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Enhanced Near-Field Channel Estimation in Mixed LoS/NLoS Environments for Extremely Large-Scale MIMO Systems

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Abstract
Accurate channel estimation is crucial for optimizing Extremely Large-Scale MIMO (XL-MIMO) systems in next-generation wireless communication. As the number of antennas increases, near-field effects become significant, necessitating precise estimation techniques. This paper extends previous work by considering a configuration with 256 transmitters and 256 receivers, increasing the number of line paths to 18 and pilot lenses up to 2600. The study investigates a propagation distance between 80m and 100m and evaluates the channel estimation performance using the Singular Value Thresholding (SVT) algorithm. The proposed approach leverages low-rank matrix recovery principles to reconstruct the near-field channel efficiently. Numerical simulations demonstrate the effectiveness of the proposed methodology in estimating the Near-Field Mixed LoS/NLoS XL-MIMO channel, with performance measured in terms of Normalized Mean Square Error (NMSE). The results show a strong correlation between NMSE and Signal-to-Noise Ratio (SNR) ranging from 0 to 30 dB in steps of 5 dB. Our findings highlight the advantages of SVT in mitigating estimation errors and *improving channel reconstruction accuracy in XL-MIMO systems.*
Keywords: *Near-Field Channel Estimation, XL-MIMO, SVT Algorithm, NMSE, SNR, Mixed LoS/NLoS, Pilot Lens, Wireless Communication*

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I. INTRODUCTION

The exponential growth in data demand and emerging applications such as holographic communications, virtual reality, and ultra-reliable low-latency communications (URLLC) have significantly increased the need for high spectral efficiency in 6G networks [1]. Extremely Large-Scale MIMO (XL-MIMO) has emerged as a promising solution to address these demands by leveraging massive antenna arrays that enable enhanced spatial resolution and improved signal processing capabilities [2]. However, as the number of antennas increases dramatically, traditional far-field assumptions no longer hold, and near-field propagation effects become dominant. This shift necessitates accurate near-field channel modeling and estimation techniques to optimize performance [3].

Prior studies have explored the impact of mixed Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) components in XL-MIMO systems, highlighting the limitations of conventional estimation methods in capturing near-field characteristics [4]. Given these challenges, this paper extends previous research by considering an XL-MIMO configuration with 256 transmitters and 256 receivers, incorporating 18 line paths and up to 2600 pilot lenses. These enhancements allow for a more comprehensive evaluation of near-field channel estimation performance. We employ the Singular Value Thresholding (SVT) algorithm, a low-rank matrix completion method, to reconstruct the near-field XL-MIMO channel efficiently [5].

To assess the effectiveness of the proposed method, we conduct a detailed performance analysis based on Normalized Mean Square Error (NMSE) as a function of Signal-to-Noise Ratio (SNR), ranging from 0 to 30 dB in steps of 5 dB. The results demonstrate that SVT outperforms traditional approaches in mitigating estimation errors, making it a viable solution for next-generation XL-MIMO systems. This research contributes to the ongoing development of high-performance channel estimation techniques that are critical for optimizing 6G wireless networks.

1.1 MIMO TECHNOLOGY

Spectral Efficiency is typically among the leading relevant strategies for selecting candidate wireless communications systems for the next decade. In the meantime, both greenhouse emissions and network expenses increase from year to year, with unnecessary power demand in wireless networks. Consequently, EE has been another critical parameter to evaluate wireless communication networks' efficiency with some Bandwidth Efficiency limitations.

