Preamble-Assisted Channel Estimation in OFDM-based Wireless Systems

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Abstract — **Accurate channel state information (CSI) is indispensable for the use of channel-adaptive transmission techniques, but it may not easily be achievable near the cell boundary in cellular environments. This paper considers the improvement of CSI estimation accuracy in OFDM-based wireless packet transmission systems by exploiting the preamble signal as well as the pilot signal. The CSIs respectively estimated from the received preamble and pilot signal are combined according to the channel correlation between the preamble and the pilot signaling. The combining weight is analytically determined to minimize the mean squared error. When multiple antennas are employed for interference cancellation, the CSI of interference channels can also be estimated in a similar manner. The proposed scheme is applied to the mobile-WiMAX system to verify the effectiveness. Simulation results show that the proposed scheme is quite effective near the cell boundary.**

I. INTRODUCTION

In recent years, orthogonal frequency division multiplexing (OFDM) has been recognized as one of key transmission techniques for next generation wireless communication systems [1]. It can provide high spectral efficiency and mitigate inter-symbol interference in frequency selective fading environments. Accurate channel state information (CSI) is indispensable for the employment of adaptive transmission techniques, but it may not be easily achievable near the cell boundary in multi-cell environments [2]. As a consequence, the performance of OFDM transceiver may significantly deteriorate near the cell boundary.

In practice, the CSI can be estimated from pilot signal using a conventional estimation technique such as the least square (LS) method [3]. Since the LS estimation yields a mean-squared error (MSE) inversely proportional to the signal-to-interference plus noise ratio (SINR), it may not work properly near the cell-boundary due to serious interference effect. An iterative interference canceller in the time domain has recently been proposed [4]. However, it can be applied only to a block type arrangement of pilot signals, where all subcarriers are reserved for pilot signaling at a specific period.

Packet-based wireless transmission systems (e.g., mobile-WiMAX) employ a preamble signal for the purpose of synchronization, which is often orthogonal to preamble signals transmitted from other cells [5]. As a consequence, the preamble signal is less interfered than the pilot signal which is common to all cells. The nature of wireless channel causes the transmission of preamble and pilot signal to experience correlation in the time and frequency domain. The accuracy of the CSI estimation can be improved by exploiting the channel correlation between the preamble and pilot signal. The CSI estimated from the received pilot signal can be improved with the aid of the CSI estimated from the received preamble signal. The two CSI can be combined to minimized the MSE. When the receiver has multiple receive antennas, it can cancel out other cell interference (OCI) by employing adaptive antenna techniques such as the minimum MSE (MMSE) nulling scheme which requires the CSI of interfering channels as well as the target CSI [6]. The proposed scheme can also be applied to the estimation of interfering CSI.

The rest of the paper is organized as follows. Section II introduces the downlink model of an OFDM-based wireless system in consideration. Section III describes the proposed estimation scheme, where the target and interfering CSIs are estimated by combing the CSI estimated from the received preamble and pilot signal. Section IV verifies the performance by computer simulation when the proposed scheme is applied to the mobile-WiMAX system. Finally, conclusions are given in Section V.

II. SYSTEM MODEL

Consider a multi-cell multi-sector structure as illustrated in Fig. 1, where the TBS denotes the target base station (BS) serving the target mobile station (MS) and the IBS denotes a BS causing interference to the MS. Define the target channel and the i -th interference channel by the channel between the TBS and the MS, and the i -th IBS

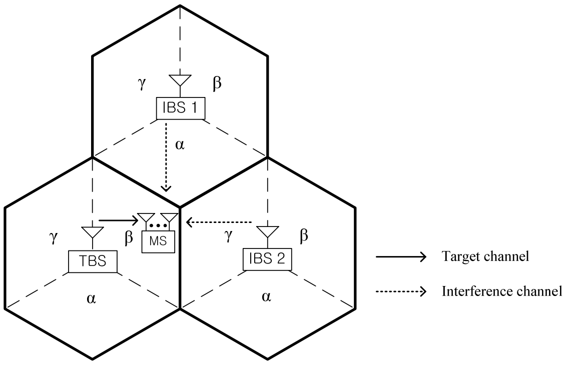

Fig. 1. Multi-cell multi-sector structure.

