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Design of Channel Estimation and Channel Equalization Scheme for Massive MIMO-OFDM Communication System

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ABSTRACT

The combination of massive MIMO (massive multiple input multiple output) technology and OFDM (orthogonal frequency division multiplexing) technology has become one of the key technologies in modern wireless communication systems. With the increase in the number of antennas and the complexity of communication channels, channel estimation and channel equalization have become important technical means to ensure system performance. In this paper, a channel estimation method and an adaptive equalization method based on the guide frequency signal are proposed to address the problems of channel distortion and inter-symbol interference (ISI) in massive MIMO-OFDM systems by designing an efficient channel estimation and equalization strategy in order to improve the system performance. In this paper, we first establish the channel model, design the system frame diagram, and analyze the data processing flow, then compare several channel estimation and equalization methods, propose a channel estimation method based on the guide signal, and select an adaptive equalization method for performance optimization. The proposed scheme has a large potential value in reducing the bit error rate (BER), improving the system capacity and anti-interference capability.

KEYWORDS

Massive MIMO; OFDM; Guide Frequency Estimation; Adaptive Equalization; BER

1. INTRODUCTION

In millimeter-wave wireless communication systems, the wireless channel is one of the most important factors affecting the performance of the system, and the complex and variable wireless transmission environment makes it impossible to artificially predict and establish a fixed model for the wireless channel [1]. This high frequency band signal has high propagation loss along with severe absorption and scattering effects, which makes the coverage of millimeter wave communication systems limited [2].

Massive MIMO technology can utilize spatial multiplexing gain to increase channel capacity and spectrum utilization by deploying a large number of antenna arrays at the base station. This technique is able to enhance the communication performance by increasing the number of antennas in a limited physical space, thus effectively countering the propagation loss in the millimeter-wave band [3]. However, the massive MIMO technique performs poorly under frequency selective fading channels and cannot effectively counter the effects of frequency selective fading [4]. Due to increased user mobility, the accuracy of channel estimation decreases, leading to the phenomenon of channel aging, which affects the throughput of the system [5].

OFDM technology can effectively deal with the frequency selective fading problem by decomposing the signal into multiple subcarriers and processing them in the frequency domain. OFDM technology improves the transmission rate and reliability through the optimization of spectral efficiency and the ability to resist multipath fading. Combining massive MIMO and OFDM techniques can fully utilize their respective advantages, which can combine the spatial advantage of MIMO with the spectral efficiency advantage of OFDM [6].

However, in massive MIMO-OFDM communication systems, signal recovery becomes particularly complex due to channel distortion, interference and noise. Therefore, channel estimation and channel equalization become key techniques to improve system performance [7]. The accuracy of channel estimation directly affects the demodulation performance of the system, while channel equalization reduces the inter-symbol interference and decreases the BER by compensating channel distortion [8]. In this study, we will explore how to achieve efficient channel estimation and equalization in massive MIMO-OFDM systems through channel modeling, data analysis, and comparison of different estimation and equalization methods.

2. SYSTEM DESIGN

2.1. System Framework

The framework diagram of this system is shown in Fig. 1. The system consists of transmitter side, channel estimation module, channel equalization module and receiver side. The transmitting end includes multiple transmitting antennas and the receiving end is equipped with multiple receiving antennas. OFDM modulation technique is used for transmitting multi-subcarrier signals and data transmission is performed on each subcarrier. The signal undergoes the effects of multipath fading, noise and interference during transmission and the receiving end needs to recover the original data by channel estimation and channel equalization techniques.

