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PERFORMANCE ANALYSIS OF LS AND LMMSE CHANNEL ESTIMATION FOR 5G NR OFDM SYSTEM

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Abstract. Accurate CSI acquisition is critical for reliable OFDM transmission in 5G NR. This paper establishes an OFDM baseband link and compares LS and LMMSE channel estimation. An AR1 model simulates slow and fast fading. To reduce approximation error in traditional LMMSE, a discrete frequency-domain autocorrelation matrix is derived. Simulations show LMMSE outperforms LS in slow fading. In fast fading, time-domain linear interpolation suppresses the error floor and tracks time-varying channels.

Keywords: ofdm, channel estimation, lmmse, time-domain linear interpolation, time-varying fading.

Introduction

Orthogonal Frequency Division Multiplexing (OFDM) is the core modulation technology for the 5G NR downlink, but it is highly sensitive to Channel State Information (CSI) accuracy. While inserting pilot symbols allows CSI acquisition, traditional Least Squares (LS) estimation is simple but highly susceptible to Additive White Gaussian Noise (AWGN) [1]. Conversely, the Linear Minimum Mean Square Error (LMMSE) algorithm offers optimal frequency-domain smoothing using second-order channel statistics, albeit with higher complexity and reliance on an accurate autocorrelation matrix.

OFDM Transceiver Link Model

This paper constructs a 5G NR-compliant OFDM baseband transmission system. As shown in the Figure 1, At the transmitter, the input bit stream is 16-QAM modulated, mapped onto N_{fft} orthogonal subcarriers with block pilots, and transformed to the time domain via IFFT [2]. A Cyclic Prefix is appended to mitigate Intersymbol Interference (ISI). At the receiver, assuming the CP length exceeds the channel's maximum multipath delay, the CP is removed and FFT is performed. The frequency-domain received signal on the $k-th$ subcarrier is expressed as

$$Y(k)=X(k)H(k)+Z(k). \tag{1}$$

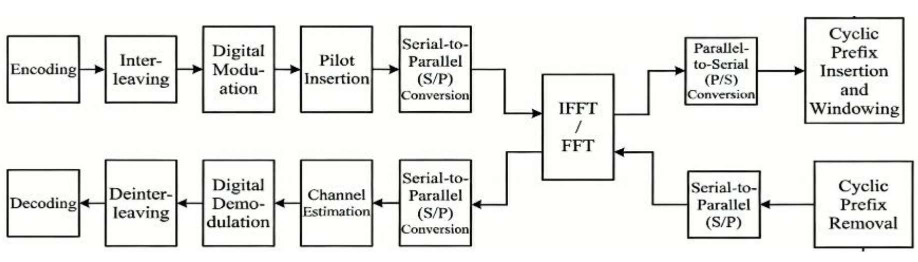

Figure 1. Matlab simulation flowchart of OFDM system

To simulate channel variations at different terminal mobility speeds, this paper adopts a first-order autoregressive (AR1) model to generate a time-varying multipath Rayleigh fading channel [2].

Let τ be the maximum multipath delay, the evolution process of the time-domain channel impulse response h_t for the $t-th$ OFDM symbol can be expressed as

$$h_t = \alpha \times h_{t-1} + \sqrt{\left(1-\alpha^2\right)} \times w_t \,, \tag{2}$$

where w_t is an independent complex Gaussian random process, and α is the time correlation coefficient, whose value is affected by the terminal's mobility speed (doppler shift). When $\alpha \approx 1$, the channel exhibits slow fading (or block fading); when $\alpha < 1$ the channel exhibits fast fading, meaning the channel response changes significantly within a single slot.

Pilot Structure Design

In OFDM systems, common pilot patterns include block pilot, comb pilot, and lattice pilot (scattered pilot), as shown in the Figure 2.

