A Deep Learning Based Bi-Directional RNN Approach to LS Channel Estimation in OFDM Systems

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Abstract

Orthogonal frequency division multiplexing (OFDM) requires accurate channel estimation (CE) to ensure reliable data detection under noisy wireless conditions. This paper presents a bidirectional recurrent neural network (Bi-RNN) based least squares (LS) CE framework for a quadrature phase shift keying (QPSK) OFDM system. A supervised learning dataset is generated using Monte Carlo simulations over frequency-selective Rayleigh fading channels at multiple SNR levels. The proposed model learns to refine LS CE using real and imaginary channel components along with SNR information. Training is performed using a normalized mean square error (NMSE) loss to improve estimation accuracy. Simulation results demonstrate that the proposed approach significantly reduces bit error rate (BER) compared to classical LS estimation. The Bi-RNN achieves BER performance close to MMSE without requiring prior channel statistics.

Ⅰ. Introduction

In recent years, orthogonal frequency division multiplexing (OFDM) has emerged as a widely adopted modulation scheme for wireless communication systems due to its high spectral efficiency and strong robustness against multipath fading. The growing demand for higher data rates and improved reliability in modern wireless networks, such as fifth-generation (5G) and beyond systems, has driven continuous research on advanced channel estimation (CE) techniques [1]. Accurate CE is essential for mitigating channel impairments, including fading, Doppler shifts, and interference, which significantly degrade the performance of OFDM-based communication systems.

Conventional CE techniques, such as least squares (LS) and minimum mean square error (MMSE), are widely used in OFDM systems [2]. While LS offers low computational complexity, it suffers from severe noise sensitivity at low signal-to-noise ratios (SNRs) [3]. MMSE improves estimation accuracy by exploiting channel statistics, but its performance depends on prior knowledge of noise variance and channel correlation, which may be unavailable or inaccurate in practice [4]. Recently, machine learning (ML), particularly deep learning (DL), has shown strong potential for enhancing physical-layer signal processing [5]. Recurrent neural networks (RNNs) are well-suited for modeling temporal dependencies in wireless channels [6], and bidirectional RNNs (Bi-RNNs) further improve learning by exploiting both past and future signal information. Despite their promise, BiRNN-based CE for OFDM systems remains relatively underexplored.

In this paper, we propose a Bi-RNN assisted LS CE framework for quadrature phase shift keying (QPSK) modulated OFDM systems. The model jointly exploits the real and imaginary components of the frequency-domain channel response, along with SNR information, to enhance estimation accuracy. Simulation results demonstrate that the proposed Bi-RNN-based estimator achieves superior normalized mean square error (NMSE) and bit error rate (BER) performance compared to conventional LS and MMSE methods, particularly in low-SNR scenarios.

Ⅱ. OFDM Channel and Receiver Architecture

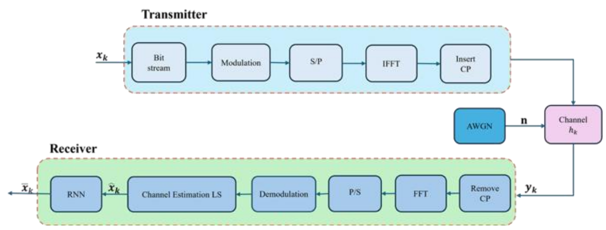

Figure 1. OFDM Architecture

In this work, we consider a QPSK-modulated OFDM system over a frequency-selective Rayleigh fading channel, as illustrated in Figure 1. At the transmitter, the modulated symbols are converted to the time domain using an inverse fast fourier transform (IFFT) and appended with a cyclic prefix (CP). After transmission through the channel, CP removal and fast fourier transform (FFT) are performed at the receiver, and the received signal on the k-th subcarrier is expressed as

$$Y_k = H_k X_k + N_k, \qquad (1)$$

Monte Carlo simulations are performed over an SNR range of 0–30 dB. The LS estimator is used as a baseline and is given by

$$\hat{H}_k^{LS} = Y_k X_k^{-1}, \quad (2)$$

which offers low complexity but suffers from noise sensitivity. To improve estimation accuracy, the MMSE estimator exploits channel statistics and noise variance, expressed as

$$\hat{H}^{MMSE} = R_{HH}(R_{HH} + \sigma_n^2 I)^{-1} \hat{H}^{LS}, \quad (3)$$

Where R_{HH} denotes the channel autocorrelation matrix.

Ⅲ. Robust Channel Estimation Using Deep Learning Techniques

A Bi-RNN-based DL model is proposed to refine the LS CE rather than replace it. The input features include the real and imaginary parts of the LS estimate and the normalized SNR, while the target output consists of the corresponding components of the true channel. Stacked Bi-RNN layers are used to capture inter-subcarrier dependencies in both directions, followed by residual connections and fully connected layers to improve convergence. The network is trained using the NMSE loss to ensure scale-invariant learning across SNRs. The refined CE is then used for frequency-domain equalization, followed by QPSK demodulation. The BER performance of the proposed Bi-RNN-based estimator is evaluated over various SNRs and compared with conventional LS and MMSE methods.

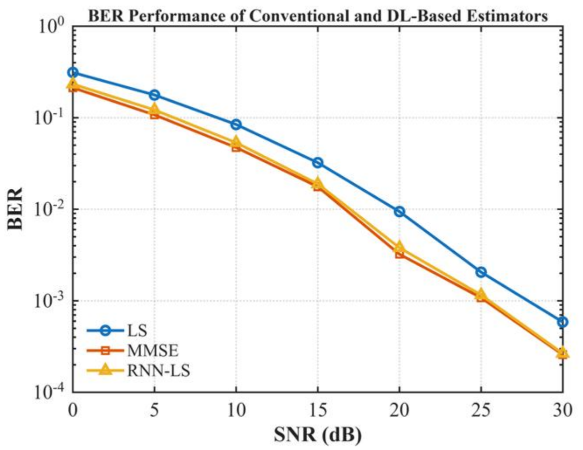

Figure 2 BER vs. SNR for LS, MMSE, and RNN-LS estimators.

In this research work, the BER performance comparison shown in Figure 2 demonstrates that the LS estimator exhibits the highest error rate, particularly at low SNRs. In contrast, the MMSE estimator provides improved performance under the assumption of ideal channel statistics. The proposed Bi-RNN-based estimator consistently outperforms LS and achieves BER performance close to MMSE across the entire SNR range by effectively mitigating noise effects.

IV. Conclusions

This paper proposed a Bi-Directional RNN-based LS CE framework for a QPSK-OFDM system, achieving significant BER improvement over classical LS and near-MMSE performance without requiring prior channel statistics. The results confirm the effectiveness of DL in enhancing CE accuracy under noisy conditions. Future work will extend the framework to higher-order modulations, larger OFDM configurations, and time-varying channels, while exploring attention-based or lightweight architectures to reduce computational complexity.

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