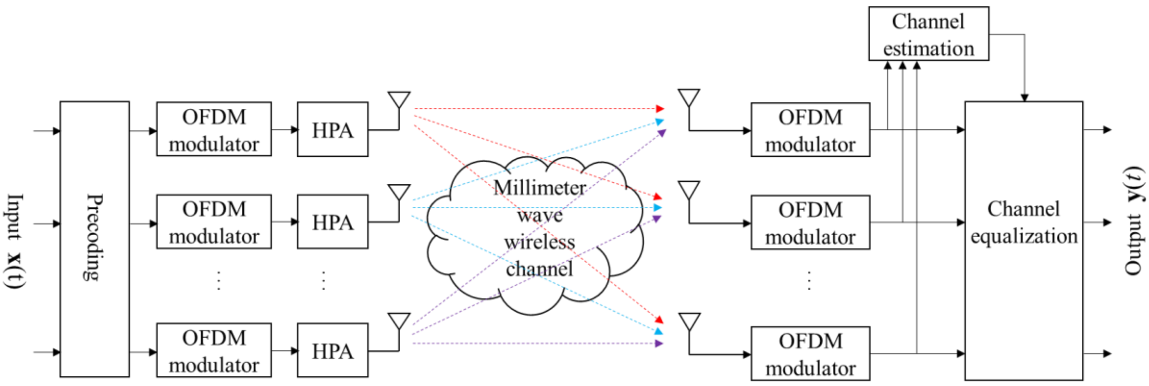

Figure 1. Block diagram of channel estimation and equalization principles for massive MIMO-OFDM system

2.2. Channel Model

In a massive MIMO-OFDM system, assume that there are N_t antennas at the transmitter side and N_r antennas at the receiver side. We need to build a multiple-input multiple-output (MIMO) channel model to describe the wireless channel between the transmitter and the receiver.

2.2.1. Basic Components of the Channel Model

Assume that the signal $\mathbf{x}(t)$ is transmitted from the transmitter, where $\mathbf{x}(t)\in\mathbb{C}^{Nt\times1}$ is the transmitted signal vector containing symbols transmitted by N_t antennas. The signal $\mathbf{y}(t)\in\mathbb{C}^{Nr\times1}$ at the receiving end contains the signals received by N_r antennas. The mathematical model of the signal transmission process can be expressed as:

$$\mathbf{y}(t)=\mathbf{H}(t)\mathbf{x}(t)+\mathbf{n}(t) \quad (1)$$

Where,

$\mathbf{H}(t)\in\mathbb{C}^{Nr\times Nt}$ is the channel matrix, which represents the channel state from the transmitter to the receiver.

$\mathbf{n}(t)\in\mathbb{C}^{Nr\times1}$ is the additive Gaussian white noise (AWGN), which is assumed to have zero mean and covariance matrix $\sigma^2\mathbf{I}$ ($\mathbf{I}$ am the unit matrix and σ^2 is the noise power).

$\mathbf{x}(t)$ is the transmitted symbol vector, which is usually normalized such that its expected power is one.

2.2.2. Channel Matrix in OFDM

In an OFDM system, the frequency domain signal is mapped to the time domain by IFFT (Inverse Fast Fourier Transform) and then transmitted in parallel over multiple subcarriers. Therefore, the channel matrix $\mathbf{H}(t)$ can have different responses on different subcarriers. Let each OFDM symbol contain N_{sc} subcarriers, then the channel matrix on each subcarrier can be expressed as:

$$\mathbf{H}_k = \mathbf{H}(f_k),\ k = 1, 2, \ldots, N_{sc} \quad (2)$$

Where f_k is the frequency of the k-th subcarrier and $\mathbf{H}_k\in\mathbb{C}^{Nr\times Nt}$ denotes the channel matrix on the k-th subcarrier.

Since the number of antennas in a massive MIMO system is usually large, the channel matrix H_k can be expressed as a high-dimensional matrix containing channel gain and phase information between multiple transmit and receive antennas. To simplify the analysis, it is assumed that the channel matrices of each subcarrier are independent in frequency but follow similar statistical properties among them.

2.2.3. Representation of channel models

Typically, the channel matrix $\mathbf{H}_k$ is modeled as a Rayleigh fading model that represents the multipath propagation characteristics of the wireless channel. For the channel matrix on the k-th subcarrier, its elements can be represented as independent complex Gaussian random variables:

$$\mathbf{H}_k = \sqrt{\frac{1}{L}}\sum_{l=1}^{L}\mathbf{a}_r(\theta_l)\mathbf{a}_t{}^H(\phi_l) \quad (3)$$

Where,

L is the number of multipaths.

$\mathbf{a}_r(\theta_l)$ and $\mathbf{a}_t(\phi_l)$ are the directional response vectors of the receiving and transmitting antenna arrays, respectively, describing the angular information of each channel path, θ_l is the receiving angle and ϕ_l is the transmitting angle.