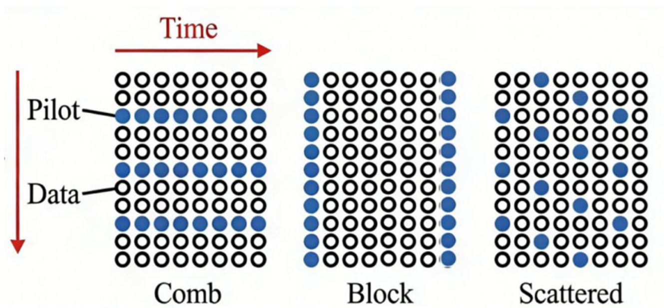

Figure 2. Typical OFDM pilot patterns: comb block, and scattered

While OFDM systems utilize various pilot patterns, this simulation employs a block pilot structure to adapt to the 5G NR slot format (14 symbols per slot). Pilots are inserted at the 1st and 8th symbol positions to enable effective tracking of the time-varying channel in subsequent processing [3].

Channel Estimation Algorithms

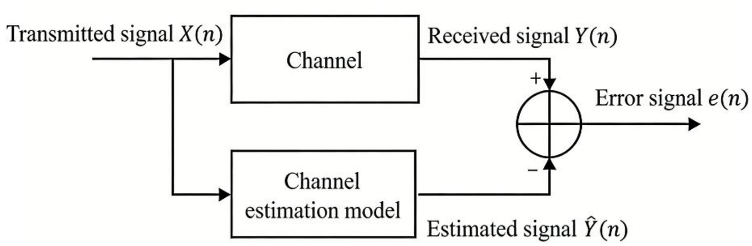

Figure 3. Channel estimation model

As shown in the Figure 3, the objective of the LS algorithm is to minimize the squared error between the received signal and the expected signal. At the block pilot positions, the frequency-domain channel response estimated by LS can be directly given by the zero-forcing formula

$$H_L S(k) = Y_p(k) / X_p(k) = H(k) + Z_p(k) / X_p(k) \,. \tag{3}$$

Building upon the LS estimation, the LMMSE algorithm utilizes the channels frequency-domain autocorrelation matrix R_{hh} and the system noise variance to smooth the estimates via Wiener Filtering. Its weight matrix W_{LMMSE} is

$$H_{LMMSE} = R_h \times \left[R_h + \frac{\beta}{SNR} \times I \right]^{-1} \times H_L H_L^H . \quad (4)$$

In traditional derivations, R_{hh} often uses an integral approximation assuming a continuous power delay profile. To eliminate the mismatch between this continuous approximation and the actual discrete FFT sampling, this paper derives an exact discrete correlation formula strictly based on a discrete uniform multipath power distribution. For subcarriers k and l, its elements are calculated as follows

$$R_h(k,l) = \frac{1}{\tau_{max}} \times \frac{1 - \exp\left(-j2\pi\tau_{max} \frac{k-l}{N_{fft}} \right)}{1 - \exp\left(-j2\pi \frac{k-l}{N_{fft}} \right)} . \quad (5)$$

While a sample-and-hold strategy suffices for slow fading, fast fading causes severe channel aging. As shown in the Table 1, this paper employs time-domain linear interpolation [4]. Using estimates from the 1st and 8th symbols, it interpolates intermediate data symbols and extrapolates the 9th to 14th symbols, recovering the entire slot's time-varying channel matrix.

Table 1. **5G NR OFDM Simulation Parameter Settings**

Parameter Name	Parameter Value
FFT Size	512
Cyclic Prefix Length (CP)	22
Number of Symbols	14
Modulation Scheme	16-QAM
Pilot Position (Symbol Index)	1,8
Maximum Multipath Delay(τ)	16

Algorithm Accuracy and System Performance Evaluation

In a slow fading environment, the channel remains static within a slot. We first evaluate the pure mathematical accuracy of the estimation algorithms.

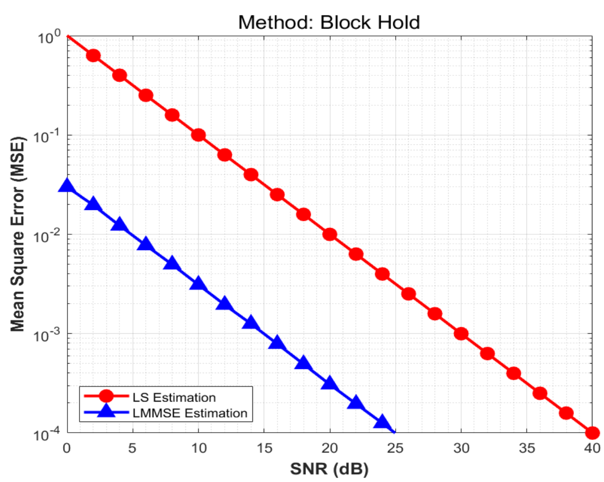

Figure 4. MSE Performance ($\alpha = 1$)

