Channel Estimation in Massive MIMO TDD Systems

Zhuyun Fan, Chaoyue Zhao, Jiyu Jin(✉), Guiyue Jin, and Lihui Wang

School of Information Science and Engineering, Dalian Polytechnic University, Dalian, China
jiyu.jin@dlpu.edu.cn

Abstract. Massive multiple-input multiple-output (MIMO) significantly improves the spectral efficiency and energy efficiency of the systems. In this paper, a channel estimation based on pilot method is proposed for multi-cell massive MIMO time division duplex (TDD) systems. The proposed estimator designs an orthogonal pilot structure to mitigate pilot contamination. Additionally, the receiver estimates the channel state information (CSI) at the pilot tone, and combines the interpolation algorithm to obtain the desired signal. The proposed method increases the accuracy of channel estimation with the lower computational complexity. Simulations results verify the effectiveness of the proposed method.

Keywords: Massive MIMO system · Channel estimation · Pilot contamination

1 Introduction

As one of the key technologies of the fifth generation (5G) wireless networks, massive multiple-input multiple-output (MIMO) system has been extensively studied. Massive MIMO significantly improves energy efficiency and spectral efficiency by configuring a large number of antenna arrays on the base station (BS) and spatial multiplexing technology [1]. However, the pilot of target cell will be interfered by other cells while non-orthogonal pilot is used for channel estimation, which is a primary bottleneck restricting the development of massive MIMO called pilot contamination [2, 3].

Compared with frequency division duplex (FDD) mode, the important distinguish of time division duplex (TDD) is channel reciprocity [1, 4], the channel state information (CSI) in the uplink can be reused in the downlink, which greatly reduces the time-domain resource overhead and brings higher energy efficiency. The cyclic shift of Zadoff-Chu (ZC) sequence is used to maintain the orthogonality of intra-cell, but the same pilot sequences are used in inter-cell, which causes serious pilot contamination [5]. Based on the multi-cell massive MIMO system, a pilot design criterion aiming at minimizing pilot contamination is deduced [6]. A semi-orthogonal pilot design method is proposed, the authors make the best of the asymptotic orthogonality of the channel to mitigate the interference by successive interference cancellation. But it requires slow time-varying characteristics of channel [7]. In a countless number of works, large-scale

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fading coefficients are assumed to be known at the BS [8, 9]. Moreover, the desired signal can be obtain by zero forcing (ZF) or minimum mean square error (MMSE).

In this paper, a pilot-based channel estimation method is proposed in multi-cell massive MIMO TDD system. Considering pilot contamination, an orthogonal pilot structure is designed by using ZC sequence whatever inter-cell or intra-cell. Additionally, the receiver estimates the CSI at the pilot tone, and combines the interpolation algorithm to obtain the desired signal. As a result, simulations show the better performance of the proposed method.

2 System Model

2.1 Multi-cell Massive MIMO System Model

A multiuser multi-cell massive MIMO TDD system is shown in Fig. 1. The system consists of L hexagonal cells, which share the same time/frequency resource. In each cell, one BS with M antennas in the center serves K single-antenna users simultaneously. The users are distributed randomly, it is required that receiving antennas M are much larger than the number of users K.

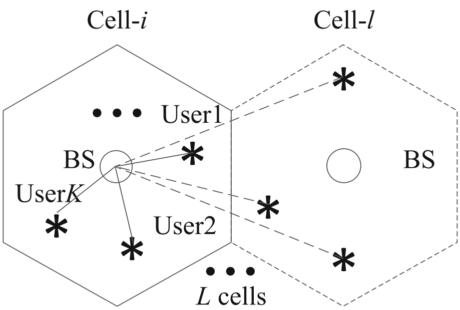

Fig. 1. Multi-cell system model.

