Iterative Multi-cell Channel Estimation for Inter-cell Interference Suppression

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Abstract

In cellular networks, when multiple base stations (BSs) of adjoining cells use the same frequency band for transmitting their signals, inter-cell interference (ICI) occurs at user equipment (UE). To suppress ICI, UE needs to know the channel state information (CSI) between each of its surrounding BSs and itself. Therefore, multi-cell channel estimation is required. However, ICI also degrades the channel estimation performance. In this paper, we propose an iterative multi-cell minimum mean square error (MMSE) channel estimation scheme. To employ the MMSE principle, UE must know the covariance matrix of its estimating channels before conducting estimation. To cope with this contradiction, our proposed scheme estimates and updates the covariance matrix as well as the channels themselves through iterative processing. From computer simulation, we can show that the proposed scheme estimates the covariance matrix effectively, and achieves a higher channel estimation performance than the multi-cell least square (LS) channel estimation scheme.

1. Introduction

In cellular systems, inter-cell interference (ICI) degrades the data throughput of user equipment (UE) [1]. To mitigate the effect of ICI, the minimum mean square error (MMSE) receiver is proposed to be used in the Long Term Evolution (LTE) downlink network [2]. By regarding interference signals as noise, the MMSE receiver prevents the throughput degradation if the power of ICI signals is smaller than that of noise. However, when UE is around the cell edge, the power of ICI signals becomes larger and the throughput is degraded. This is more noticeable when base stations (BSs) of adjoining cells use the same frequency band for transmitting their signals. Therefore, in the current LTE-Advanced (LTE-A) downlink network, the use of the interference rejection combining (IRC) receiver is considered [1]-[3].

The IRC receiver can suppress ICI on condition that the receiver knows the channel state information (CSI) between each of its surrounding BSs and itself [3]. Therefore, UE must perform multi-cell channel estimation. To realize multi-cell channel estimation, the pilot signals which are transmitted from BSs of adjoining cells must be orthogonal to each other. However, the orthogonality of the pilot signals is usually spoiled due to multipath channels as well as the limitation of the number of orthogonal signal subspaces. That is, multi-cell channel estimation is also affected by ICI. This prevents the IRC receiver from providing its full performance. Therefore, the ICI suppression is required in multi-cell channel estimation.

For multi-cell channel estimation, least square (LS) estimation and MMSE estimation schemes which estimate multiple channels simultaneously are proposed [4]. As it is indicated in the estimation theory, the multi-cell MMSE channel estimation provides a better estimation performance than the multi-cell LS estimation [4]. However, to use the MMSE channel estimation in practice, it is necessary to cope with a contradictory problem. That is, UE must know the covariance matrix of its estimating channels beforehand. In [4], [5], it is assumed that the receiver knows the perfect covariance matrix of the channels. However, this assumption is not realistic.

In this paper, we propose an iterative multi-cell MMSE channel estimation scheme. To cope with the contradictory problem, our proposed scheme calculates the covariance matrix of a channel by the use of an adaptive algorithm is proposed [6]. In [6], the initial value of the covariance matrix is set to the identity matrix with the same size, and the covariance matrix is updated through iterative processing. Each time UE estimates the channel through iterative processing, the covariance matrix is calculated using the estimated CSI, and updated with the use of the forgetting factor. However, since this scheme does not take ICI into account, it cannot directly be used in the environment where ICI occurs.

In this paper, we propose an iterative multi-cell MMSE channel estimation scheme. To cope with the contradictory problem, our proposed scheme calculates the covariance matrix from the MMSE-estimated CSI, and updates it without using the adaptive algorithm. That is, the covariance matrix is updated by simply being replaced with the estimated new one at each iterative processing. After the estimation of the covariance matrix, our scheme estimates multiple channels using the cancellation principle. From computer simulation, we
show that the cumulative distribution function (CDF) of the normalized mean square error (NMSE) of the proposed channel estimation scheme provides a better property than that of the multi-cell LS channel estimation scheme.

2. System Model

In this paper, we consider a downlink cellular network in which each cell site consists of three sectors. Figure 1 illustrates the layout of cell sites. We consider seven cell sites, each of which is divided into three sectors by the horizontal radiation patterns of antennas. Without loss of generality, we can consider the channel estimation of only one UE which is located within Sector-1 and is displayed as UE-1 in Fig. 1. Therefore, the signal transmitted from BS-1 is the desired signal and those from other BSs become interference signals to UE-1. We assume the system uses multiple-input multiple-output orthogonal frequency division multiplexing (MIMO-OFDM). We also assume BSs and UE-1 are equipped with \(N_t\) transmit antennas and \(N_r\) receive antennas, respectively.