As shown in the Figure 4, in the Mean Square Error (MSE) performance evaluation, the LMMSE algorithm significantly outperforms the traditional LS algorithm across the entire SNR range. LMMSE reduces the estimation error by approximately one order of magnitude [5]. This is because the LS algorithm is highly susceptible to severe AWGN contamination, whereas the LMMSE algorithm fully exploits the low-rank nature of the frequency-domain autocorrelation matrix, achieving optimal smoothing and noise suppression in the frequency domain.

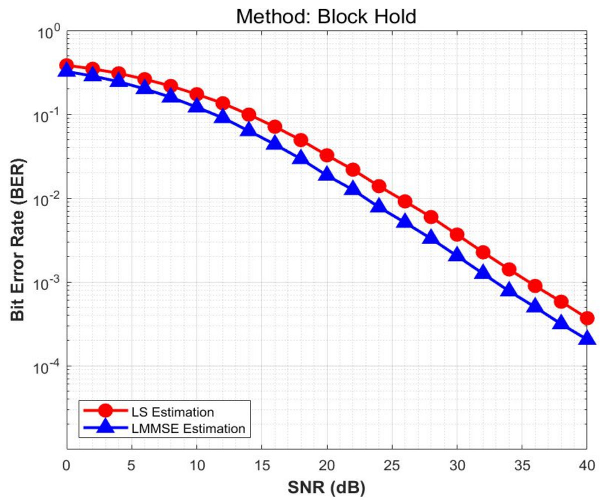

Figure 5. BER Performance slow fading ($\alpha = 1$)

As shown in the Figure 5, in extremely low SNR environments, the background white noise on data symbols dominates the total error. Consequently, the massive data noise floor during constellation decision-making masks the system-level gain brought by LMMSE's improved channel estimation.

In actual 5G NR mobile communications, the terminal's mobility speed (doppler shift) determines the time correlation of the channel. This paper selects two typical time-varying fading scenarios for comparative simulation: quasi-static or low-speed fading and high-mobility fast fading.

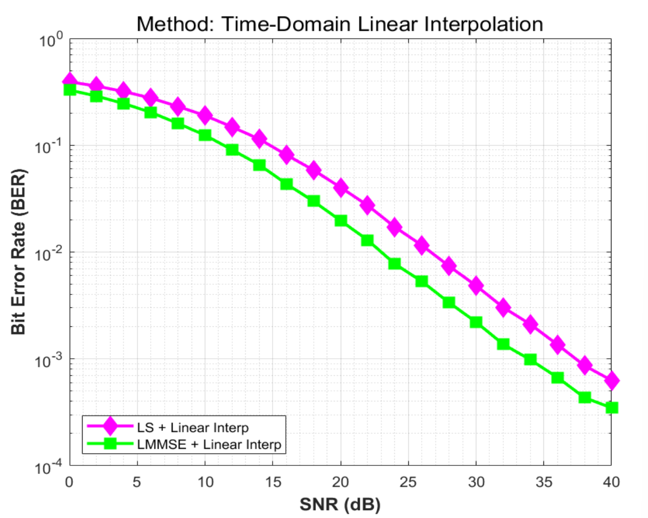

Figure 6. BER Performance under high-mobility fast fading ($\alpha = 0{,}999$)

The channel characteristics in this specific scenario exhibit an extremely slow evolution pattern in terms of both phase and amplitude within a single slot, which spans 14 symbols. Leveraging this property, the time-domain linear interpolation algorithm can fit this minute linear drift with exceptionally high precision.

As shown in the Figure 6, by examining the bit error rate (BER) curves, it is evident that the performance of both the Least Squares (LS) interpolation and Linear Minimum Mean Square Error (LMMSE) interpolation schemes demonstrates a consistent and smooth downward trend as the Signal-to-Noise Ratio (SNR) increases. Notably, no visually apparent error floor is observed across the entire SNR range, indicating robust system performance under high SNR conditions.