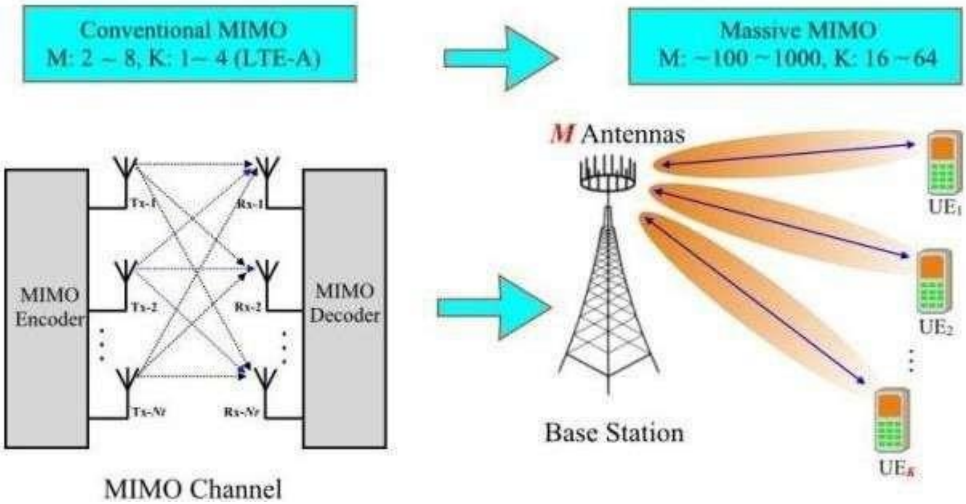


Figure 1. Conventional MIMO vs. XL MIMO

1.2 Conventional MIMO versus XL MIMO

In wireless communications, MIMO technology has drawn substantial interest, because it enables substantial changes in data throughput and the connectivity area without increasing bandwidth or transmitting capacity MIMO technology has attained considerable attention in wireless networking since the data output, and connection range has increased considerably, and no need for bandwidth increased, or power transmits. Figure 1.5 shows the conventional MIMO and XL MIMO with M and K transceiver antennas. Today the XL MIMO is widely accepted for its distinctive spectral performance, reliability, and overall capabilities in TDD/FDD systems, both in academia and industry.

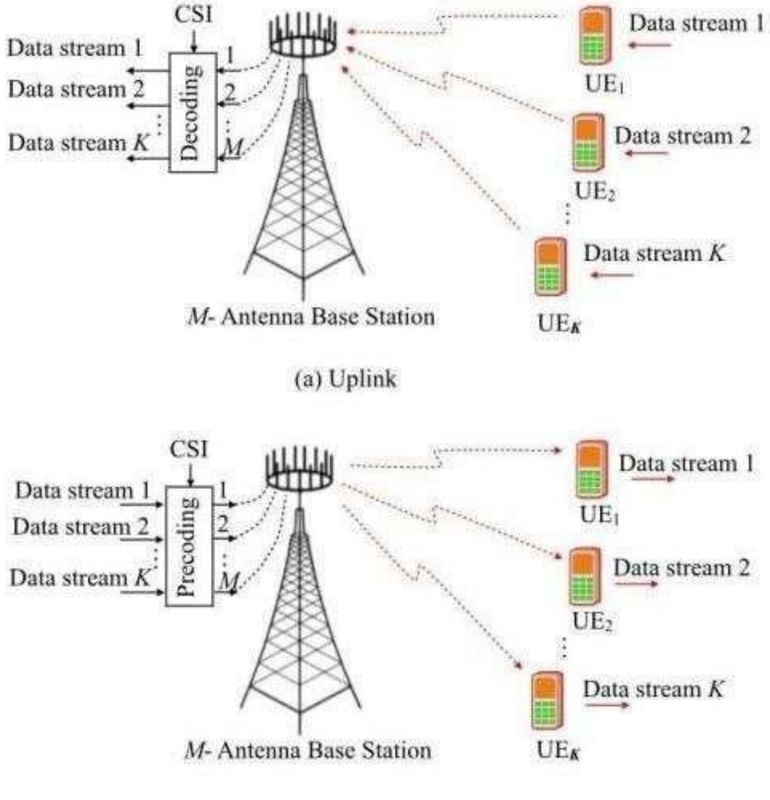
1.3 Introduction to XL MIMO

A cellular network's highly spectrally pre-eminence tier is summarized as follows: It allows for multiplexing gains utilizing SDMA by connecting many UEs to the corresponding time-frequency service. Furthermore, it has more base station antennas than user equipment per cell, as seen in Figure 1.6, to effectively eliminate interference. The BS should intensify the number of antennas proportionally if the predicted number of UEs in a cell increases. TDD mode reduces the overhead CSI recovery induced by many antennas and does not rely on channel models.

The large-scale MIMO incorporates these architecture principles to make high SE in the coverage level of future wireless systems an effective way. Each base station is fitted with a wide variety of antennas, M, and serves a cell, K. Each terminal usually has a single antenna. Various bases represent different cells. With the possible limitation of power management and pilot allocations, XL MIMO does not depend on base station cooperation

In both uplink and downlink transmissions, all terminals have used the entire time- frequency capabilities simultaneously. The multiplexing and de-multiplexing signal processing of the base station is provided with multiplicative antennas and CSI due to TDD methods, calculating the terminals' pilots and reciprocating the uplink and downlink transmissions. The CSI needs transceiver hardware reciprocity calibration.

