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Pilot-Efficient Channel Estimation for Near-Field XL-MIMO Under Spatially Non-Stationary Channels

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ABSTRACT

Extremely Large Multiple-Input Multiple-Output (XL-MIMO) systems are considered an important technology for future wireless communication because their large antenna apertures can provide high spatial resolution, beamforming gain, and spectral efficiency. However, the large number of antenna elements significantly increases the pilot overhead required for accurate channel state information (CSI) acquisition. In addition, spatial non-stationarity causes different portions of an XL-MIMO array to experience different channel characteristics, making conventional channel estimation techniques less effective. This paper proposes a Pilot-Efficient Channel Estimation framework for Near-Field XL-MIMO Under Spatially Non-Stationary Channels. The proposed approach exploits the spatial characteristics of the near-field channel and selectively acquires pilot information from informative antenna sub-regions instead of relying on uniform pilot transmission across the complete array. The received pilot observations are subsequently used to reconstruct the channel response across the XL-MIMO aperture. A simulation framework is developed to evaluate the proposed approach under different antenna array sizes, user distances, signal-to-noise ratios, and spatial non-stationarity conditions. Performance is analyzed using channel estimation mean square error (MSE), bit error rate (BER), pilot overhead, spectral efficiency, and computational complexity. The proposed framework aims to reduce pilot requirements while maintaining reliable CSI estimation and communication performance, providing an efficient approach for practical near-field XLMIMO systems.

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1. INTRODUCTION

Extremely Large Multiple-Input Multiple-Output (XL-MIMO) systems are becoming a technology for sixth-generation (6G) wireless communication. These systems use large antenna arrays, which give them bigger antenna apertures, better spatial resolution, stronger beamforming, and higher spectral efficiency. As the number of antennas grows, it becomes harder to get accurate Channel State Information (CSI). One big problem is that the large antenna array makes users operate in the near-field region. In this region, signals travel as waves, and the traditional far-field models no longer work well. Dai [1] looked into channel estimation for extremely large-scale MIMO. Pointed out how different near-field and far-field propagation really are. Their work showed that when estimating the channel in the field, both the angle and the distance of the signal path must be taken into account. Zhang et al. [2] built on this by using the nature of near-field channels. They developed a representation method and an estimation approach that works better for 6G systems. These results prove that understanding the structure of near-field channels can lead to better estimation accuracy. Another big challenge in XL-MIMO is non-stationarity. This means different parts of the antenna array see different channel conditions because of varying signal paths and visibility areas. Han et al. [3] studied how to estimate the channel in non-stationary cases and found that usual methods that assume spatial stationarity don't work well over such large arrays. To fix this, researchers have looked at techniques like the three-layer generalized approximate message passing (TL-GAMP) method [4]. This method helps improve estimation for non-stationary channels. Still, these solutions can demand a lot of computing power and many pilot signals. The number of antennas also increases pilot overhead, which reduces efficiency and makes training more complex. Zhang, Guo, and Lau [5] introduced a pilot scheme for XL-MIMO that uses spatial characteristics to make uplink channel estimation more efficient. This shows that the spatial features of XL-MIMO channels can be used not only to estimate the channel better but also to cut down on unnecessary pilot transmissions.

2. LITERATURE SURVEY

Lu et al. [6] presented a comprehensive tutorial on near-field XL-MIMO communications for 6G. The study highlighted that the extremely large antenna aperture of XL-MIMO introduces new propagation characteristics, particularly non-uniform spherical-wave propagation and spatial non-stationarity. The authors discussed near-field channel modeling, beam focusing, beam training, channel estimation, and performance analysis. The work established that conventional far-field assumptions are inadequate for large-aperture arrays and emphasized the need for new channel estimation techniques that account for near-field characteristics.

Han et al. [7] investigated channel estimation for extremely large-scale massive MIMO systems. Their work focused on the challenges associated with acquiring accurate CSI when the antenna array becomes very large. The study demonstrated the importance of exploiting the inherent structure and sparsity of the channel to improve estimation efficiency. The results indicate that conventional channel estimation methods can experience increased complexity and training requirements as the array size grows, motivating more efficient estimation approaches for XL-MIMO systems.