Furthermore, the LMMSE interpolation scheme offers distinct advantages at the pilot anchor points (specifically Symbol 1 and Symbol 8). This is primarily attributed to its superior subspace noise reduction capability, which effectively exploits statistical information to achieve a more favorable signal-to-interference ratio (SIR) and thereby enhances overall link quality compared to the LS method.

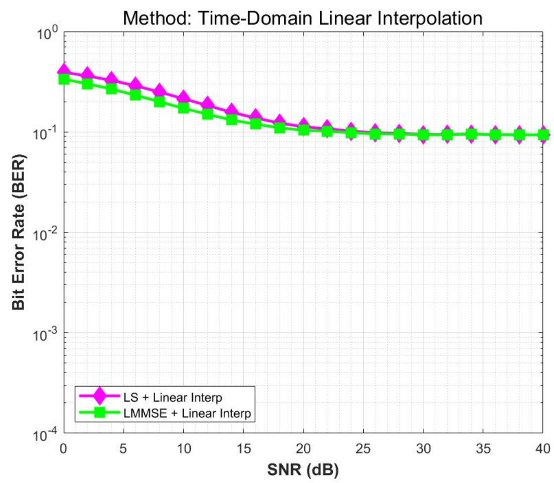

Figure 7. BER Performance under high-mobility fast fading ($\alpha = 0{,}985$)

As shown in the Figure 7, the system faces a high-mobility scenario, physically corresponding to highway or high-speed rail environments), the theoretical limitations of the algorithm are completely exposed [5]. As shown in Figure 5, when the SNR exceeds 20 dB, the BER curves of both algorithms stop descending and fall into a severe error floor effect, converging at the 10^{-1} order of magnitude.

The fundamental mechanism producing this starkly different phenomenon lies in the geometric mismatch of the interpolation model. According to the first-order autoregressive (AR1) channel evolution model, high doppler shifts cause drastic nonlinear fluctuations in the channel between adjacent pilot intervals (7 symbol periods) and continuously inject random innovation noise. First-order linear interpolation can only depict macroscopic linear trends and is completely incapable of tracking the high-frequency random fluctuations occurring on intermediate data symbols. In the low-to-medium SNR region, the AWGN background is the primary contradiction; here, the accurate pilot initial values provided by LMMSE can still bring system-level BER improvements. However, in the high SNR region, AWGN tends toward zero. At this point, the "nonlinear interpolation residual" caused by drastic channel changes takes over and becomes the dominant interference source in the system. This effective background interference, caused by insufficient geometric approximation capability, cannot be eliminated by increasing transmission power, thus forming an unbreakable error floor.

In summary, objective comparative simulations define the application boundaries of the proposed algorithm: the LMMSE linear interpolation scheme based on large-interval block pilots is perfectly competent for 5G NR low-speed or quasi-static scenarios; but facing high-mobility fast fading environments, excessive time-domain pilot intervals will lead to linear interpolation failure. This conclusion provides an important reference for pilot pattern design in practical systems: in extreme scenarios like high-speed rail, the system must sacrifice some spectral efficiency to densify time-domain pilots or introduce higher-order nonlinear tracking algorithms to break through this physical limit.

Conclusion

Targeting the 5G NR standard, this paper evaluates OFDM channel estimation and time-varying channel tracking using a block pilot architecture. By employing a strictly discrete autocorrelation matrix, the LMMSE algorithm comprehensively outperforms LS in MSE due to its excellent subspace noise reduction, while providing a stable parallel BER gain in the medium-to-high SNR region. The low-SNR BER convergence of both algorithms is fundamentally driven by the system-level ceiling effect of data symbol background noise.

Furthermore, simulations define the physical applicability boundary of the time-domain linear interpolation architecture [6]. While highly effective for quasi-static and low-speed fading environments, this first-order interpolation fails to track drastic nonlinear channel fluctuations in high-mobility fast fading scenarios (e.g., high-speed rail), inevitably resulting in a severe high-SNR error floor. These findings underscore the necessity of dynamic DMRS configurations in 5G networks: to break physical geometric approximation limits in extreme mobility scenarios, networks must sacrifice some spectral efficiency for denser time-domain pilot structures or adopt higher-order dynamic tracking algorithms.

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