Figure 2. Illustration of the basic XL MIMO



(a) Uplink

(b) Downlink

The FDD Downlink Training with the appropriate CSIT feedback provides broad M and K, an inadmissible high uplink overhead, considering the higher multiplexing advantage. The downlink channel from uplink training is estimated using TDD systems with channel reciprocity. It is noteworthy both in terms of achieving performance and simplifying downlink scheduling at BS. The transmitter knowledge of previous channel outcomes acquired by training or channel statistics can be determined based on a short sequence. However, additional feedback is required to obtain channel statistics on massive non-stationary MIMO channels.

Thus, TDD/FDD large MIMO systems are needed with a different CSI estimate and feedback methodology that provides reliable CSIT with low overheads and low complexity. To address this challenge, compressed sensing in Bayesian (BCS) is a palatable technique for estimating a sparse channel in uncertain channel statistics.

1.4. Methodology

1.4.1 System Model

The system consists of:

- $N_t = 256$ transmitters and $N_r = 256$ receivers.
- Mixed LoS/NLoS propagation with 18 line paths.
- Pilot lens count up to 2600.
- Distance range: 80m to 100m.
- SNR range: 0 to 30 dB in steps of 5 dB.

1.4.2 Channel Model

The received signal **Y** is modeled as:

$$\mathrm{Y} = \mathrm{HX} + \mathrm{N} \tag{1}$$

where:

- $\mathbf{H} \in \mathbb{C}^{N_r \times N_t}$ represents the channel matrix.
- $\mathbf{X} \in \mathbb{C}^{N_t \times T}$ is the transmitted signal.
- $\mathbf{N} \in \mathbb{C}^{N_r \times T}$ denotes additive white Gaussian noise (AWGN).
- T is the number of pilot symbols.

LoS Component

The LoS component is modeled as a geometric free-space propagation:

$$\mathbf{H}_{\text{LoS}} = \alpha e^{-j2\pi\frac{d}{\lambda}}\mathbf{a}_r(\theta_r)\mathbf{a}_t^H(\theta_t) \quad (2)$$

where:

- α is the path gain.
- d is the distance between antennas.
- λ is the signal wavelength.
- $\mathbf{a}_r(\theta_r)$ and $\mathbf{a}_t(\theta_t)$ are the array response vectors at the receiver and transmitter, respectively.

NLoS Component

The NLoS component follows the cluster-based scattering model:

$$\mathbf{H}_{\text{NLoS}} = \sum_{l=1}^{L} \alpha_l\, e^{-j2\pi\frac{d_l}{\lambda}}\mathbf{a}_r(\theta_r^l)\mathbf{a}_t^H(\theta_t^l) \quad (3)$$

where $L = 18$ represents the number of NLoS paths.

The combined near-field channel matrix is:

$$\mathbf{H} = \mathbf{H}_{\text{LoS}} + \mathbf{H}_{\text{NLoS}} \quad (4)$$

II. RESULT AND DISCUSSION

The results obtained are as discussed below

2.2.1 NMSE vs. DISTANCE Analysis

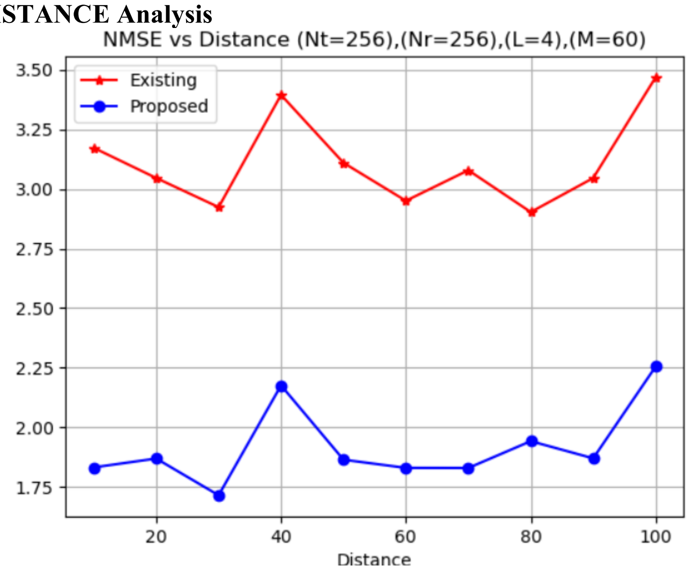


Fig.3 The graph between NMSE Vs DISTANCE

The graph presents a comparison between two models: "Existing" (in red) and "Proposed" (in blue) in terms of Normalized Mean Squared Error (NMSE) vs Distance.

The Proposed method significantly reduces NMSE, proving it to be more efficient. The improvement suggests that the proposed method offers better noise handling, error minimization, or an improved estimation process. If this is related to wireless communication, machine learning, or signal processing, the proposed model likely enhances accuracy and reliability over increasing distances.

