Group-based Pilot Design Method in Mobile OFDMA Systems

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Abstract—In mobile communication systems, users move with various speeds. Therefore, pilot designs using the fixed arrangement of pilot subcarriers and channel estimation method are not suitable. In this paper, we propose a group-based pilot design method in mobile orthogonal frequency division multiple access (OFDMA) systems. In the proposed method, we divide users into several groups based on the users’ speeds and allocate an appropriate pilot arrangement for each group. Using the proposed method, we minimize the channel estimation errors of high-speed users while maximizing the resource efficiency of low-speed users.

Keywords — OFDMA, group-based pilot design method, channel estimation.

I. Introduction

Recently, orthogonal frequency division multiplexing (OFDM) becomes a suitable technique for wideband mobile communication systems requiring high data rate transmission. Channel estimation methods in OFDM systems when a channel is time-invariant during one OFDM symbol are studied in [1]–[3]. The minimum mean-square error (MSE) estimators and least-squares (LS) estimators are presented in [1], [2]. Pilot subcarriers should be equally spaced to reduce the noise effect in estimating the channel [3]. In [4], various interpolation techniques needed to estimate channels of data subcarriers are represented.

In fast fading channels, the channel varies during one OFDM symbol due to the Doppler spread, which results in the intercarrier interference (ICI) destroying the orthogonality between subcarriers. Channel estimation methods in time-varying channels are studied in [5], [6]. In those methods, interpolation weight matrices are used to reduce the number of values to be estimated and matrix inversion calculation considering the ICI is required.

In mobile communication systems, users move with various speeds. Therefore, fixed pilot arrangements and channel estimation techniques are not suitable. In [7], adaptive pilot patterns are proposed. However, the pilot pattern for each user is determined based on some quality of service (QoS) criterions, not on the user’s speed. In addition, [7] is based on a time division multiple access (TDMA) system, in which it is easy to apply a different pilot pattern to each user since one user uses all subcarriers at a time. However, in OFDMA systems, it is hard to allocate a different pilot pattern to each user since multiple users use resources in frequency domain at a time.

In this paper, we propose a group-based pilot design method in mobile OFDMA systems. In the proposed method, we group users based on the users’ speeds and allocate an appropriate pilot arrangement for each group. Using the proposed method, we minimize the channel estimation errors of high-speed users while maximizing the resource efficiency of low-speed users.

The rest of this paper is organized as follows. In section II, we introduce the OFDM system model and channel estimation methods for time-invariant channels and time-varying channels. In section III, we present a group-based pilot design method. In section IV, we show the simulation results and finally, we conclude with discussion in section V.

II. Channel Estimation in OFDM Systems

A. OFDM System Model

In a multipath environment, a general discrete-time input-output model can be shown as

\[ y(k) = \sum_{l=0}^{N-1} h(k;l)x(k-l) + z(k) \]

where \( h(k;l) \) is the sampled time-varying channel impulse response with the channel length \( v \); \( x(k) \) is input data, \( y(k) \) is output data, and \( z(k) \) is the additive Gaussian noise.

For the OFDM system with \( N \) subcarriers, a general input-output model can be represented as [5]

\[ y = H^{(N)}x + z \]  \hspace{1cm} (1)

where \( x \), \( y \), and \( z \) are input, output, and noise vector, respectively, and \( H^{(N)} \) is defined as

\[
H^{(N)} = \begin{bmatrix}
h(0;0) & 0 & \cdots & h(0;2) & h(0;1) \\
h(1;1) & h(1;0) & \cdots & h(1;3) & h(1;2) \\
\vdots & \vdots & \ddots & \vdots & \vdots \\
h(v-1;v-1) & h(v-1;v-2) & \cdots & 0 & 0 \\
0 & 0 & \cdots & h(N-2;0) & 0 \\
0 & 0 & \cdots & h(N-1;1) & h(N-1;0) \\
\end{bmatrix}
\]

When the channel is time-invariant during one OFDM symbol the system is described as a set of parallel Gaussian channels [1].
\[ \mathbf{Y} = \mathbf{H}\mathbf{X} + \mathbf{Z} \]

where \( \mathbf{H} \) is a diagonal matrix composed of the DFT of channel impulse responses, \( \mathbf{X}, \mathbf{Y}, \) and \( \mathbf{Z} \) are the DFTs of \( \mathbf{x}, \mathbf{y}, \) and \( \mathbf{z} \), respectively.