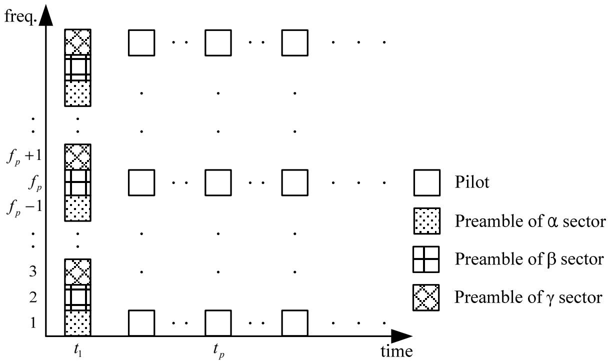

Fig. 2. Preamble and pilot signal structure.

and the MS, respectively. Assume that each cell is divided into three sectors (say, α, β and γ sector), and the BS has a single transmit antenna and the MS has N receive antennas, and that the target MS is located in the β sector of the TBS. Assume also that the BS transmits preamble and pilot signals for the purpose of synchronization and channel estimation, respectively, as illustrated in Fig. 2, where all the sectors transmit the same pilot signal at the same time through the same frequency band, but they transmit preamble signals at the same time through different frequency bands.

Consider the transmission of pilot signal allocated to the t_p-th OFDM symbol and the f_p-th subcarrier. Assuming that the major interference comes from at most two adjacent sectors, the received pilot signal through the n-th antenna can be represented as

$$\begin{aligned} Y(t_p,f_p,n) &= H_t(t_p,f_p,n)P_t(t_p,f_p,n) \\ &\quad + \sum_{i=1}^{2} H_i(t_p,f_p,n)P_i(t_p,f_p,n) \\ &\quad + W(t_p,f_p,n) \end{aligned} \qquad (1)$$

where $H_t(t_p,f_p,n)$ and $P_t(t_p,f_p,n)$ are respectively the frequency response of the target channel and pilot signal transmitted from the TBS, $H_i(t_p,f_p,n)$ and $P_i(t_p,f_p,n)$ are respectively the frequency response of the i-th interference channel and the pilot signal transmitted from the i-th IBS, and $W(t_p,f_p,n)$ is the frequency response of the background noise and other minor interfering signals. The additive noise term can be modeled as a complex zero-mean Gaussian random variable with variance σ_W^2. It can be assumed that the pilot signal is transmitted with the same average transmit power, i.e., $E\left\{\left|P_t(t_p,f_p,n)\right|^2\right\} = E\left\{\left|P_i(t_p,f_p,n)\right|^2\right\} = \sigma_P^2$. For simplicity of description, the receive antenna index n will be omitted since the estimation procedure for each receive antenna is identical.

Consider preambles near the pilot signal $Y(t_p,f_p)$ in the frequency domain (e.g., the preambles at the (f_p-1)-th, f_p-th and (f_p+1)-th subcarriers). For ease of description, assume that the preamble at the (f_p-1)-th, f_p-th and (f_p+1)-th subcarriers is transmitted from sector α, β and γ, respectively. Then, the received preamble transmitted from the TBS and the i-th IBS can be represented respectively as

$$Y(t_1,f_p) = H_t(t_1,f_p)S_t(t_1,f_p) + W(t_1,f_p) \qquad (2)$$

and

$$\begin{aligned} Y(t_1,f_p+(-1)^i) &= H_i(t_1,f_p+(-1)^i)S_i(t_1,f_p+(-1)^i) \\ &\quad + W(t_1,f_p+(-1)^i) \end{aligned} \qquad (3)$$

where $S_t(t_1,f_p)$ and $S_i(t_1,f_p+(-1)^i)$ denote the preamble transmitted from the TBS and the i-th IBS, respectively. It can also be assumed that the the preamble signal is transmitted with the same average transmit power, i.e., $E\left\{\left|S_t(t_1,f_p)\right|^2\right\} = E\left\{\left|S_i(t_1,f_p+(-1)^i)\right|^2\right\} = \sigma_S^2$.

