불완전 동기 환경에 강인한 OFDMA 채널 추정기법

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A Robust OFDMA Channel Estimation Against Imperfect Synchronization

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요 약

OFDMA 하향링크 시스템에서 시간, 주파수 동기 오프셋이 존재하는 환경에 강인한 채널추정 기법을 제안한다. 본 논문에서는 시간 동기, 주파수 동기, 및 채널추정을 동시에 수행하는 방법을 제안함으로써, 시간 및 주파수 동기화 과정에서 생기는 에러가 채널 추정 과정에 주는 영향을 최소화하였다. 시뮬레이션 결과 제안된 채널추정 기법은 time windowing과 time advancement를 통해서 inter-carrier interference (ICI)와 inter-symbol interference (ISI)를 제거하고 동기화 과정간의 조화를 이룸으로써 기존의 채널추정 기법들에 비해 약 3dB 성능이 향상되었다.

Key Words : OFDMA, Channel Estimation, Time offset, Frequency offset.

ABSTRACT

We propose a robust channel estimation method against imperfect synchronization in orthogonal frequency division multiple access (OFDMA) downlink systems. We address time and frequency synchronization, and the channel estimation at the same time, and try to minimize the error propagation from the time and frequency synchronization steps into the channel estimation. The simulation results show that the proposed channel estimation method outperforms the conventional algorithms by about 3dB, and circumvents the problem of mismatch among the synchronization tasks.

Ⅰ. Introduction

The orthogonal frequency division multiple access (OFDMA) is a bandwidth efficient multiple access technology which provides high aggregate data rates in multi-user wireless communication systems. The OFDM applied in the OFDMA is quite effective in handling time dispersion in multipath fading channels, since the inter-symbol interference(ISI) which is caused by time dispersive channels can be generally eliminated by inserting cyclic prefix (CP)[1]. However, since the multi-carrier modulation itself is very sensitive to frequency offset and phase noise, the ISI and the inter-carrier interference (ICI) which are caused by the frequency offset and phase noise still exist even with the CP.

Assuming perfect frequency synchronization, various pilot-symbol-aided channel estimation methods have been proposed in OFDM[2]. The least square (LS) estimators can be readily implemented even without any knowledge about the channel

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논문번호 : KICS2005-05-204, 접수일자 : 2005년 5월 20일
※ 본 연구는 한국산업기술평가원 차세대신기술개발사업(00013069) 지원으로 수행되었습니다.

statistics. In perfect frequency synchronization, the minimum mean square error (MMSE) estimators are even more robust against noise. However, the performance of the MMSE estimators on channel statistics and the operating signal to noise ratio (SNR) degrades, when there is no a priori knowledge of channel statistics and the operating SNR. Furthermore, under an imperfect frequency synchronization condition, the performance of such estimators further degrades due to the frequency offset and the phase noise. Therefore, it is important to minimize the error propagation from the time and frequency synchronization steps into the channel estimation. In the previous studies, the negative effects from the frequency offset and those from the phase noise have been addressed separately, assuming the other parameter is perfectly known[3-5]. However, since the frequency offset and the phase errors affect each other, a combined estimation algorithm which can address time synchronization, frequency synchronization and the channel estimation at the same time is desired. In this paper, we propose a new robust channel estimation method for the OFDMA downlink using the most likely channel impulse response (CIR) length to counteract the effects of the frequency offset and the phase noise.

In section II, we describe the system model of OFDMA downlink and present the proposed robust channel estimation scheme in section III. We then discuss the computer simulation results in section IV, and summarize our conclusion in section V.

Ⅱ. System Model

In the OFDMA transmitter system, each data symbol is divided into N subcarriers. The OFDM symbol is generated by taking the N-point inverse fast Fourier transform (IFFT) and a CP is added. Here the length of the CP and the CIR are defined as N_g and L, respectively. The total length of symbol becomes $N_s=N+N_g$. We also assume the CIR is finite and its length is less than that of the CP, that is, $L<N_g$.

