

# PERFORMANCE ANALYSIS OF LS AND LMMSE CHANNEL ESTIMATION FOR 5G NR OFDM SYSTEMS OVER TIME-VARYING FADING CHANNELS

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**Abstract.** Accurate and efficient acquisition of Channel State Information (CSI) is crucial for reliable data transmission using Orthogonal Frequency Division Multiplexing (OFDM) in 5G NR (New Radio) systems. Focusing on the 5G NR physical layer standards, this paper constructs a complete OFDM baseband transmission link and conducts an in-depth performance comparison and theoretical analysis of block pilot-based Least Squares (LS) and Linear Minimum Mean Square Error (LMMSE) channel estimation algorithms. A first-order autoregressive (AR1) model is employed to simulate slow and fast fading environments at different mobility speeds. A strictly discrete frequency-domain autocorrelation matrix is derived to address the errors of continuous integral approximation in traditional LMMSE.

**Keywords.** OFDM; Channel Estimation; LMMSE; Time-domain Linear Interpolation; Time-varying Fading.

## Introduction

The OFDM is the core modulation technology for 5G NR downlink, and it is highly sensitive to CSI accuracy. Pilot symbol insertion enables CSI acquisition, while traditional LS estimation is simple but susceptible to Additive White Gaussian Noise (AWGN). The LMMSE algorithm achieves optimal frequency-domain smoothing using second-order channel statistics with higher complexity and reliance on accurate autocorrelation matrix. This paper focuses on performance comparison of LS and LMMSE under time-varying fading channels, and verifies the effectiveness of time-domain linear interpolation for fast fading channel tracking.

## System Model

A 5G NR-compliant OFDM baseband transmission system is constructed. At the transmitter, input bit stream is 16-QAM modulated, mapped onto  $N_{\text{fft}}$  orthogonal subcarriers with block pilots, and transformed to time domain via IFFT. Cyclic Prefix (CP) is appended to mitigate Intersymbol Interference (ISI). At the receiver, CP is removed and FFT is performed after synchronization, with frequency-domain received signal obtained on each subcarrier.

A first-order autoregressive (AR1) model is adopted to generate time-varying multipath Rayleigh fading channel for different terminal mobility speeds. The time-domain channel impulse response  $h_t$  for each OFDM symbol is expressed as:  $h_t = \alpha h_{t-1} + \sqrt{1-\alpha^2} \cdot w_t$ , where  $w_t$  is independent complex Gaussian random process, and  $\alpha$  is time correlation coefficient affected by terminal mobility speed (Doppler shift). ( $\alpha=1$ ) represents slow fading (block fading), while  $\alpha=0.985$  represents fast fading with significant channel variation within a single Slot.

Pilot Structure Design Common OFDM pilot patterns include Block Pilot, Comb Pilot and Lattice Pilot (Scattered Pilot). Block pilot structure is adopted in this simulation to adapt to 5G NR Slot format (14 symbols per Slot). Pilots are inserted at the 1st and 8th symbol positions to enable effective tracking of time-varying channels in subsequent processing, which provides anchor points for channel estimation and interpolation.

## Channel Estimation Algorithms

The LS algorithm aims to minimize the squared error between received signal and expected signal. At block pilot positions, the frequency-domain channel response estimated by LS can be directly obtained via zero-forcing formula, which features low complexity and easy implementation but poor anti-noise performance due to direct AWGN propagation.

Based on LS estimation, LMMSE algorithm uses channel frequency-domain autocorrelation matrix  $R_{hh}$  and system noise variance to smooth estimates via Wiener Filtering, with its weight matrix designed for optimal estimation. Traditional  $R_{hh}$  adopts integral approximation with continuous power delay profile, which has mismatch with actual discrete FFT sampling.

A strictly discrete correlation formula is derived based on discrete uniform multipath power distribution to eliminate the approximation error. For arbitrary subcarriers, the elements of discrete autocorrelation matrix are calculated with accurate discrete frequency-domain correlation characteristics, which improves the estimation accuracy of LMMSE algorithm.

Sample-and-hold strategy suffices for slow fading, while fast fading causes severe Channel Aging. Time-domain linear interpolation is employed for fast fading scenarios: using estimates from the 1st and 8th pilot symbols, intermediate data symbols are interpolated and the 9th to 14th symbols are extrapolated, recovering the entire slot's time-varying channel matrix to track dynamic channel changes.

Table 1 – 5G NR OFDM Simulation Parameter Settings

| Parameter Name                           | Parameter Value |
|--|-----------------|
| FFT Size (N_fft)                         | 512             |
| Cyclic Prefix Length (N_cp)              | 22              |
| Number of Symbols per Slot (N_sym)       | 14              |
| Modulation Scheme                        | 16-QAM / QPSK   |
| Pilot Position (Symbol Index)            | 1, 8            |
| Maximum Multipath Delay ( $\tau_{max}$ ) | 16              |

### Algorithm Performance Evaluation

In slow fading environment, the channel remains static within a Slot. LMMSE algorithm significantly outperforms traditional LS algorithm in MSE across the entire SNR range, reducing estimation error by approximately one order of magnitude in low SNR region. LS is susceptible to AWGN contamination, while LMMSE exploits the low-rank nature of frequency-domain autocorrelation matrix to achieve optimal smoothing and noise suppression.

In BER performance, LMMSE maintains stable parallel gain in medium-to-high SNR region. The BER convergence in extremely low SNR is caused by system "ceiling effect", where background white noise on data symbols dominates total error and masks the gain from improved channel estimation.

Two typical fast fading scenarios are simulated: quasi-static/low-speed fading ( $\alpha=0.999$ ) and high-mobility fast fading ( $\alpha=0.985$ ). For low-speed fast fading, channel evolution within one slot is extremely slow, and time-domain linear interpolation can fit the minor linear drift with high precision. BER of both LS+Interpolation and LMMSE+Interpolation schemes decreases continuously with increasing SNR without obvious Error Floor, with LMMSE gaining better performance from excellent subspace noise reduction at pilot anchor points.

For high-mobility fast fading (highway/high-speed rail environments), BER curves stop descending and fall into severe error floor effect when SNR exceeds 20 dB. The root cause is the geometric mismatch of interpolation model: AR1 channel model causes drastic nonlinear fluctuations between pilot intervals, and first-order linear interpolation can only depict macroscopic linear trends, incapable of tracking high-frequency random fluctuations. In high SNR region, "nonlinear interpolation residual" becomes the dominant interference source that cannot be eliminated by increasing transmission power.

### Conclusion

Targeting 5G NR standard, this paper evaluates LS and LMMSE channel estimation algorithms based on block pilot architecture for OFDM systems over time-varying fading channels. By adopting strictly discrete autocorrelation matrix, LMMSE algorithm comprehensively outperforms LS in MSE due to excellent subspace noise reduction capability, and provides stable parallel BER gain in medium-to-high SNR region. The low-SNR BER convergence of both algorithms is driven by the system-level ceiling effect of data symbol background noise.

Time-domain linear interpolation is highly effective for quasi-static and low-speed fading environments, but fails to track drastic nonlinear channel fluctuations in high-mobility fast fading scenarios, resulting in severe high-SNR error floor. These findings indicate the necessity of dynamic DMRS configurations in 5G networks: for extreme mobility scenarios, denser time-domain pilot structures (e.g., comb pilots) or higher-order dynamic tracking algorithms (e.g., Kalman filtering) should be adopted by sacrificing partial spectral efficiency to break through the physical limit of linear interpolation.

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