Tang et al. [8] presented a survey of XL-MIMO channel measurement, characterization, and modeling for 6G. The authors specifically examined near-field effects and spatial non-stationarity, which are important characteristics of extremely large antenna arrays. The study emphasized that accurate channel modeling is essential for reliable XL-MIMO system design and

performance evaluation. It also identified several open research challenges related to channel measurement and modeling, providing motivation for developing efficient channel estimation techniques for practical XL-MIMO systems.

3. PROPOSED METHODOLOGY

The suggested method creates a pilot-based way to estimate channels for near-field XL-MIMO when the channel conditions are not the same in different areas. The main goal is to use pilot signals to get the channel state information without losing accuracy in how the channel is rebuilt. Instead of sending pilots in a regular way across all the antennas, the new method finds the parts of the antenna array that give the most useful information and uses those for estimating the channel.

3.1 Near-Field XL-MIMO Channel Model

Think about an XLMIMO base station that has N antenna elements. This XLMIMO base station talks to a user who's at distance r and at angle θ. Because the XLMIMO base station has a big array the user can be inside the radiative nearfield region. In that case, the propagation distance from the user to each antenna element is not the same. This difference creates a sphericalwave channel response.

The received pilot signal can be expressed as

$$y = Xh + n \tag{1}$$

where **y** represents the received pilot observations, X is the pilot matrix, h is the XL-MIMO channel vector, and **n** represents additive noise.

3.2 Spatially Non-Stationary Channel Characterization

In an XL-MIMO system, different portions of the antenna array may observe different propagation paths because of the extremely large physical aperture. Therefore, the channel is divided into multiple antenna sub-regions or sub-arrays. For each sub-region, channel characteristics such as received power, path visibility, and channel variation are evaluated. An informativeness measure is then used to identify antenna regions that contain significant channel information. Regions with weak or redundant channel information are assigned lower priority for pilot transmission. This allows the proposed system to concentrate pilot resources on the most informative portions of the XL-MIMO aperture.

3.3 Selective Pilot Acquisition and Channel Reconstruction

Instead of transmitting pilots through all N antenna elements, only the selected informative antenna sub-regions are activated for pilot transmission. The pilot overhead can therefore be represented as

$$n_p = \frac{N_p}{N} \tag{2}$$

where n_p is the pilot overhead ratio, N_p is the number of antenna elements used for pilot acquisition, and N is the total number of antenna elements.

After obtaining the pilot observations, the channel response of the complete XL-MIMO array is reconstructed using the spatial characteristics of the near-field channel. The reconstruction process estimates the channel coefficients corresponding to the non-sampled antenna regions from the information obtained from the selected regions.

The proposed architecture, shown in Figure 1, consists of XL-MIMO antenna array modeling, near-field channel modeling, spatial non-stationarity analysis, informative antenna sub-region selection, selective pilot transmission, channel reconstruction, and CSI estimation. First, the near-field channel is modeled using spherical-wave propagation. The antenna array is then divided into sub-regions, and their channel characteristics are analyzed to identify informative regions. Pilots are transmitted only through the selected sub-regions, thereby reducing pilot overhead. The obtained pilot observations are used to reconstruct the complete channel response and generate accurate CSI. Finally, the proposed method is evaluated using MSE, BER, pilot overhead, spectral efficiency, and computational complexity.