In the presence of frequency offset and phase noise, we can express the received nth sample of the ith symbol for the kth user in time domain by

$$y_i^{(k)}(n) = x_i^{(k)}(n) \otimes h_i^{(k)}(n) \cdot e^{j2\pi\left((i\cdot N_s+n)\cdot\varepsilon^{(k)}/N+\phi_i^{(k)}(n)\right)} + z_i^{(k)}(n), \quad (1)$$

where $x_i^{(k)}(n)$, $h_i^{(k)}(n)$ and $\phi_i^{(k)}(n)$ are defined as the transmitted symbol, the CIR and the phase noise, respectively. $z_i^{(k)}(n)$ and $\varepsilon^{(k)}$ represent the AWGN noise and the normalized frequency offset for the kth user, respectively. We assume that $\varepsilon^{(k)}$ is a uniformly distributed random variable in [-0.5, 0.5] and the 3dB bandwidth of phase noise is much less than the frequency offset. Then, (1) can be expressed in frequency domain as

$$Y_i^{(k)}(m) = H_i^{(k)}(m)\cdot X_i^{(k)}(m)\cdot I_i^{(k)}(0) + \sum_{\substack{p=0\\p\neq m}}^{N-1} H_i^{(k)}(p)\cdot X_i^{(k)}(p)\cdot I_i^{(k)}(p-m) + Z_i^{(k)}(m), \quad (2)$$

where $H_i^{(k)}(m)$, $X_i^{(k)}(m)$ and $Z_i^{(k)}(m)$ are equivalent to the frequency domain expressions of $h_i^{(k)}(n)$, $x_i^{(k)}(n)$ and $z_i^{(k)}(n)$, respectively. $I_i^{(k)}(q)$ is a function of $\varepsilon^{(k)}$ and $\phi_i^{(k)}(n)$ given by

$$I_i^{(k)}(q) = \frac{1}{N}\sum_{n=0}^{N-1} e^{j2\pi[((i\cdot N_s+n)\cdot\varepsilon^{(k)}+q\cdot n)/N+\phi_i^{(k)}(n)]}, \quad (3)$$

where q =0,..., N-1. Equation (2) with (3) verifies that ICI and ISI can be caused by frequency offset and common phase error (CPE). (2) can be represented in matrix form

$$\mathbf{Y}^{(k)} = \mathbf{I}^{(k)}\mathbf{X}^{(k)}\mathbf{H}^{(k)} + \mathbf{Z}^{(k)}, \quad (4)$$

where $\mathbf{Y}^{(k)} = \left[Y_i^{(k)}(0) \quad Y_i^{(k)}(1) \quad \cdots \quad Y_i^{(k)}(N-1)\right]^T$,

$\mathbf{H}^{(k)} = \left[H_i^{(k)}(0) \quad H_i^{(k)}(1) \quad \cdots \quad H_i^{(k)}(N-1)\right]^T$,

$\mathbf{Z}^{(k)} = \left[Z_i^{(k)}(0) \quad Z_i^{(k)}(1) \quad \cdots \quad Z_i^{(k)}(N-1)\right]^T$,

and these are all $N\times1$ vectors.

$$\mathbf{X}^{(k)} = diag\left(\left[X_i^{(k)}(0) \quad X_i^{(k)}(1) \quad \cdots \quad X_i^{(k)}(N-1)\right]\right),$$

$$\mathbf{I}^{(k)}=\begin{bmatrix} I_i^{(k)}(0) & I_i^{(k)}(-1) & \cdots & I_i^{(k)}(N-1) \\ I_i^{(k)}(1) & I_i^{(k)}(0) & \cdots & I_i^{(k)}(N-2) \\ \vdots & \vdots & \ddots & \vdots \\ I_i^{(k)}(1-N) & \cdots & \cdots & I_i^{(k)}(0) \end{bmatrix},$$

and these are $N\times N$ matrices. $\mathrm{I}^{(k)}$ which includes the frequency offset and the CPE should eventually be reduced to an identity matrix in order to guarantee the performance of channel estimation.