However, when the channel is time-varying during one OFDM symbol we represent (1) as [5]

\[ \mathbf{Y} = \mathbf{G}\mathbf{X} + \mathbf{Z} \]

where \( \mathbf{G} = \mathbf{Q}\mathbf{H}^{(N)}\mathbf{Q}^H \) and \( Q(i, k) = 1/\sqrt{N}e^{-j2\pi ik/N} \) for \( 0 \leq i, k \leq N - 1 \). \( \mathbf{G} \) is evaluated as

\[ G(m, s) = \frac{1}{N} \sum_{r=0}^{N-1} \sum_{l=0}^{N-1} h(r, l)e^{j2\pi(s-m)/N}e^{-j2\pi s l/N} \]

and each output of the DFT of \( \mathbf{y} \) is represented as

\[ Y(p) = G(p, p)X(p) + \sum_{q \neq p}^{N-1} G(p, q)X(q) + Z(p) \]

for \( p = 0, \ldots, N - 1 \). In (2), \( \sum G(p, q)X(q) \) term represents the ICI.

**B. Channel Estimation**

In time-invariant channels, to minimize the mean square error (MSE) of the channel, pilot subcarriers should be equally spaced [3]. When the pilot subcarriers are grouped together, the noise enhancement effect appears. The MMSE and LS estimators are presented in [2], [4]. The MMSE estimator shows better performance than the LS estimator because the LS estimation method is susceptible to noise and ICI. However, the MMSE estimator requires high complexity. To reduce the complexity of the MMSE method, some works are proposed [2].

After estimating the channels at pilot subcarriers, various interpolation techniques are needed to estimate the channels at data subcarriers, such as linear interpolation, second-order interpolation, low-pass interpolation, spline cubic interpolation, and time domain interpolation [4].

In time-varying channels, estimating channels means that we have \( Nv \) values. However, during one OFDM symbol, we can use at most \( Np \) pilot subcarriers. In [5], \( M \) “markers” are used for the channel interpolation between \( N \) different channel impulse responses, therefore we can estimate the channel using \( P \) pilot subcarriers for \( P \geq Mv \). The interpolation weight matrices for \( N \) different channel impulse responses are determined using a linear interpolation method or a Jakes-based method. In [5], the placement of pilot subcarriers is also proposed. Intuitively speaking, since for a subcarrier, most ICI due to the Doppler spread comes from adjacent subcarriers in the time-varying channel, the channel estimation is accomplished reducing estimation errors if we place the pilot subcarriers grouped together. In frequency-selective channels, the number of pilot groups should be larger than the number of delay taps in the channel.

**III. Group-based Pilot Design Method**

In mobile communication systems, users move with various speeds. However, with a fixed pilot arrangement and channel estimation technique, the channel estimation error of the high-speed users increases or pilot overhead and complexity of estimators for the low-speed users increases redundantly. Therefore, an adaptive pilot design method is required.

Since all subcarriers are not assigned to one user at a time in OFDMA systems, we propose a group-based pilot design method. We divide users into some groups based on their speeds and split a PHY frame into several parts in time domain. After that, we map user groups onto each part and assign an appropriate pilot arrangement to each part, as shown in Fig. 1. In the proposed method, we assume that users can estimate their speeds and feedback the speed information to the base station (BS) since various speed estimation methods have been studied. For example, in [8], a velocity estimation method using the power spectral density (VESP) estimates Doppler frequency using the slope of power spectral density (PSD) of the received signal envelope.

To determine the time duration of each part, we use the number of users in each group and the amount of data to be transmitted. If a group contains many users and those users have a large amount of data to be transmitted, we allocate the longer time duration to the part that group belongs to. Adaptively adjusting the time duration of each part, we may use given resources without wasting.

Channel estimation methods are selected based on the groups. Users in low-speed groups estimate the channels using

\[ \bar{H}_p(k) = Y_p(k)/X_p(k) \]

for \( k = 0, \ldots, N_p - 1 \), where \( \bar{H}_p(k), X_p(k), \) and \( Y_p(k) \) are the estimated channel, pilot input, and received output at the \( k \)th pilot subcarrier, respectively. \( N_p \) is the number of pilot subcarriers. To estimate the channels at data subcarriers, we use the linear interpolation method.

