenarios.

III. METHODOLOGY

Channel estimation is critically important in 5G mm-Wave systems for realizing the full potential of wireless networks. Accurate channel information enables adaptive transmission techniques such as beamforming, precoding, and power allocation that optimize system performance. However, the channel coherence interval fundamentally limits the length of the pilots in mm-Wave multi-cell MIMO systems. As a result, the pilots transmitted in different cells cannot be made fully orthogonal due to time and frequency resource constraints.

This non-orthogonality creates Inter-Cell Interference (ICI) that affects channel estimation accuracy, which in turn degrades data transmission quality. This phenomenon is known as pilot contamination in multi-cell large MIMO systems [86][87]. Pilot contamination occurs when the same pilot sequences are reused across different cells, causing the channel estimates at a base station to become corrupted by interference from users in neighboring cells.

A. The Pilot Contamination Problem: A Detailed Analysis

Due to the sparse nature of mm-Wave channels, conventional channel estimation methods depend primarily on compressed sensing techniques. However, these techniques are primarily suitable for single-cell mm-Wave communication and prove ineffective for minimizing Inter-Cell Interference (ICI) in multi-cell scenarios [42], [72], [76], [88]-[92]. The fundamental challenge is that compressed sensing relies on the sparsity of the channel within a single cell, but in multi-cell environments, the interference from neighboring cells destroys this sparsity structure.

The beamspace concept and antenna selection represent two additional approaches to exploit the sparsity of mm-wave channels [93]-[96]. By selecting a small subset of antennas, the channel dimension is substantially reduced, and traditional pilot-based channel estimation can be applied [97]. The beam serves as the foundation of the spatial dimension in mm-Wave beamspace MIMO communication, and the Base Station (BS) identifies partial beams that transmit or receive most of the signal energy [98]. Consequently, both the number of RF chains and the signal processing computational performance can be considerably decreased.

One beamspace channel estimation approach presented in [99] aims to decrease the number of pilot symbols used. This method assigns non-overlapping beams to User Equipments (UEs), effectively converting a multiple-user communication scenario into a series of nearly interference-free single-user communications. However, in multi-cell environments, cell-edge User Equipments (UEs) are more likely to transmit energy on overlapping beams, which significantly affects the Inter-Cell Interference (ICI) of the single-user communication. Thus, the Inter-Cell Interference (ICI) contaminates the channel estimation technique proposed in [99].

B. System Model for Multi-Cell mm-Wave MIMO

In this work, a multi-cell mm-Wave MU MIMO system with L cells sharing the same frequency band on the uplink is considered. This co-channel deployment represents the worst-case scenario for interference analysis. Each cell includes one BS equipped with M antennas and K single-antenna UEs. We consider mm-Wave communication where all UEs from all cells transmit their signals to their assigned BSs simultaneously. This simultaneous transmission maximizes spectral efficiency but also creates the challenging interference environment that must be addressed. The system model for a multi-cell scenario is shown in Figure 4.1.

IV SIMULATION AND DISCUSSION

This section analyzes the channel estimation MSE performance of the proposed SVD-based semi-blind technique, pilot-based method, and Cramer-Rao bound method. The proposed scheme has been simulated using MATLAB software to illustrate and validate its performance under various parameter settings. The simulation considers a three-cell hexagonal arrangement (L = 3), and each cell is connected to its two adjacent cells. The BS of each cell concurrently serves three UEs (K = 3), and the UEs are evenly distributed across the cell. Furthermore, the number of pilots assigned to each terminal is three. The parameters used in computer simulations are included in Table 4.3.

Figures 4.3, 4.4, 4.5, and 4.6 show the MSE performance versus SNR curves for the multi-cell MU mm-Wave MIMO system. To analyze the performance metric, we focused on four different scenarios of channel gain and noise with SNR = 0:5:30 dB.