Let ρ_t be the correlation coefficient between the channel of the pilot signal and the preamble transmitted from the TBS, defined by

$$\rho_t \triangleq E\left\{ \frac{H_t(t_p,f_p)\left(H_t(t_1,f_p)\right)^*}{\left|H_t(t_p,f_p)\right|^2} \right\} \qquad (4)$$

where $E\{\,\cdot\,\}$ denotes the expectation and the superscript * denotes complex conjugate. Similarly, let ρ_i be the correlation coefficient between the channel of the pilot signal and the preamble transmitted from the i-th IBS, defined by

$$\rho_i \triangleq E\left\{ \frac{H_i(t_p,f_p)\left(H_i(t_1,f_p+(-1)^i)\right)^*}{\left|H_i(t_p,f_p)\right|^2} \right\}. \qquad (5)$$

III. CONVENTILANL CHANNEL ESTIMATION

The target and the i -th interference channel can be estimated from the received pilot signal using a conventional LS estimation method as [3]

$$\begin{aligned}\hat{H}_t(t_p,f_p) &= \frac{Y(t_p,f_p)}{P_t(t_p,f_p)}\\ &= H_t(t_p,f_p)+\sum_{i=1}^{2}H_i(t_p,f_p)\frac{P_i(t_p,f_p)}{P_t(t_p,f_p)} \qquad (6)\\ &+\frac{W(t_p,f_p)}{P_t(t_p,f_p)}\end{aligned}$$

and

$$\begin{aligned}\hat{H}_i(t_p,f_p) &= \frac{Y(t_p,f_p)}{P_i(t_p,f_p)}\\ &= H_i(t_p,f_p)+H_t(t_p,f_p)\frac{P_t(t_p,f_p)}{P_i(t_p,f_p)} \qquad (7)\\ &+\sum_{\substack{j=1\\ j\neq i}}^{2}H_j(t_p,f_p)\frac{P_j(t_p,f_p)}{P_i(t_p,f_p)}+\frac{W(t_p,f_p)}{P_i(t_p,f_p)}.\end{aligned}$$

It can be shown that the corresponding MSEs of the target CSI and interference CSI estimation are respectively

$$\varepsilon^2_{conv,t} \triangleq E\left\{|\,H_t(t_p,f_p)-\hat{H}_t(t_p,f_p)\,|^2\right\}=\sum_{i=1}^{2}\sigma_i^2+\frac{\sigma_W^2}{\sigma_P^2} \quad (8)$$

and

$$\begin{aligned}\varepsilon^2_{conv,i} &\triangleq E\left\{|\,H_i(t_p,f_p)-\hat{H}_i(t_p,f_p)\,|^2\right\}\\ &= \sigma_t^2+\sum_{\substack{j=1\\ j\neq i}}^{2}\sigma_j^2+\frac{\sigma_W^2}{\sigma_P^2}\end{aligned} \quad (9)$$

where σ_t^2 and σ_i^2 are the gain of the target and the i -th interference channel, respectively. It can be conjectured from (8) and (9) that the LS estimation may not provide good performance in the presence of large interference (e.g., near the cell-boundary). Furthermore, this estimation method does not exploit either the channel correlation between the OFDM symbols nor that between the subcarriers.

IV. PROPOSED CHANNEL ESTIMATION

We consider the improvement of the CSI estimation accuracy in the presence of interference by exploiting the channel correlation properties in the time and frequency domain. The target CSI is respectively estimated from the received preamble and pilot signal using a conventional LS method. Then, these two CSIs are combined for better CSI estimation, which is also used for the estimation of interference channel.