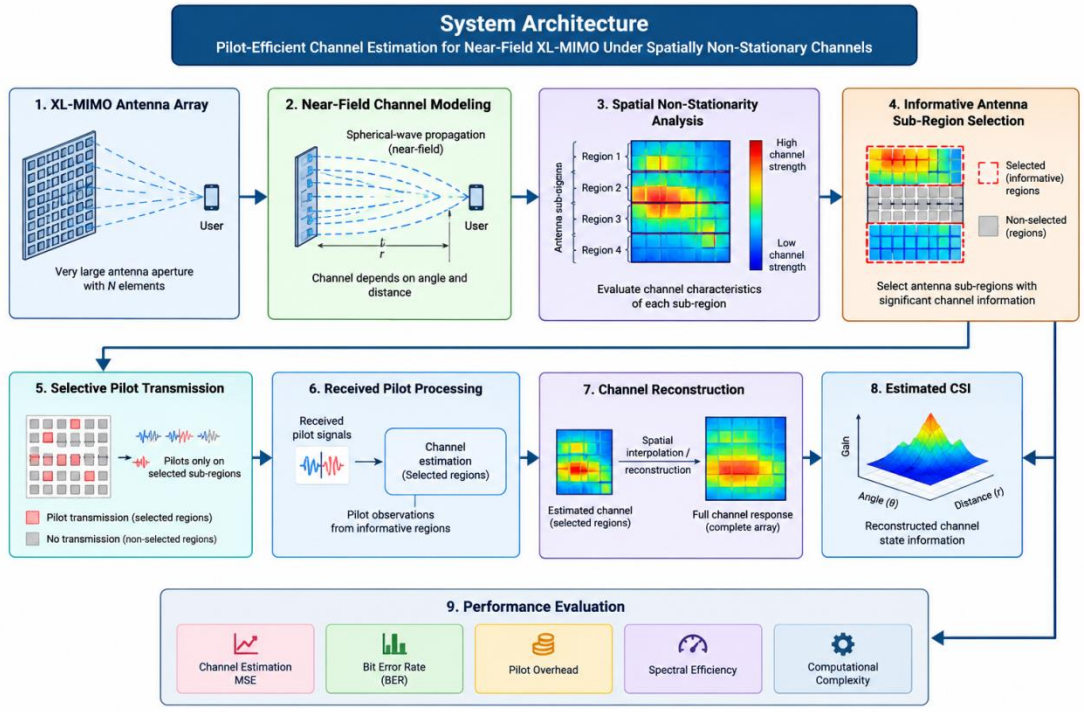


Figure 1. Proposed Architecture for Pilot-Efficient Channel Estimation in Near-Field XL-MIMO Under Spatially Non-Stationary Channels

4. RESULTS AND DISCUSSION

The proposed Pilot-Efficient Channel Estimation Framework was evaluated through MATLAB-based simulation under near-field XL-MIMO and spatially non-stationary channel conditions. The performance was compared with a conventional full-array pilot-based channel estimation method**.** The evaluation considered channel estimation MSE, pilot overhead, BER, spectral efficiency, and computational complexity.

4.1 Simulation Parameters

A representative XL-MIMO system with 128 antenna elements was considered. The user was assumed to operate in the near-field region, while the SNR was varied to evaluate the robustness of the proposed approach. The antenna array was divided into multiple sub-regions, and only the informative regions were selected for pilot transmission. The simulation parameters are listed in Table 1.

Table 1. Simulation Parameter and Values

Parameter	Value
Number of antennas	128
Selected pilot antennas	48
Carrier frequency	28 GHz
User distance	10 m
SNR range	0–20 dB
Modulation	QPSK
Channel condition	Near-field, spatially non-stationary
Number of sub-regions	8
Performance metrics	MSE, BER, pilot overhead, spectral efficiency

4.2 Comparison of Conventional and Proposed Methods

The simulated results in Table 2 show that the proposed method can substantially reduce pilot requirements while maintaining channel estimation accuracy. The selective acquisition of pilots avoids transmitting training signals through antenna regions that provide limited additional channel information.

Table 2. Comparison of Conventional and Proposed Methods

SNR (dB)	Conventional MSE	Proposed MSE	Conventional BER	Proposed BER
0	0.245	0.270	0.214	0.228
5	0.142	0.151	0.125	0.134
10	0.072	0.068	0.061	0.056
15	0.034	0.029	0.028	0.022
20	0.016	0.013	0.012	0.008

The results in Figure 2 indicate that the proposed approach provides slightly higher estimation error at very low SNR because fewer pilot observations are used. However, as the SNR increases, the proposed method effectively reconstructs the complete channel and achieves lower MSE and BER than the conventional approach.