We assume wireless channel is composed of large-scale fading and small-scale fading. The large-scale fading represents path loss and shadow fading, while the small-scale fading refers to the changes of amplitude and phase in small regions [10]. The channel response from the kth user in the ith cell to the mth antenna of the BS in the lth cell is

$$g_{ilkm} = h_{ilkm} \beta_{ilk}^{1/2}, \tag{1}$$

Where β_{ilk} is the large-scale fading coefficient and assumed constant since the path loss and shadow fading change slowly [10–12], h_{ilkm} is the small-scale fading coefficient, it is assumed to be independent and identically distributed (i.i.d), which follows a circularly symmetric complex normal distribution. The channel matrix from ith cell to the BS in lth cell is

$$\mathbf{G}_{il} = \mathbf{H}_{il}\mathbf{D}_{il} \in \mathbb{C}^{M\times K}, \tag{2}$$

Where $\mathbf{H}_{il} \in \mathbb{C}^{M\times K}$ and $[\mathbf{H}_{il}]_{m,k} = h_{ilkm}, \mathbf{D}_{il} \in \mathbb{C}^{K\times K}$ is a diagonal matrix and $[\mathbf{D}_{il}]_{k,k} = \beta_{ilk}^{1/2}$.

2.2 Uplink Frame Structure

Suppose the channel is quasi-static within the coherent time, and the inter-cell frequency reuse factor is one. The pilot sequence utilizes ZC sequence because of its constant envelope, ideal periodic autocorrelation and good cross correlation [13]. On the other hand, it still has the properties mentioned after Fourier transforms. The conventional frame structure in one coherent time can be shown in Fig. 2. By adding cyclic prefix (CP) which is intercepted from the tail of data, the cyclic convolution characteristic of signal and channel can be formed. The length of the CP is larger than the maximum multipath delay P.

CP1	Pilot	Data1	CP2	Pilot	Data2	• • •

Fig. 2. The conventional frame structure.

ZC sequences are used for pilot due to their properties, the kth user's pilot can be represented by $\mathbf{s}_k = [s_k(0), s_k(1)\ldots s_k(N-1)]^T$, where $(\bullet)^T$ is the transpose, N is the length of pilot and $N > KP$. The cyclic convolution matrix as show

$$\mathbf{S}_k = \begin{bmatrix} s_k(0) & s_k(N-1) & \cdots & s_k(N-P+1) \\ s_k(1) & s_k(0) & \cdots & s_k(N-P+2) \\ \vdots & \vdots & \ddots & \\ s_k(N-1) & s_k(N-2) & \cdots & s_k(N-P+N) \end{bmatrix}, \tag{3}$$

$\mathbf{S}_k$ is a $N \times P$ cyclic shift version of $\mathbf{s}_k$ with property $\mathbf{S}_k^H\mathbf{S}_k = N\mathbf{I}_P$.

3 The Proposed Pilot Design and Channel Estimation

In order to mitigate the pilot contamination and obtain more accurate CSI, a pilot design method in frequency domain is proposed, which makes the pilot inter-cell or intra-cell be orthogonal. This paper selects ZC sequence of L-size that makes the pilot signals non-interfere among cells. After Fourier transform, the pilot signals of different users in the same cell are placed on orthogonal carriers, there is localized or distributed [14, 15].

As shown in Fig. 3, there are P carriers for each user. The pilot of 1st user is $\mathbf{a}_1 = [s_1, s_2 \ldots s_P]^T$. Fast Fourier Transform (FFT) of P points is applied to $\mathbf{a}_1$, and then mapped to $K \times P$ carriers in frequency domain. The figure shows distributed method, and remain carriers are empty. Then the frequency domain signal is converted into time domain by inverse FFT (IFFT).

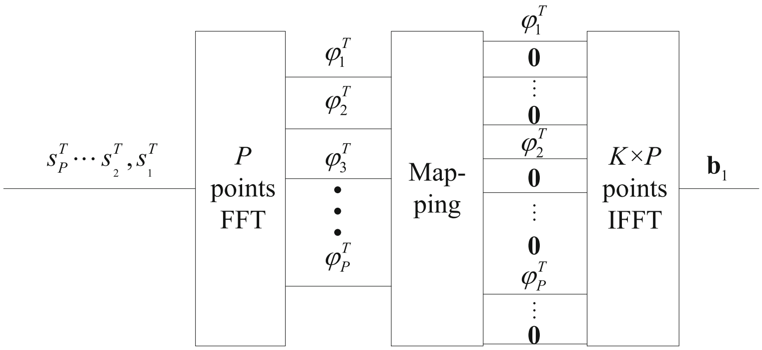

Fig. 3. Pilot design diagram.