A. Preamble Channel Estimation

The CSI can be estimated from the preambles transmitted from the TBS and IBSs using the LS method as

$$\hat{H}_t(t_1,f_p)=\frac{Y(t_1,f_p)}{S_t(t_1,f_p)}=H_t(t_1,f_p)+\frac{W(t_1,f_p)}{S_t(t_1,f_p)} \quad (10)$$

$$\begin{aligned}\hat{H}_i(t_1,f_p+(-1)^i) &= \frac{Y(t_1,f_p+(-1)^i)}{S_i(t_1,f_p+(-1)^i)}\\ &= H_i(t_1,f_p+(-1)^i) \qquad (11)\\ &+\frac{W(t_1,f_p+(-1)^i)}{S_i(t_1,f_p+(-1)^i)}\end{aligned}$$

Unlike the CSI estimation from the pilot signal, this CSI estimation from the preamble signal is only affected by additive noise.

B. Target Channel Estimation

The target CSI can be estimated from (6) and (10) as

$$\tilde{H}_t(t_p,f_p)=\mathbf{H}_t\mathbf{W}_t \quad (12)$$

where $\mathbf{H}_t=\left[\hat{H}_t(t_p,f_p)\ \ \hat{H}_t(t_1,f_p)\right]$ and $\mathbf{W}_t$ is a weight vector for target CSI estimation. We analyze the weight vector $\mathbf{W}_t$ minimizing the MSE of estimation by applying Wiener equation [7]. Let $\mathbf{R}_t$ and $\mathbf{P}_t$ be the auto-covariance matrix and cross-covariance vector of the target channel respectively defined by

$$\mathbf{R}_t \triangleq E\left\{\mathbf{H}_t\mathbf{H}_t^*\right\}=\begin{bmatrix}\sigma_t^2+\frac{\sigma_W^2}{\sigma_P^2}+\sum_{i=1}^{2}\sigma_i^2 & \sigma_t^2\rho_t\\ \sigma_t^2\rho_t^* & \sigma_t^2+\frac{\sigma_W^2}{\sigma_S^2}\end{bmatrix} \quad (13)$$

$$\mathbf{P}_t \triangleq E\left\{\mathbf{H}_t\left(H_t(t_p,f_p)\right)^*\right\}=\begin{bmatrix}\sigma_t^2\\ \sigma_t^2\rho_t^*\end{bmatrix}. \quad (14)$$

The optimum weight vector $\mathbf{w}_t$ for the target CSI can be determined by

$$\mathbf{W}_t=\mathbf{R}_t^{-1}\mathbf{P}_t. \quad (15)$$

$$\mathbf{R}_i \triangleq E\left\{\mathbf{V}_i\mathbf{V}_i^*\right\} = \begin{bmatrix} \varepsilon_{prop,t}^2 + \left(1-2\,\mathrm{Re}\left\{\mathbf{W}_t(1)\right\}\right)\left(\dfrac{\sigma_W^2}{\sigma_P^2}+\sum_{i=1}^{2}\sigma_i^2\right) & \sigma_i^2\rho_i\left(1-\mathbf{W}_t(1)\right) \\ \sigma_i^2\rho_i^*\left(1-\mathbf{W}_t(1)\right)^* & \sigma_i^2+\dfrac{\sigma_W^2}{\sigma_S^2} \end{bmatrix} \tag{19}$$

The corresponding MSE of the target CSI estimation can be represented as [7]

$$\begin{aligned} \varepsilon_{prop,t}^2 &\triangleq E\left\{\left|H_t(t_p,f_p)-\tilde{H}_t(t_p,f_p)\right|^2\right\} \\ &= \sigma_t^2 - \mathbf{P}_t^H\mathbf{R}_t^{-1}\mathbf{P}_t \end{aligned} \tag{16}$$

where the superscript H denotes conjugate transpose.