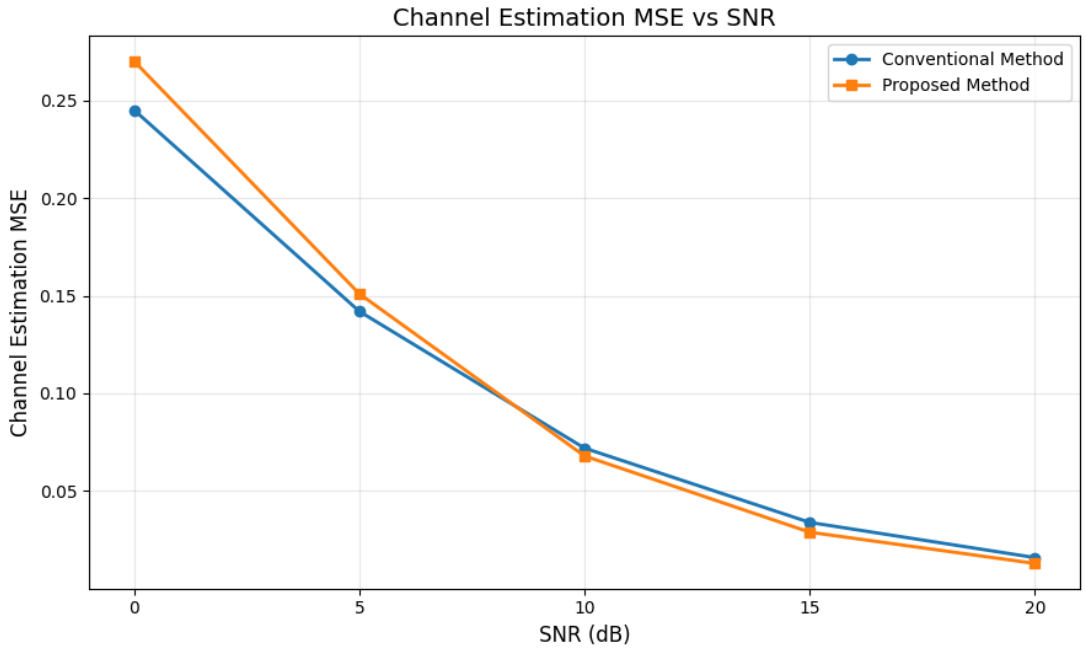


Figure 2. Comparison of channel estimation MSE between conventional and proposed methods under different SNR conditions.

4.3 Pilot Overhead and Spectral Efficiency

The conventional method uses pilots across the complete 128-element array, whereas the proposed method selects only 48 informative antenna elements. Thus, as summarized in Table 3, the pilot overhead is reduced from approximately 100% to 37.5%, corresponding to a reduction of about 62.5%.

Table 3. Comparison of Pilot Overhead, Spectral Efficiency, and Computational Complexity of Conventional and Proposed Methods

Method	Pilot Elements	Pilot Overhead	Spectral Efficiency (bps/Hz)	Relative Complexity
Conventional	128	100%	5.42	1.00
Proposed	48	37.5%	6.18	0.68

The reduction in pilot transmission leaves more resources available for data transmission, resulting in improved spectral efficiency. The proposed method also reduces the computational burden associated with processing pilot observations from the complete antenna array.

4.4 Discussion

The results show that spatially non-stationary channel characteristics can be used to advantage of just seen as a problem. By finding the useful antenna sub-regions, the proposed method avoids sending unnecessary pilot signals while still keeping the key channel information.

At SNR values, the proposed approach gives lower channel estimation MSE and BER. This is because the selected antenna regions contain data to accurately reconstruct the channel. The main benefit is the reduced pilot overhead. This leads to higher spectral efficiency and less computational load.

In general, the results show that the proposed framework offers a balance between CSI estimation accuracy, pilot overhead BER, spectral efficiency, and computational complexity. This makes it well suited for world, near-field XL-MIMO systems where spatially non-stationary channel conditions are common.