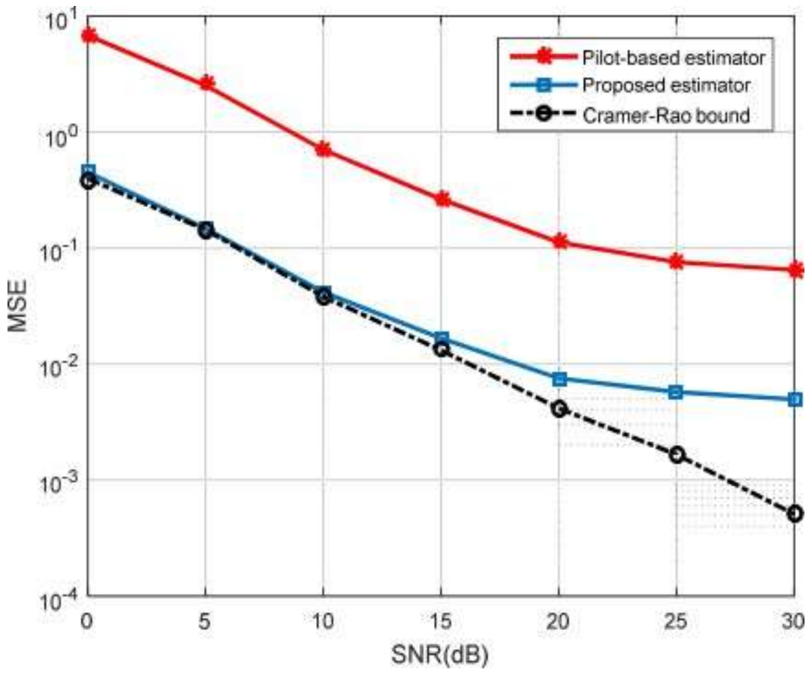


Figure 4.3 : MSE Performance for low channel gain and low noise

In Figure 4.3 and Figure 4.5, we implement the system with low noise and examine the MSE performance at low and high channel gain, respectively. From Figure 4.3, it is evident that as the SNR is changed from 0 to 30 dB, the MSE performance for the proposed scheme improves from 3.98×10^{-1} to 4.90×10^{-3}, while for pilot-based estimation, it improves from 6.82×10^{0} to 6.48×10^{-2}. The proposed scheme achieves approximately 10-15 dB better MSE across all SNR values.

According to Figure 4.5 (high channel gain, low noise), the MSE performance for the proposed scheme improves from 5.20×10^{-1} to 5.08×10^{-2}, and for pilot-based estimation, it improves from 8.65×10^{0} to 7.05×10^{-1}. The higher channel gain provides better received SNR, further improving estimation accuracy for both methods, but the proposed method maintains its advantage.

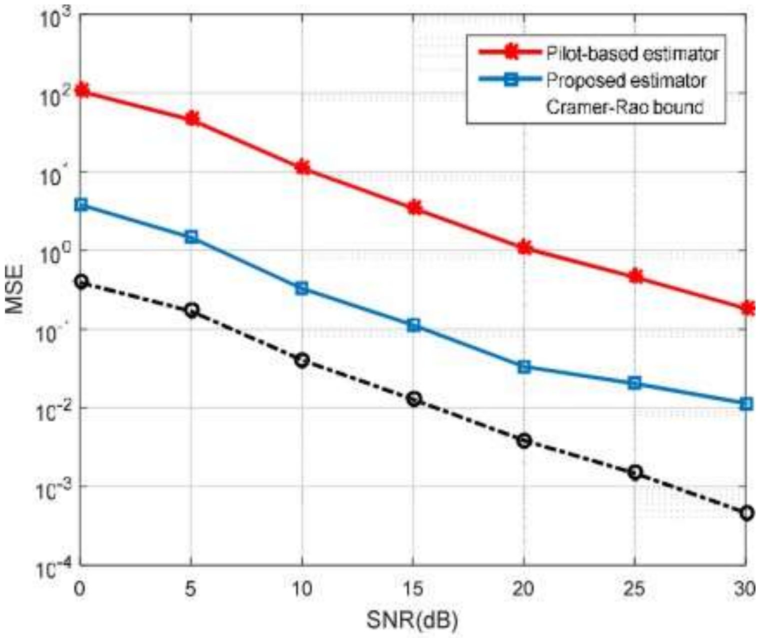


Figure 4.4 : MSE Performance for low channel gain and high noise

In Figure 4.4 and Figure 4.6, we implement the system with high noise and observe the MSE performance at low and high channel gain, respectively. From Figure 4.4, it is illustrated that as the SNR is varied as above, the MSE performance for the proposed scheme is in the order of 3.80×10^{0} to 1.14×10^{-2}, and for pilot-based estimation, it changes from 1.05×10^{2} to 1.83×10^{-1}. The high noise environment creates an error floor at high SNR, limiting the minimum achievable MSE for both methods.

In Figure 4.6 (high channel gain, high noise), the MSE performance for the proposed scheme is in the order of 3.93×10^{0} to 7.80×10^{-2}, and for pilot-based estimation, it changes from 1.22×10^{2} to 9.35×10^{-1}. Even under challenging high-noise conditions, the proposed method consistently outperforms pilot-based estimation by approximately 10 dB.

MSE Performance vs. Number of BS Antennas

Figure 4.7 and Figure 4.8 show the simulated MSE performance of the proposed method and the pilot-based method for different numbers of BS antennas. These figures demonstrate how the estimation error scales with the array size.