Each of \(M=7\) BSs generates its own pilot OFDM signal that occupies \(N\) subcarriers in the same frequency band. We assume that all the BSs transmit their pilot signals synchronously, but the pilot signals are unorthogonal to each other. Thus,ICI occurs at UE-1. The channel impulse response (CIR) vector between all the BSs and UE-1 is expressed as

\[
h_{n_r,n_t} = \begin{bmatrix} h_{1,n_r,n_t} & \cdots & h_{m,n_r,n_t} & \cdots & h_{M,n_r,n_t} \end{bmatrix}^T
\]

(1)

where \(\cdot^T\) stands for the transpose. In Eq. (1), \(h_{m,n_r,n_t} = [h_{m,n_r,n_t,1} \cdots h_{m,n_r,n_t,1} \cdots h_{m,n_r,n_t,L}]^T\) represents the CIR vector between the \(n_t\)th transmit antenna \((n_t = 1, \ldots, N_t)\) of the \(m\)th BS \((m = 1, \ldots, M)\) and the \(n_r\)th receive antenna \((n_r = 1, \ldots, N_r)\) of UE-1. \(h_{m,n_r,n_t,l} = \alpha_m g_{m,n_r,n_t,l}\) represents the CIR of the \(l\)th path \((l = 1, \ldots, L)\). Furthermore, \(\alpha_m\) and \(g_{m,n_r,n_t,l}\) represent the large scale fading coefficient and the small scale fading coefficient, respectively.

The received pilot signal is a superposition of pilot signals transmitted from \(M\) different BSs. At the \(n_t\)th receive antenna of UE-1, the time domain received pilot signal is expressed as

\[
r_{n_r} = X_{1,n_r} h_{1,n_r,n_t} + \cdots + X_{M,n_r} h_{M,n_r,n_t} + n
\]

(2)

where \(X_{m,n_t} = [x_{m,n_t,1} \cdots x_{m,n_t,1} \cdots x_{m,n_t,L}]\) is the matrix composed of the pilot signal sample column vector \(x_{m,n_t,1}\) and its cyclic shifted versions. \(x_{m,n_t,l}\) is the \(l\)-sample cyclic shifted column vector which corresponds to the pilot signal transmitted through the \(l\)th path of the channel. Furthermore, \(X_{n_r} = [X_{1,n_t} \cdots X_{M,n_t}]\) represents the matrix of all the pilot signals transmitted from all the BSs. \(n\) is the zero-mean complex Gaussian noise column vector.

3. Multi-cell Channel Estimation [4]

In this section, the multi-cell LS channel estimation and the multi-cell MMSE channel estimation are described. The LS-estimated CIR is expressed in the vector form as

\[
\hat{h}_{n_r,n_t}^{\text{LS}} = (X_{n_t}^T X_{n_t})^{-1} X_{n_t}^T r_{n_r}
\]

(3)

where \((\cdot)^T\) stands for the complex conjugate transpose. Furthermore, when UE knows the covariance matrix of the estimating channels beforehand, the multi-cell MMSE estimation can be used. The MMSE-estimated CIR is expressed as

\[
\hat{h}_{n_r,n_t}^{\text{MMSE}} = X_{n_t}^T X_{n_t} + \sigma^2 R_{r_{n_r},n_t}^{-1} X_{n_t}^T r_{n_r}
\]

(4)

where \(\sigma^2\) is the power of noise. In Eq. (4), \(R_{r_{n_r},n_t} = \text{diag} (\alpha_1^2 R_{1,n_t,n_t} \cdots \alpha_M^2 R_{M,n_t,n_t})\) is the covariance matrix of the channel, and \(R_{m,n_r,n_t} = h_{m,n_r,n_t} h_{m,n_r,n_t}^H\). Since the MMSE estimation exploits the properties of channels, the multi-cell MMSE channel estimation provides a better performance than the multi-cell LS channel estimation. However, to use the principle of the MMSE estimation, UE must know the covariance matrix of the estimating channels. This is a contradictory problem.

4. Iterative MMSE Channel Estimation [6]

As a possible solution to the contradictory problem, the use of a substitute covariance matrix can be considered. In [6], the identity matrix is used as a substitute for the covariance matrix. Moreover, to improve the estimation performance, the MMSE estimation is performed several times against the same received pilot signal and the covariance matrix is updated each time the MMSE-estimated CIR is obtained. The covariance matrix is updated using the following equation.

\[
\hat{R}_{n_r,n_t}^{(i)} = \lambda \hat{R}_{n_r,n_t}^{(i-1)} + (1 - \lambda) \hat{h}_{n_r,n_t}^H \hat{h}_{n_r,n_t}
\]

(5)
where \( i \) and \( \lambda \) stand for the number of iterations and the forgetting factor, respectively. By introducing the iterative processing, the accuracy of the covariance matrix is improved, and thus the estimation performance is improved. However, this scheme does not take the effect of ICI into account. Therefore, we propose another MMSE channel estimation scheme.

5. Proposed Iterative Multi-cell MMSE Channel Estimation

In this section, we explain our proposed iterative multi-cell MMSE channel estimation scheme. The processing of the proposed channel estimation is divided into two stages. First is the covariance matrix estimation stage, and the second is the CIR estimation stage. The proposed scheme is summarized in Fig. 2. In the first stage, UE-1 estimates the covariance matrix obtained in the previous iteration. After iterating this processing several times, UE-1 moves on to the second stage.