Ⅲ. Proposed Robust OFDMA Channel Estimation Against Imperfect Synchronization

In the previous section, we observed that the performance of the channel estimation is degraded in the presence of a carrier frequency offset between the transmitter and the receiver. We should estimate both CIR length and channel characteristics in presence of frequency offset and time offset to guarantee good receiver performance. A new scheme which iteratively searches for the most likely CIR length will be proposed and then such information is supplied to the time and frequency synchronization. The proposed scheme is shown in Fig. 1.

Under multipath channel environment, the timing reference point normally gets some random delay with respect to the actual point due to the dispersion. To compensate this, the timing reference point can be advanced by some amount λ. The appropriate value of λ depends on the channel characteristics such as power delay profile , the effective maximum channel delay spread, the CP length, and the timing estimation performance. A good design rule is that the CP length should be such that with the timing advancement, the reference timing point can be locatedwithin the ISI-free region most of the time. If the CP length is large enough that the timing distribution fits well within the ISI-free region, then λ can be set to about half of the ISI-free length.

We assume that the channel statistics is unknown. LS estimation method is advantageous over MMSE estimation in its simplicity and independency of channel statistics. So, we will apply the LS estimation method. However, the proposed scheme can be applied to any types of channel estimation methods.

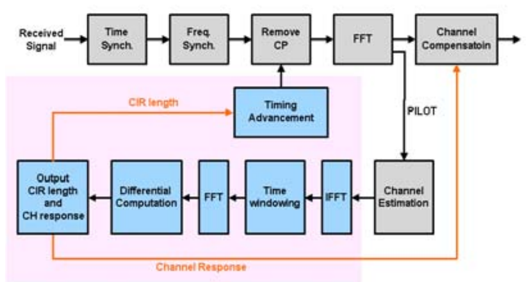

Fig. 1. Proposed scheme for synchronization and channel estimation

When the frequency offset is compensated, we can express that

$$\hat{\mathbf{Y}}_1^{(k)} = \mathbf{I}_1^{'(k)}\mathbf{X}^{(k)}\mathbf{H}^{(k)} + \mathbf{Z}^{(k)}, \quad (5)$$

where $\mathrm{I}^{(k)}$ in (4) is replaced by $\mathrm{I}_{\ell}^{'(k)}$ and $\mathrm{I}_i^{(k)}(q)$, $\hat{\varepsilon}_1^{(k)}$ are given by

$$I_i^{'(k)}(q)=\frac{1}{N}\sum_{n=0}^{N-1}e^{j2\pi[((i\cdot N_s+n)\cdot(\varepsilon^{(k)}-\hat{\varepsilon}_1^{(k)})+q\cdot n)/N+\phi_i^{(k)}(n)]}, \quad (6)$$

where $\hat{\varepsilon}_1^{(k)}=\frac{1}{2\pi}angle\left(\sum_{i=0}^{S-1}\sum_{n=-N_g+1}^{-1}(y_i^{(k)*}(n)\cdot y_i^{(k)}(n+N))\right)$. ℓ is the CIR length which is unknown, and S is the number of symbols used for averaging. ℓ is initially set to one and then found as the estimate for the most likely CIR length by iteration. Though the channel statistics is unknown, we can estimate the frequency offset by ℓ with close proximity.