C. Interference Channel Estimation

Since the signal from the target channel behaves as an additive noise in the estimation of interference CSI, the interference CSI can be estimated as

$$\hat{H}_i'(t_p,f_p) = \frac{Y(t_p,f_p)-\tilde{H}_t(t_p,f_p)P_t(t_p,f_p)}{P_i(t_p,f_p)}. \tag{17}$$

The interference channel can further be re-estimated as

$$\tilde{H}_i(t_p,f_p) = \mathbf{V}_i\mathbf{W}_i \tag{18}$$

where $\mathbf{V}_i = \left[\hat{H}_i'(t_p,f_p) \quad \hat{H}_i(t_p,f_p+(-1)^i)\right]$ and $\mathbf{W}_i$ is a weight vector for the i-th interfering CSI estimation. The auto-covariance matrix and cross-covariance vector of the i-th interference channel can respectively be represented as (19) and

$$\mathbf{P}_i \triangleq E\left\{\mathbf{V}_i\left(H_i(t_p,f_p)\right)^*\right\} = \begin{bmatrix} \sigma_i^2\left(1-\mathbf{W}_t(1)\right) \\ \sigma_i^2\rho_i^* \end{bmatrix} \tag{20}$$

where $\mathbf{W}_t(1)$ denotes the first element of $\mathbf{W}_t$. Similarly, the optimum weight vector $\mathbf{W}_i$ for the i-th interfering CSI is determined by

$$\mathbf{W}_i = \mathbf{R}_i^{-1}\mathbf{P}_i. \tag{21}$$

The corresponding MSE of the i-th interference CSI estimation is represented as

$$\begin{aligned} \varepsilon_{prop,i}^2 &\triangleq E\left\{\left|H_i(t_p,f_p)-\tilde{H}_i(t_p,f_p)\right|^2\right\} \\ &= \sigma_i^2 - \mathbf{P}_i^H\mathbf{R}_i^{-1}\mathbf{P}_i \end{aligned}. \tag{22}$$

V. PERFORMANCE EVALUATION

The performance of the proposed scheme is verified by computer simulation when applied to the mobile-WiMAX system, where the MS has two receive antennas to cancel out other cell interference through a MMSE nulling scheme [6]. The simulation parameters are summarized in Table I [5]. It is assumed that the gain of two interfering channels is the same (i.e., $\sigma_1^2 = \sigma_2^2$) and the symbol distance in the time domain between the preamble and pilot signaling is $d_t = t_p - t_1$.

Fig. 3 depicts the correlation between the preamble and pilot signal according to the user mobility and symbol distance in the time domain. It can be seen that the channel correlation between the preamble and pilot signaling decreases as the mobility increases and/or the symbol distance between the two signals increases.

Fig. 4 depicts the normalized MSE of the pilot CSI estimation scheme when the MS has a mobility of $30\,km/h$ and $d_t = 10$. It can be seen that the LS scheme accuracy is significantly affected by the SINR, but the proposed scheme is not. This is mainly due to the use of adaptive weight minimizing the MSE. It can also be seen that the proposed scheme noticeably outperforms the LS estimation scheme.

Fig. 5 depicts the MSE of the pilot CSI estimation normalized with respect to the channel gain according to the user mobility and the symbol distance in the time domain. It can be seen that the LS scheme provides performance almost independent of the user mobility since it does not exploit the channel correlation, but the proposed scheme is susceptible to the mobility because it exploits the channel correlation between the preamble and the pilot signaling, which is affected by the mobility and the symbol distance. Nevertheless, the proposed scheme outperforms the LS estimation by combining the two CSIs.

VI. CONCLUSION

In this paper, we have proposed a channel estimation scheme that utilizes the preamble as well as the pilot signal. The proposed scheme estimates the channel by combining the CSI estimated from the received preamble and pilot signal. The combining weight is analytically determined to minimize the MSE of the channel estimation. When the proposed scheme is applied to the mobile-WiMAX system, the simulation results show that the proposed scheme is quite effective in the cell boundary, especially highly correlated channel environments.