Users in high-speed groups assume that the channel is time-varying in one OFDM symbol. The channel estimation method which considers the effect of the ICI and placement of pilot subcarriers is used as follows [5]:

\[ \hat{h} = \begin{bmatrix} \mathbf{h}^{(p,1)} & \vdots & \mathbf{h}^{(p,N_p-1)} \end{bmatrix} \begin{bmatrix} Y_p(0) \\ \vdots \\ Y_p(N_p-1) \end{bmatrix} \]

where \( \hat{h} = [\mathbf{h}^T_{m(1)} \ldots \mathbf{h}^T_{m(M)}] \) and \( \mathbf{h}^{P,q} = \sum_{q=0}^{N_p-1} X_p(q)\mathbf{h}^{P,q} \)

\[ \mathbf{h}^T_n = [h(n;0) \ldots h(n;v-1)] \] for \( 0 \leq n \leq N-1 \) and
choose the values for elements of \( \mathbf{A}_{m(0)} \), some methods such as linear interpolation or Jakes-based estimation are used [5], [6]. In our simulation, for simplicity, we use the linear interpolation method. After calculating \( \hat{\mathbf{h}} \), we find the estimated channel, \( \hat{\mathbf{h}} \) using \( \mathbf{A}_{m(0)} \).

The MSE in the channel estimation is calculated as

\[
mse = E \left\{ \| \mathbf{h} - \hat{\mathbf{h}} \|^2 \right\}
\]

IV. Simulation Results

In our simulation, we assume an OFDM environment with 64 subcarriers, channel bandwidth of 200 KHz, and carrier frequency of 3.5 GHz. We use a one-sided exponential profile model to generate multipath delay taps in simulation channels. We assume that the number of channel delay taps is four and each channel tap follows the Rayleigh distribution.

Considering the practical environments, we classify mobile users into three classes and define four pilot arrangement sets:

- **User classes**
  - Walking or running users (0 km/h–30 km/h)
  - Users in medium-speed vehicles such as cars (60 km/h–120 km/h)
  - Users in high-speed vehicles such as railroads (240 km/h–300 km/h)

- **Pilot sets**
  - Set A: 16 pilot subcarriers equally spaced
  - Set B: 16 pilot subcarriers composing four groups
  - Set C: 24 pilot subcarriers composing four groups
  - Set D: 32 pilot subcarriers composing four groups.
We refer the channel estimation method in (3) as time-invariant least-squares (TILS) and the method in (4) as time-varying least-squares (TVLS). Fig. 2(a) illustrates the performance of the channel estimation when the Doppler frequency is 10 Hz. In this environment, the equispaced pilot arrangement with the TILS method shows the better performance than the grouped pilot arrangement even though less pilot subcarriers are used. For low complexity of the channel estimator and low pilot overhead, the equispaced pilot arrangement with the TILS method should be used for low-speed users. In Fig. 2(b), we show the performance when the Doppler frequency is 400 Hz. In this environment more than 16 pilot subcarriers are needed for the channel estimation with reasonable MSEs, and pilot subcarriers should be grouped. When the Doppler frequency is 800 Hz, equal to or more than 32 pilot subcarriers are needed for the channel estimation with reasonable MSEs as in Fig. 2(c). From simulation results shown above, it is obvious that an adaptive pilot design method is needed when users move with various speeds.

We show the performance of the proposed pilot design method. In the simulation, the number of users is 24. Among the users, 40% of users belong to the low-speed group (group 1), 30% to the medium-speed group (group 2), and 30% to the high-speed group (group 3). The Doppler frequency is distributed uniformly from 0 to 100 Hz, from 200 Hz to 400 Hz, and from 800 Hz to 1000 Hz in each group. For the comparison, we assume four scenarios. In scenario 1, the fixed pilot arrangement for low-speed users (set A) is used to all users with the TILS. In scenario 2, the fixed pilot arrangement for moderate-speed users (set C) is used to all users with the TVLS. In scenario 3, the fixed pilot arrangement for high-speed users (set D) with the TVLS is used, and in the proposed method, we adaptively use set A with the TILS, set C with the TVLS, and set D with the TVLS to each group.

Fig. 3 shows the channel estimation performance and pilot overhead in four scenarios. In scenario 1, since the set A pilot arrangement is used to all users, pilot overhead is low. However, since the placement and number of pilot subcarriers are not appropriate for users in group 2 and 3, the average MSE increases. In the case of scenario 2, users in group 1 have redundant pilot overhead and users in group 3 require more pilot subcarriers to reduce the MSEs. In scenario 3, though the average MSE of all users is minimized, pilot overhead is high. Since the proposed method adaptively assigns the pilot arrangements, it shows average MSE similar to that of scenario 3 while maintaining moderate pilot overhead.

V. Conclusion

In this paper, we have proposed the group-based pilot design method in mobile OFDMA systems where mobile users move with various speeds. In the proposed method, we divide users into several groups based on their speeds, and assign the appropriate pilot arrangement and channel estimation method to each user group considering the characteristics of channel environments. Simulation results show that using the proposed method, we can minimize the channel estimation errors of high-speed users while maximizing the resource efficiency of low-speed users.

References