Then, the channel estimation performed by using the LS method can be given by

$$\mathbf{H}_{\mathrm{LS},1}^{(k)} = \mathbf{X}^{(k)^{-1}}\hat{\mathbf{Y}}_1^{(k)}. \quad (7)$$

The LS estimation method is quite sensitive to interference and noise. With the imperfect frequency and phase synchronization, the ICI cannot be entirely removed, so the performance of the LS estimator can be deteriorated. Therefore, some method must be introduced to reduce the effect of the ICI and noise. We propose to use the CIR estimate as a control parameter. As the CIR has a finite length in time domain, any response beyond the CIR length is mostly due to the ICI and noise. Hence, we propose to apply a window function to filter out this ICI and noise region on channel estimation. Applying the window function in time domain in (7) yields

$$\hat{\mathbf{H}}^{(k)}_{LS,\ell} = \mathbf{W}\mathbf{B}_1\mathbf{W}^H\mathbf{H}^{(k)}_{LS,\ell}, \qquad (8)$$

where $\mathbf{W} = \frac{1}{\sqrt{N}}\begin{bmatrix} 1 & 1 & \cdots & 1 \\ 1 & e^{-j2\pi/N} & \cdots & e^{-j2\pi(N-1)/N} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & e^{-j2\pi(N-1)/N} & \cdots & e^{-j2\pi(N-1)(N-1)/N} \end{bmatrix}$, is an $N\times N$ Fourier transform matrix, and $\mathbf{B}_1 = diag\left(\left[b_1(0)\ b_1(1)\ \cdots\ b_1(N-1)\right]^T\right)$ is an $N\times N$ diagonal matrix defined by the Blackman function[7].

The most likely CIR length can be found by minimizing the cost function

$$\left\|\mathbf{H}^{(k)} - \mathbf{H}^{(k)}_{LS,\ell}\right\|^2. \qquad (9)$$

If we can find the proper ℓ that produces the frequency offset estimation minimizing (9), then the window function needs not to be applied during the search period to simplify the process. However, a direct minimization is difficult since $H^{(k)}$ and $\varepsilon^{(k)}$ in (9) are unknown parameters. Without AWGN noise, as ℓ becomes larger, the frequency offset estimation and channel estimation become more accurate. And it becomes minimum when ℓ is equal to or greater than the CIR length. So, we can get the minimization of (9) by the first occurrence of a local minimum of

$$\left\|\mathbf{H}^{(k)}_{LS,\ell} - \mathbf{H}^{(k)}_{LS,\ell-1}\right\|^2. \qquad (10)$$

With AWGN noise, we should affirm that ℓ which minimizes (9) is equal to ℓ which minimizes (10) before we use (10). If noise is not so high, statistically, the minimum of (9) would be obtained when ℓ is the most likely CIR length. As ℓ becomes larger from one to the CIR length, the value of equation (10) becomes smaller since the CIR effects decrease. However, as ℓ becomes larger, the value of equation (10) also becomes larger when ℓ is between the CIR length and the CP length. The meaning of the increasing ℓ is the same as using fewer samples, so the frequency offset estimation and the channel estimation become less accurate. So, we can find that the minimum of (10) appears when the probability that ℓ is the same as the CIR length is high. Therefore, the most likely CIR length can be found by ℓ which satisfies the following equations $\left\|\mathbf{H}^{(k)}_{LS,\ell} - \mathbf{H}^{(k)}_{LS,\ell-1}\right\|^2 \le \left\|\mathbf{H}^{(k)}_{LS,\ell-1} - \mathbf{H}^{(k)}_{LS,\ell-2}\right\|^2$, and

$$\left\|\mathbf{H}^{(k)}_{LS,\ell} - \mathbf{H}^{(k)}_{LS,\ell-1}\right\|^2 \le \left\|\mathbf{H}^{(k)}_{LS,\ell+1} - \mathbf{H}^{(k)}_{LS,\ell}\right\|^2. \qquad (11)$$

Then, we can express the final channel estimate with

$$\hat{\mathbf{H}}^{(k)}_{LS,\hat{\ell}} = \mathbf{W}\mathbf{B}_1\mathbf{W}^H\mathbf{X}^{(k)^{-1}}\hat{\mathbf{Y}}^{(k)}_{\hat{\ell}}, \qquad (12)$$

where $\hat{\ell}$ represents the estimated value of ℓ. Since the CIR length dose not change so quickly even in a time variant channel, the CIR length can be found with only a few search in most cases.