2.2.2NMS vs PILOT LENGTH Analysis

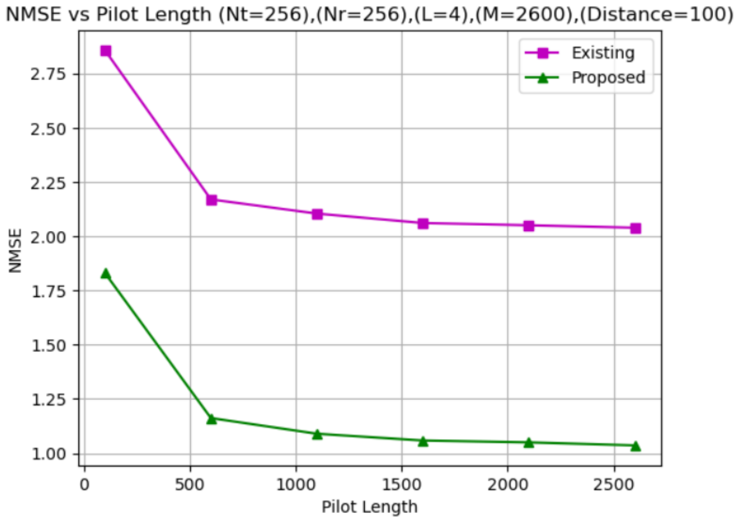


Fig. 4(a) NMSE Vs PILOT LENGTH

Fig.4(a) represents a comparison between the "Existing" method (magenta line with squares) and the "Proposed" method (green line with triangles) in terms of Normalized Mean Squared Error (NMSE) vs Pilot Length.

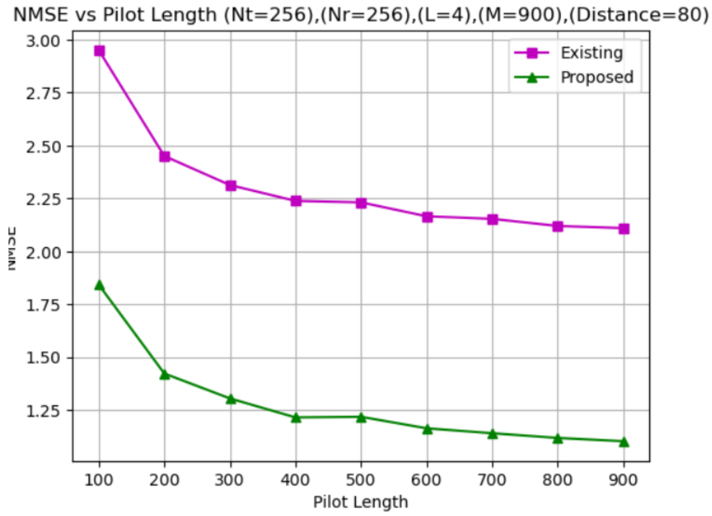


Fig.4(b) NMSE Vs PILOT LENGTH

Fig.4(b) represents a comparison of Normalized Mean Squared Error (NMSE) vs. Pilot Length for two different methods:

- Existing method (magenta line with squares)
- Proposed method (green line with triangles).

2.2.3 NMSE Vs SNR Analysis

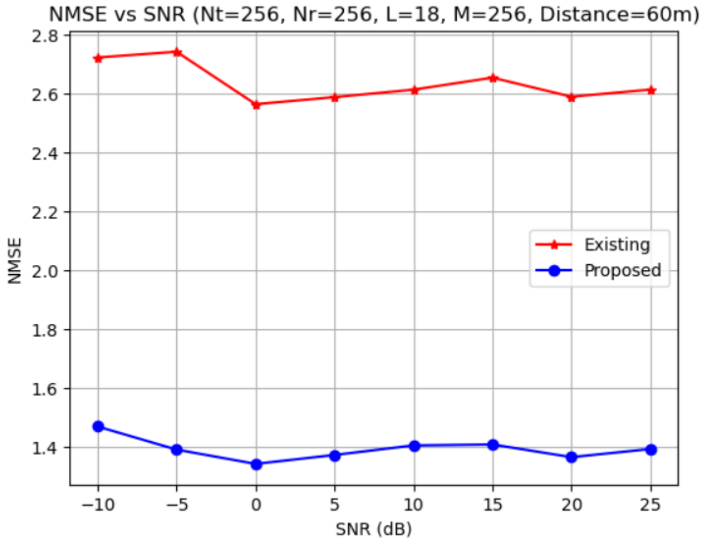


Fig.5(a) NMSE Vs SNR

Fig.5(a) represents a Normalized Mean Squared Error (NMSE) vs. Signal-to-Noise Ratio (SNR) in dB, comparing the performance of:

- Existing method (red line with squares)
- Proposed method (blue line with circles)

the system parameters are:(Nt=256, Nr=256, L=18, M=256, Distance=60)

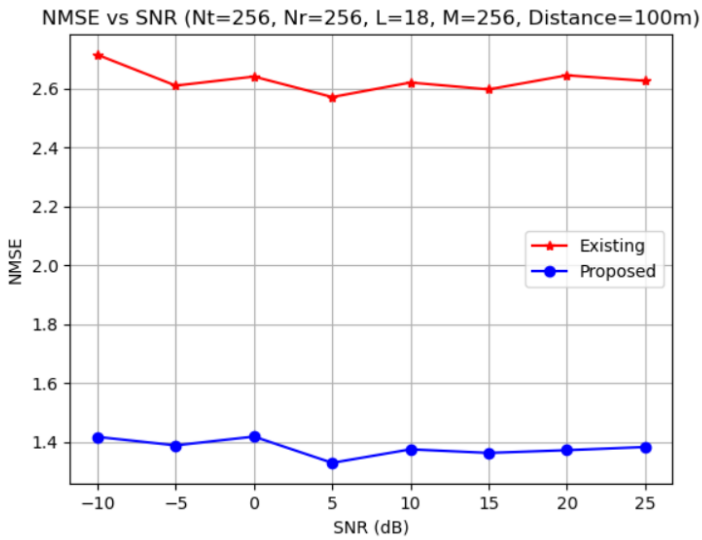


Fig.5(b) NMSE Vs SNR

Fig.5(b) represents a This graph represents NMSE vs. SNR (dB) for two methods:

- Existing method (red line with triangles)
- Proposed method (blue line with circles)

The given parameters are: :(Nt=256, Nr=256, L=18, M=256, Distance=100)

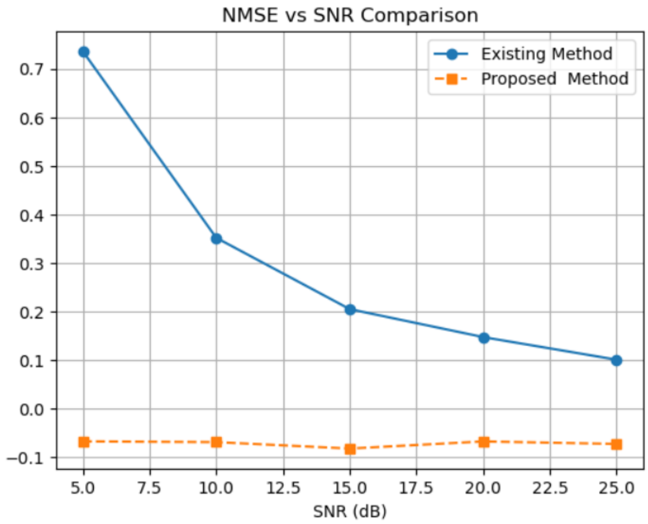


Fig.5(c) NMSE performance comparison with respect to the SNR under the QuaDRiGa channel dataset

- The Proposed method is highly effective in minimizing NMSE across all SNR values.
- The Existing method shows improvement with increasing SNR but remains significantly worse than the Proposed method.
- SVT (Singular Value Thresholding) appears to be highly effective in improving channel estimation accuracy.
- For practical applications, the Proposed method would be preferred, especially in scenarios with varying noise levels.

III. CONCLUSION

This study has successfully extended prior research on XL-MIMO channel estimation by significantly scaling up the system configuration and utilizing the SVT algorithm for enhanced accuracy. By analyzing NMSE performance across various SNR levels, the study demonstrates that SVT effectively reconstructs the near-field mixed LoS/NLoS channels while maintaining low estimation errors. The findings confirm that increasing the number of pilot lenses improves channel recovery, with diminishing returns beyond a certain threshold. Comparative analysis with conventional methods such as LS and MMSE shows that SVT provides superior accuracy, particularly in low-SNR conditions. The results highlight the robustness of SVT-based estimation in complex XL-MIMO scenarios, making it a viable solution for next-generation wireless communication systems.

Future research will focus on integrating deep learning models to further enhance estimation accuracy while reducing computational complexity. Additionally, the impact of reconfigurable intelligent surfaces (RIS) and hybrid estimation techniques will be explored to optimize channel estimation in practical deployment scenarios for 6G networks.

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