$\mathbf{a}_r(\theta_l)$ and $\mathbf{a}_t(\phi_l)$ are vectors related to the geometry of the antenna array, which reflect the characteristics of the signal propagation between the transmitting and receiving antennas.

2.2.4. Channel Model for Massive MIMO-OFDM System

For a massive MIMO-OFDM system, the channel model can be simplified as the following equation:

$$\mathbf{y}_k = \mathbf{H}_k x_k + \mathbf{n}_k \tag{4}$$

Where,

$\mathbf{y}_k \in C^{Nr\times1}$ is the received signal at the k-th subcarrier at the receiver.

$\mathbf{H}_k \in C^{Nr\times Nt}$ is the channel matrix at the k-th subcarrier.

$\mathbf{x}_k \in^{CNt\times1}$ is the signal at the transmitter.

$\mathbf{n}_k \in C^{Nr\times1}$ is the noise at the receiving end.

The channel matrix $\mathbf{H}_k$ describes the channel characteristics from the transmitting antenna to the receiving antenna, including factors such as multipath propagation, response of the antenna array, and so on. In practical system design, channel estimation techniques are required to obtain an estimate of this channel matrix $\mathbf{H}_k$ for effective signal demodulation and equalization.

3. DATA ANALYSIS PROCESS

3.1. Channel Estimation

The purpose of channel estimation is to estimate the value of the channel matrix **H**, which is usually achieved by inserting the guide signal into the OFDM symbols. Since the channel matrix usually has a high dimension, accurate estimation of channel information is crucial for subsequent equalization and data recovery.

3.1.1. Guide Frequency Insertion

In OFDM systems, the guide frequency signals are known, periodic signals whose position and content can be predetermined. The transmitter inserts guide-frequency symbols into the transmitted data symbols, and these guide-frequency symbols are used to estimate the state of the channel. The frequency-conducting symbols are usually inserted at specific subcarrier positions of each OFDM symbol, forming a frequency-conducting matrix **X**p.

The insertion process of the guide frequency matrix can be expressed as:

$$\mathbf{x}(t) = \mathbf{X}_p + \mathbf{x}_d(t) \tag{5}$$

Where $\mathbf{x}_d(t)$ is the data symbol and $\mathbf{X}_p$ is the frequency-conducting matrix.

3.1.2. Received Signal Model

After receiving the signal at the receiving end, the channel can be estimated from the known guide frequency symbols. At the receiving end the received guide frequency symbol is Yp and the true channel matrix is Hp. Due to the presence of noise, there will be a difference between the received signal and the ideal signal. The estimation of channel matrix is done by Least Squares (LS) or Minimum Mean Square Error (MMSE) method:

$$\text{LS:} \quad \hat{\mathbf{H}}_p = \mathbf{Y}_p \mathbf{X}_p^{-1} \tag{6}$$

$$\text{MMSE:} \quad \hat{\mathbf{H}}_p = (\mathbf{X}_p^H \mathbf{R}_n^{-1} \mathbf{X}_p + \mathbf{R}_h^{-1})^{-1} \mathbf{X}_p^H \mathbf{R}_n^{-1} \mathbf{Y}_p \tag{7}$$

Where,

$\hat{\mathbf{H}}_p$ is the channel matrix obtained by guide frequency estimation.

$\mathbf{X}_p$ is the matrix of guided frequency signals sent by the transmitter.

$\mathbf{Y}_p$ is the received guided frequency signal at the receiving end.

$\mathbf{R}_n$ is the noise covariance matrix.

$\mathbf{R}_h$ is the covariance matrix of the channel.

3.1.3. Channel Interpolation

Since the guide frequency only appears on some subcarriers, the channel matrix of other subcarriers needs to be estimated by interpolation methods. Common interpolation methods include linear interpolation, least squares interpolation, and least mean square error interpolation.

The channel matrix $\widehat{\mathbf{H}}_p$ of the entire OFDM symbol (including channel information at both the pilot and non pilot positions) can be obtained by pilot interpolation.

3.2. Channel Equalization

The purpose of channel equalization is to recover the original data by compensating for channel distortion and multipath interference. The adaptive equalization method adjusts the parameters of the equalizer according to the real-time estimated channel information to optimize the quality of the received signal. In massive MIMO-OFDM systems, the use of adaptive equalization algorithms can effectively handle dynamically changing channels.