ACKNOWLEDGEMENT

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TABLE I

SIMULATION PARAMETERS

PARAMETERS	Values
Carrier frequency	2.3 GHz
Bandwidth	10 MHz
OFDM symbol duration	115.2 us
Number of subcarriers	1024
Channel	Rayleigh fading
Power delay profile	Pedestrian A
Doppler spectrum	Jakes’ model

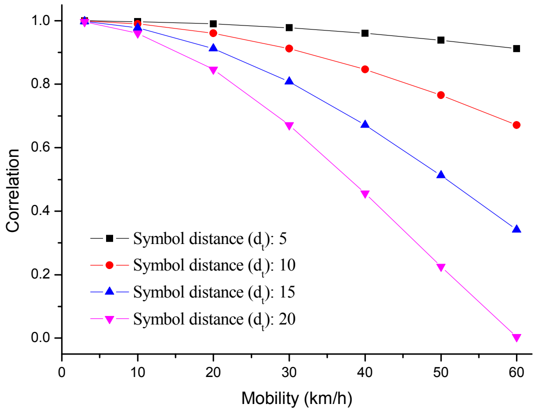


Fig. 3. Correlation between preamble and pilot signal.

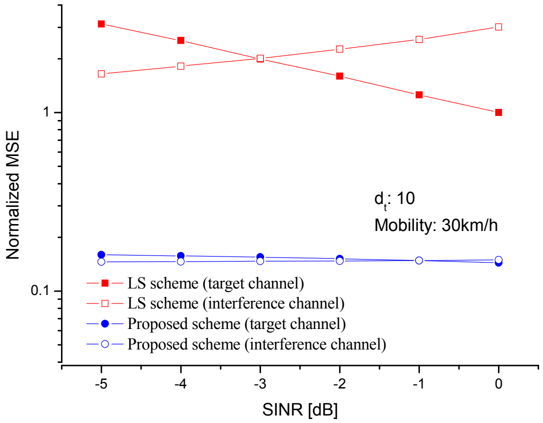
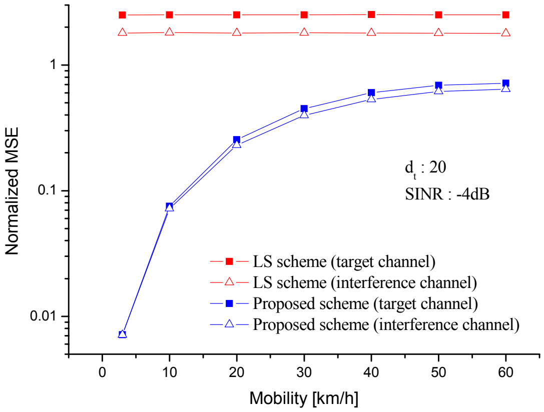
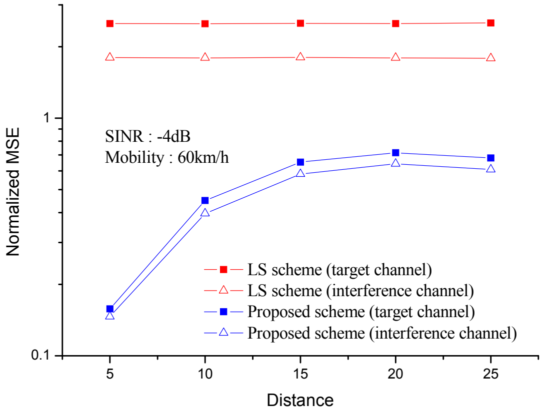


Fig. 4. MSE according to the SINR.



(a) MSE according to the mobility.



(b) MSE according to the symbol distance

Fig. 5. MSE performance according to the channel correlation.