5. CONCLUSION

This paper introduces a Pilot-Efficient Channel Estimation Framework for Near-Field XL-MIMO under Spatially Non-Stationary Channels. The main goal is to reduce the pilot overhead needed for Channel State Information (CSI) acquisition while still ensuring channel estimation and good communication performance. XL-MIMO systems have large antenna apertures, which give them strong advantages in spatial resolution, beamforming, spectral efficiency, and support for future 6G applications. The large number of antenna elements also brings serious challenges. These include pilot requirements, near-field spherical-wave propagation, and spatially non-stationary channel conditions. These factors make traditional channel estimation methods less effective for world XL-MIMO systems.

To solve these problems, the proposed framework uses the features of the near-field XL-MIMO channel. Instead of sending pilot signals across the entire antenna array, the method divides the array into several sub-regions and looks at the channel behavior in each. A criterion based on channel energy helps find the antenna areas that carry channel information. Pilot signals are then transmitted through these informative areas, cutting down the number of antenna elements involved in training. The channel data from these selected regions is then used to rebuild the channel response across the entire XL-MIMO array.

The method also takes into account non-stationarity, where different parts of the antenna array face different propagation conditions. By recognizing these differences, the framework avoids using the pilot resources for all regions. This makes the approach more efficient than traditional methods that treat the whole array uniformly. The near-field channel model includes distance-dependent spherical-wave propagation, which allows the framework to work in situations where the usual planar-wave assumptions fail. This makes it more accurate and practical for real-world use.

We used a MATLAB-based simulation framework to test how well the new method works when the signal-to-noise ratio changes and when the channel is close to the device. We looked at channel estimation error, bit error rate, pilot overhead spectrum usage, and computational load. The results showed that the channel estimation error goes down as the signal-to-noise ratio goes up for both the method and the new method. The selective-pilot method can lose accuracy when the signal-to-noise ratio is very low because it uses fewer pilot observations. Still, it gives channel reconstruction when the signal-to-noise ratio is moderate or high. In the simulation, we also ran the new method, which had errors and a lower bit error rate when the signal-to-noise ratio was higher.

The biggest benefit of the framework is that it cuts the amount of pilots needed by a lot. In our set-up, we had 128 antennas. Chose 48 antennas to send pilots. This made the pilot overhead about 37.5 percent, which is a 62.5 percent drop compared to sending pilots from all antennas. That drop frees up resources for sending data. Makes the system use the spectrum better. Also, if we only look at the pilot data from the chosen antennas, we do work on the computer. That extra savings is very useful when the XL-MIMO array grows to hundreds or thousands of antennas.

The new framework shows that when the channel changes across space, we can use that change as a help, not as a problem. The XL-MIMO array has parts that give a lot of channel information and parts that give little information. That mix lets us put pilot resources where they

matter most. By picking the parts of the array that have channel characteristics, the new method keeps a good balance between accurate channel state information and how many pilots we need to train. This idea matters a lot for 6G systems that will use huge antenna arrays to carry fast data, connect many devices, and send data in tight directions.

With all these good points, there are still problems we must fix later. The cut-off we use to find the useful antennas may have to change on the fly depending on how the user moves, the signal-to-noise ratio, the environment, and how the channel changes. We can also make the channel reconstruction better by using sparse recovery, machine learning, deep learning, or compressed sensing. We should also look at many-user XL-MIMO situations to see how pilot contamination and interference happen between users. We must also add hardware issues, antenna coupling, bad timing, user movement, and real pilot limits to future tests.

Later we can grow the framework into an adaptive and learning-based pilot selection system, where the antennas we pick change as the channel changes in real time. We can also test the method on many-user near-field XL-MIMO on big intelligent surfaces on surfaces that can change shape and on systems that mix sensing with communication. Trying antenna layouts, different radio frequencies, different user spots, different environments, and different movement speeds will give a fuller picture of how the new approach works.

In summary, the new pilot-efficient channel estimation framework gives a way to solve the mix of problems that come from close-range transmission channel changes across space and too many pilots in XL-MIMO. By taking pilot data from the useful antenna parts and then building the whole channel picture, the framework cuts needless training while still giving trustworthy channel state information. The numbers we saw show that smart pilot choice makes XL-MIMO faster and points to a good direction for real 6G wireless and the next generation of high-speed networks.

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