Ⅳ. Computer Simulation

To evaluate the performance of the proposed algorithm, we have performed computer simulations for OFDMA downlink system. The system parameters used in the simulations are given in the Table 1. We assumed time division duplex (TDD) transmission. The comb-type pilot arrangement is used for channel estimation. We applied the spline cubic interpolation to produce a smooth and continuous polynomial. We also assumed that the frequency offset could be modeled as a uniformly distributed random variable in [-0.5, 0.5] without loss of generality. For the channel models, we

Table 1. Simulation parameter.

Item	Value
FFT size	1024
Cyclic Prefix Length	128
Carrier Frequency	5GHz
Bandwidth	20MHz
Allocation scheme	Block tone assignment
Subband size of block tone assignment	16 subcarriers/each
Modulation	16QAM
Pilot Ratio	1/8
Frequency offset	Uniform in [-0.5, 0.5]
Channel model	Indoor B, Pedestrian B and Vehicular B

tried various frequency selective fading channels for the simulation. They characterize delay time and power delay profile of each channel tap over 20 MHz, and the number of multiple taps is 6. The Vehicular B channel model is the most frequency selective channel among the three different channel models.

Fig. 2 shows the BER performance of the proposed channel estimation algorithm compared with the conventional channel estimation algorithms under imperfect synchronization in the Indoor B channel. For conventional channel estimation algorithms, we compared the LS and the MMSE channel estimations using pilots. The performance degradation due to errors in synchronization is shown in this figure. Even in such environment, our proposed LS channel estimation algorithm outperforms the conventional LS channel estimation by about 1.5dB at the BER of 0.01. The proposed LS algorithm gets close to the case of the perfect synchronization and channel estimation by 2dB. The performance gap can be viewed as the sensitivity of the channel estimation to the synchronization errors.

We have also evaluated the proposed channel estimation algorithm under more frequency selective channel model in Fig. 3 and 4. For most part, the BER performance under the Vehicular channel model B is the least among all the channel models simulated in this paper. The proposed channel estimation algorithm outperforms the conventional

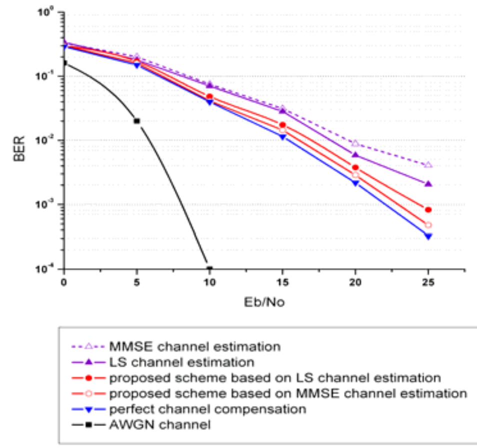

Fig. 2. BER Performance of the proposed channel estimation method under imperfect synchronization in Indoor B channel

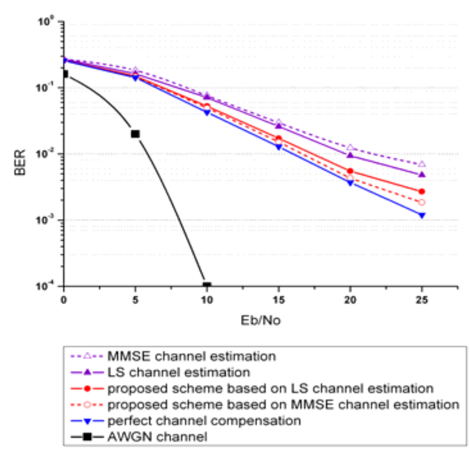

Fig. 3. BER Performance of the proposed channel estimation method under imperfect synchronization in Pedestrian B channel