The frame structure as shown in Fig. 4, unlike Sect. 2.2, the CP is tail of pilot that both pilot and data can form a circular matrix. The channel estimation algorithm is designed by using the properties of cyclic convolution and Fourier transform, this

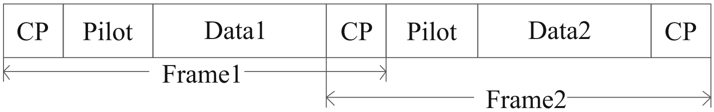

Fig. 4. Proposed frame structure.

reduces computational complexity.

The received pilot signal can be expressed as

$$r_{i-pilot} = \sqrt{q_{pilot}} \sum_{l=1}^{L} \mathbf{G}_{il} \mathbf{A} + \mathbf{N}_i, \tag{4}$$

where $(\cdot)^H$ is the conjugate transpose. $\mathbf{A} = [\mathbf{A}_1, \mathbf{A}_2, \ldots \mathbf{A}_K]$ is the cyclic matrix of $\mathbf{a}$, $r_{i-pilot}$ is a $M \times N$ matrix. $q_{i-pilot}$ is the transmit signal to noise ratio (Tx-SNR), $\mathbf{N}_i$ is a $M \times N$ additive white Gaussian noise matrix. $\mathbf{W}_1$ is the FFT transformation matrix, and $\mathbf{W}_1^H$ is the IFFT transformation matrix. The received pilot signal in frequency domain is

$$R_{i-pilot} = \mathbf{W}_1 r_{i-pilot}. \tag{5}$$

According to the Fig. 5, the received signal in frequency domain of kth user is obtained by

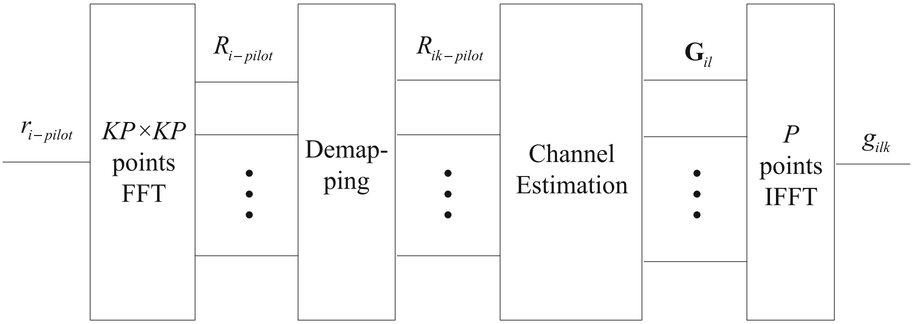

Fig. 5. Block diagram of channel estimation.

$$R_{ik-pilot} = \mathbf{V}R_{i-pilot} = \mathbf{V}\mathbf{W}_1 r_{i-pilot}, \tag{6}$$

where $\mathbf{V}$ is the demapping matrix. The channel coefficient of pilot tone is

$$\mathbf{G}_{il} = diag\left(R_{ik-pilot}\mathrm{F}_k\right), \tag{7}$$

diag(•) is the diagonal matrix, $\mathbf{F}_k$ is the pilot signal of kth user in frequency domain. The time domain impulse response of the channel is obtained by

$$g_{ilk} = \left(\mathbf{W}_2^k\right)^H \mathbf{G}_{il}, \tag{8}$$

Where $\mathbf{W}_2$is intercepted from $\mathbf{W}_1$.

$$\mathbf{W}_2^k = \begin{bmatrix} \mathbf{W}_1^{1,k} & \cdots & \mathbf{W}_1^{1,k+(K-1)P} \\ \vdots & \ddots & \vdots \\ \mathbf{W}_1^{K,k} & \cdots & \mathbf{W}_1^{K,k+(K-1)P} \end{bmatrix} \tag{9}$$

The channel estimator is shown in Fig. 5.

After channel estimation of pilot tone, the CSI is estimated by DFT interpolation algorithm. It padding zeros on the time domain of g_{ilk} so that keeping consistent with the length of the data. Finally, the desired signal can be equalized in the frequency domain. The simulation results show this method can accurately obtain the time domain impulse response of the channel when the noise is ignored. The algorithm is more accurate and flexible, it utilizes the characteristics of cyclic convolution and fourier transform to design pilot.