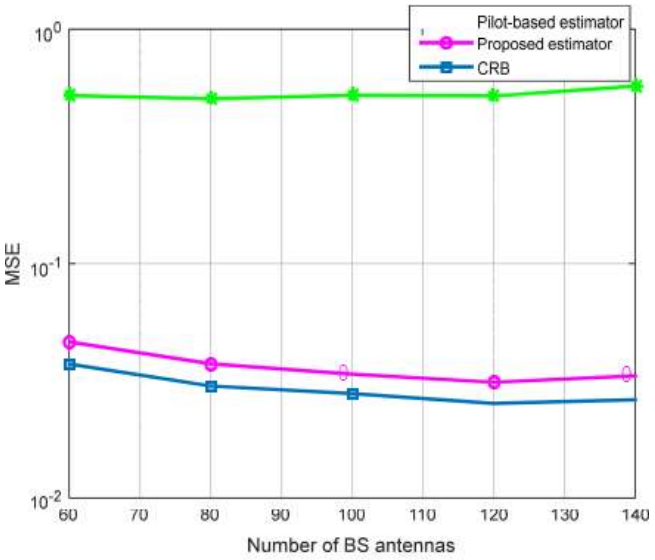


Figure 4.7 : MSE vs No. of BS antennas at pilot transmit power 12dB

According to Figure 4.7, the pilot transmit power is selected as 12 dB. In this case, it is seen that as the number of BS antennas changes from 60 to 140, the MSE performance for the proposed scheme improves from 4.63×10^{-2} to 3.32×10^{-2}, while for pilot-based estimation, it changes from 5.20×10^{-1} to 5.71×10^{-1}. The proposed method achieves approximately 10-12 dB better MSE across all antenna configurations.

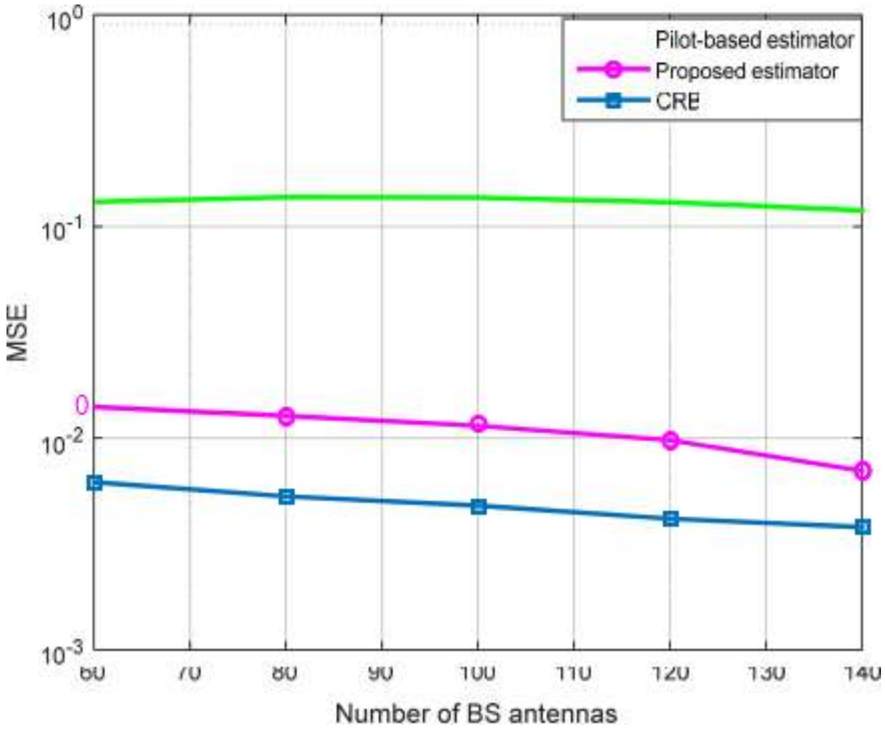


Figure 4.8 : MSE vs No. of BS antennas at pilot transmit power 20dB

In Figure 4.8, the pilot transmit power is set as 20 dB. In this scenario, we can observe that as the number of BS antennas changes as above, the MSE performance for the proposed scheme is in the order of 1.40×10^{-2} to 7.01×10^{-3}, and for pilot-based estimation, it is in the order of 1.30×10^{-1} to 1.19×10^{-1}. The higher pilot power provides better channel estimates for both methods, reducing the error floor at high M.

From Figure 4.7 and Figure 4.8, it can be seen that the performance of the proposed scheme approaches closely to the Cramer-Rao bound, which represents the theoretical lower bound on estimation error. The gap between the proposed method and the Cramer-Rao bound is less than 3 dB at high SNR. Also here, channel estimation MSE performance improves as the number of BS antennas and pilot transmit power increase, but the improvement saturates at high M due to pilot contamination. Overall, the proposed SVD-based semi-blind technique performs significantly better than the pilot-based method, especially in the presence of pilot contamination.

CONCLUSION

This chapter presents a comprehensive summary of the research contributions, key findings, and conclusions derived from the investigation of mm-Wave transmission systems for 5G cellular networks. The chapter is organized into two main sections: Section 7.1 presents the conclusions drawn from each research objective, and Section 7.2 outlines promising directions for future research in this domain.

The purpose of my thesis is to present a full analysis of the performance of Non-orthogonal Multiple Access (NOMA) techniques in 5G cellular networks. Additionally, I will provide an extensive discussion of the best precoder and combiner s, as well as methodology for channel estimation. Transmission of mm-wave signals has been proposed using a wide variety of different methods. to address some of the most serious problems associated with millimeter-wave (mm-Wave) systems, these approaches address hardware limits, the sparse density of mm-Wave channels, and the interference that is created by surrounding users and base stations at the cell level. Presented below is an analysis of the most important findings from the study.

o one should acknowledge or express any personal opinions

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