3.2.1. Adaptive Equalization Model

In adaptive equalization, the weights $\mathbf{W}$ of the equalizer are adjusted according to the estimated channel information $\widehat{\mathbf{H}}$ and noise statistical characteristics. Adaptive equalization continuously optimizes the equalizer weights through a feedback mechanism to minimize the error of the output signal.

Assuming that the received signal is y, the estimate $\hat{\mathbf{x}}$ of the received symbol is calculated by the equalizer:

$$\hat{\mathbf{x}} = \mathbf{W}\mathbf{y} \tag{8}$$

Where $\mathbf{W}$ is the weight matrix of the adaptive equalizer, and the weights are usually dynamically adjusted using the least mean square error (LMS) or recursive least squares (RLS) algorithms.

3.2.2. Adaptive Algorithms

The LMS algorithm minimizes the error between the received signal and the target signal by iteratively updating the weight matrix **W**. It has low computational complexity and is suitable for real-time processing. The RLS algorithm minimizes the mean square value of the error by recursively calculating the weight matrix **W**. It has a fast convergence speed and is more suitable for rapidly changing channel conditions. The update formulas are respectively:

$$\text{LMS:} \quad \mathbf{W}(k+1) = \mathbf{W}(k) + \mu\mathbf{e}(k)\mathbf{y}^H(k) \tag{9}$$

$$\text{RLS:} \quad \mathbf{W}(k+1) = \mathbf{W}(k) + \mathbf{K}(k)\mathbf{e}(k) \tag{10}$$

Where,

$\mathbf{W}(k)$ is the weight matrix at moment k.

$\mathbf{e}(k)$ is the current estimation error, defined as the difference between the target signal and the current output signal.

μ is the step factor, which controls the convergence speed of the algorithm.

$\mathbf{K}(k)$ is the gain vector.

3.2.3. Data Recovery

After equalization, the signal $\hat{\mathbf{x}}$ recovers the original data through demodulation and decoding. Commonly used demodulation methods include QPSK, 16-QAM, etc., and the decoding process can use channel coding such as convolutional coding, Turbo coding, etc. to recover the data.

4. DATA ANALYSIS AND PERFORMANCE EVALUATION

4.1. Performance Evaluation Metrics

To evaluate the performance of channel estimation and equalization methods, commonly used metrics include:

(1) Bit Error Rate (BER): a measure of the error between the recovered data and the original data. BER is the most direct measure of channel estimation and equalization performance.

(2) Signal-to-Noise Ratio (SNR): the ratio of the strength of the signal to the strength of the noise. the performance of different channel estimation and equalization methods at different SNRs is usually evaluated through simulation analysis.

(3) Throughput: the amount of data successfully transmitted per unit time, which is used to evaluate the efficiency of the system.

4.2. Simulation Analysis

Simulations are usually performed under different channel conditions, SNR values and different estimation and equalization algorithms. By comparing the BER, throughput and other metrics of different channel estimation and equalization methods, the advantages and disadvantages of each method are analyzed and the most suitable scheme is finally selected.

5. CONCLUSION AND OUTLOOK

5.1. Conclusion

In this study, a channel estimation and channel equalization design scheme for massive MIMO-OFDM systems has been proposed, which can effectively improve the performance of the system by combining the guide-frequency estimation and adaptive equalization methods. Specifically, this scheme is:

(1) Reduce the channel estimation error and improve the accuracy of channel state information.

(2) Suppress multipath interference and improve the transmission quality of the system through adaptive equalization technique.

(3) Demonstrate better BER and throughput performance under different SNR environments.

5.2. Outlook

The application of this research in massive MIMO-OFDM systems is of great practical significance, especially in 5G and future 6G networks, which can effectively improve the spectral efficiency and network capacity of wireless communications. Channel estimation and equalization techniques are not only crucial in high-speed data transmission, but also valuable for reducing interference, improving user experience, and enhancing fading resistance.

Future research can further optimize the channel estimation and equalization algorithm and explore the adaptive algorithm based on machine learning, which can further enhance the performance of massive MIMO-OFDM systems in high-speed, low-delay, and high-capacity communication environments, and satisfy the demand for efficient communication in future networks.

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