4 Numerical Result

The parameters involved in the simulations as Table 1. Consider the frequency reuse factor is one, the large-scale coefficient is assumed constant, $\beta_{ilk} = 1$ and $\beta_{ilk} = 0.05$, $\forall l \neq i$.

Table 1. Simulation parameter.

Parameter	Description	Value
L	The number of cells	7
K	The number of users per cell	10
P	The number of paths per channel	20
M	The number of antenna per BS	30
β	The large-scale coefficient	0.05

Figure 6 depicts the mean square error (MSE) performance comparison between the proposed method in this paper and method in [5]. It can be seen the channel estimation MSE versus the signal to noise ratio at the transmitter (Tx-SNR), and the MSE of all channel estimators decreases with the increase of Tx-SNR. The MSE of proposed method is much better than [5] due to less pilot contamination. However, the system overhead will be raise by the increase of pilot length.

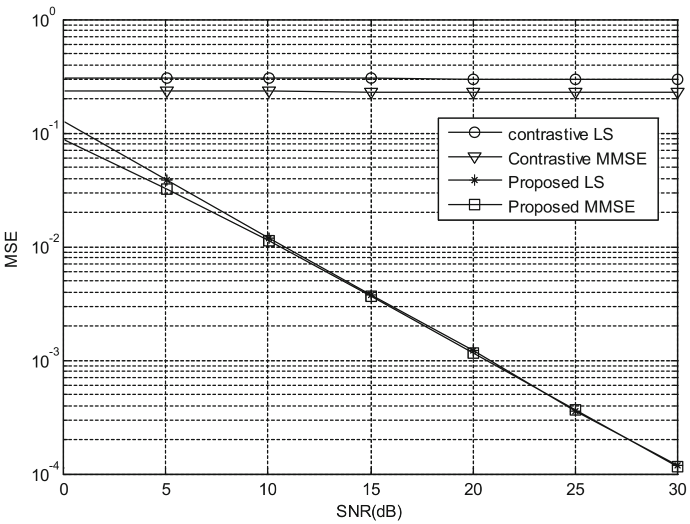

Fig. 6. The MSE of comparison for two methods.

Figure 7 shows the bit error rate (BER) performance of the proposed method. It can be noticed that the better BER performance with the increase of the number of receiving antenna M. This is because the diversity gain of the receiver increases and the better resistant to noise in this case. ZF is considered here. The BER performance in [5] is poor because of pilot contamination.

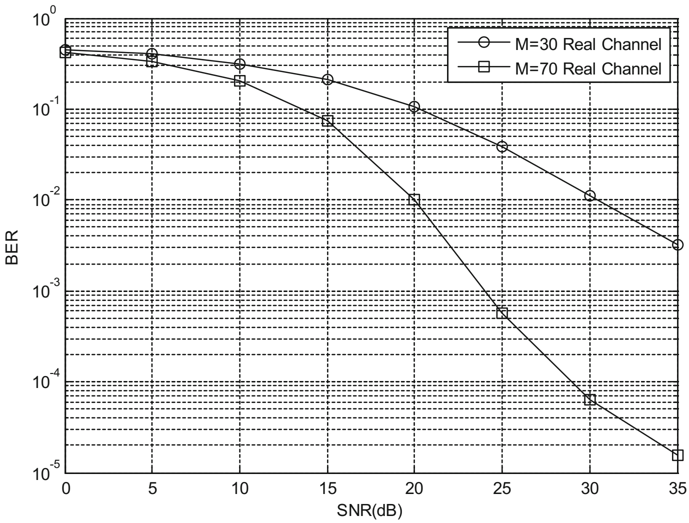

Fig. 7. The BER of proposed method.

5 Conclusion

In this paper, a pilot-based channel estimation method is proposed which takes into account pilot contamination, and guarantees the orthogonality of pilot inter-cell and intra-cells by using the characteristics of ZC sequence. At the same time, the properties of cyclic convolution and Fourier transform are utilized. At the receiver, the CSI at the pilot position is obtained firstly, and then deduce the whole channel information by using DFT interpolation algorithm. The simulation results show that the proposed method has better performance in channel estimation.

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