In the second stage, CIR of each channel is estimated using the covariance matrix calculated using the MMSE-estimated CIR obtained in the previous iteration. Here, we have another choice that we make UE-1 estimate the interfering channels in turn by the use of the cancellation principle. However, for the reduction of the computational complexity, UE-1 estimates all the interfering channels at a time. Since the power of the pilot signal from BS-1 is generally larger than each power of the interfering pilot signals, the amount of degradation in the estimation accuracy should be small.

6. Simulation Results

In this section, we evaluate the performance of the proposed scheme by computer simulation. Table 1 shows the simulation parameters. In cellular networks, the signal-to-noise-plus-interference power ratio (SINR) of UE-1 varies according to its position. Therefore, we evaluate the cumulative distribution function (CDF) of the normalized mean square error (NMSE) of the proposed scheme. In our simulation, two thousand positions which are uniformly distributed within the central cell site of Fig. 1 were selected for positions of UE-1. At each position, fifty trials of the channel estimation were conducted.

First, we compare the CDF of the NMSE of the proposed scheme with that of the multi-cell LS channel estimation scheme in Fig. 3. In Fig. 3, the horizontal axis is the NMSE of channel estimation, and the vertical axis is the CDF. The solid lines represent the CDFs of the proposed scheme with different numbers of iterations, and the dashed line represents the CDF of the multi-cell LS channel estimation scheme. From Fig. 3, we find that more than fifty percent trials of the proposed scheme resulted in NMSEs of less than \( 7.5 \times 10^{-2} \) at the BSs of the neighboring cells. Finally, UE-1 estimates all the remaining channels simultaneously using the covariance matrix which was also obtained in the first stage.

| Table 1: Simulation parameters |
|--------------------------------|
| Parameter                      | Value                     |
| Carrier frequency              | 2 [GHz]                  |
| System bandwidth               | 5 [MHz]                  |
| Number of subcarriers          | 64                       |
| Number of FFT points           | 64                       |
| Number of BSs                  | 7                        |
| Number of antennas of BS       | 1                        |
| Number of antennas of UE       | 2                        |
| Modulation scheme              | QPSK                      |
| Channel model                  | 6-path Rayleigh fading with 1-dB decaying per sampling period |
| Normalized Doppler frequency   | \( 8.88 \times 10^{-5} \) |
| Inter-BS distance              | 500 [m]                  |
| Distance dependent path loss   | \( 128.1 \times 37.6 \log_{10}(d) \) [dB], \( d \) [km] |
| Transmission power             | 43 [dBm]                 |
| Noise power                    | \(-174\) [dBm]           |
| Radiation pattern of transmit antennas [7] | \( A(\theta) = \min \left( 12 \left( \frac{\theta}{\theta_{3dB}} \right)^2, A_{m} \right) \), \( \theta_{3dB} = 70 \) degrees, \( A_{m} = 20 \) [dB] |

First, UE-1 generates the replica of the received pilot signal from BS-1. The replica signal is subtracted from the entire received pilot signal. As a result, UE-1 obtains the interfering pilot signals \( r_{\text{interference}} \) which are transmitted from
the third iteration, whereas those of the multi-cell LS channel estimation scheme resulted in NMSEs of less than $9.8 \times 10^{-2}$. In the proposed scheme, the estimation accuracy is improved along with the increase in the number of iterations. However, since the CDFs at the second and the third iterations provide almost the same result, two iterations are sufficient for the proposed scheme.

Next, to estimate the impact of the number of iterations on the covariance matrix estimation, we evaluate the CDF of the NMSE of the covariance matrix estimation using different numbers of iterations. In Fig. 4, the horizontal axis is the NMSE of the covariance matrix estimation, and the vertical axis is the CDF. The solid and the dashed lines represent the CDFs of the NMSE of the covariance matrix estimation with three iterations and without iteration, respectively. From Fig. 4, we find that more than fifty percent trials of the proposed scheme with three iterations resulted in NMSEs of less than $1.7 \times 10^{-5}$, whereas those of the proposed scheme without iteration resulted in NMSEs of less than $2.0 \times 10^{-5}$. Therefore, the amount of improvement due to the iterative processing in the accuracy of the covariance matrix estimation is small. However, even a small amount of improvement in the accuracy of the covariance matrix greatly affects the channel estimation performance. Thus, the improvement of the covariance matrix estimation is important for the multi-cell MMSE channel estimation.

7. Conclusion

In this paper, we proposed an iterative multi-cell MMSE channel estimation scheme for ICI suppression in cellular systems. To cope with the contradiction of the MMSE estimation, the proposed scheme estimates the covariance matrix first by the use of iterative processing. After that, the proposed scheme estimates channels between UE and each of multiple BSs using the cancellation principle. From computer simulation, we can show that the proposed channel estimation achieves a better estimation performance than the multi-cell LS channel estimation scheme. Therefore, the proposed scheme is useful for multi-cell channel estimation.

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