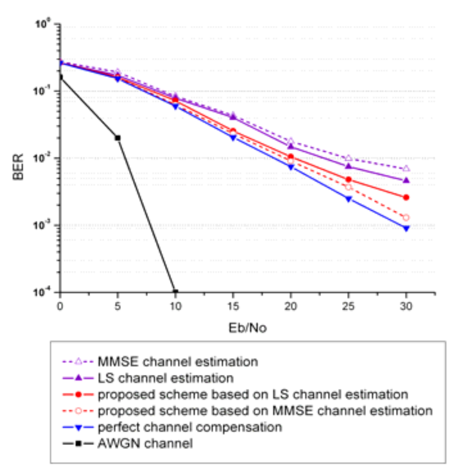

Fig. 4. BER Performance of the proposed channel estimation method under imperfect synchronization in Vehicular B channel

channel estimation under all these channel models. Throughout these figures, the robust OFDMA channel estimation scheme can achieve the BER performance without synchronization error propagation. Under Pedestrian B channel model, the proposed LS scheme outperforms the conventional LS scheme by about 2.5dB at BER 0.01. Under Vehicular B channel model, the proposed LS scheme outperforms the conventional LS scheme by about 3 dB at BER 0.01. From these observations, it can be concluded that the proposed scheme is more efficient than conventional scheme in highly frequency selective channel.

In Fig. 5, we have compared the mean squared error (MSE) of the proposed channel estimation method with the MSE of the conventional LS channel estimator. As is shown, when the LS channel estimator is combined with the proposed method, it outperforms the conventional LS channel estimation.

We also note that when LS estimator and the MMSE estimator are each applied to our channel estimation method, the proposed method with the LS estimator comparatively performs better at lower Eb/N0, and the proposed method based on the MMSE estimator performs better at higher Eb/N0. At perfect situation, the MMSE estimators are more robust against interference and perform better than the LS estimators. However, when the operating SNR gets lower, it takes wrong estimates of the channel, so the performance degrades. By the way, the MMSE estimator is not feasible in cases when the CIR length is unknown. In this case, however, the CIR length was supplied from the iterative time windowing included in the proposed scheme.

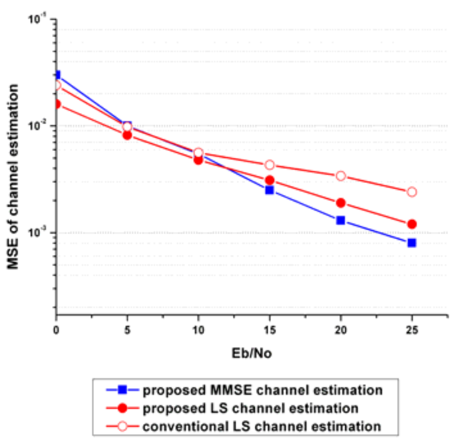

Fig. 5. Mean Square Error comparison conventional channel estimation and proposed channel estimation

Ⅴ. Conclusion

In this paper, we have considered the problem of channel estimation which can be affected by the errors in synchronization in OFDMA downlink systems. We proposed a robust channel estimation scheme in the presence of frequency offset and phase noise. The frequency offset causes ICI and phase noise causes ISI. The proposed channel estimation scheme eliminates the effect of ICI and ISI through timing windowing and timing advancement. Moreover, we can obtain the CIR length through iterative time windowing. We can also apply the MMSE channel estimation to our proposed channel estimation scheme when the signal power is rather high. In the computer simulation, we compared the average BER and the MSE of the proposed channel estimation scheme with the conventional channel estimation methods. Computer simulations show that the proposed scheme offers a performance gain as well as the robustness under the highly frequency selective channel. The performance of our proposed channel estimation is superior to that of the conventional channel estimation by about 3dB at BER 0.01 under Vehicular B channel model.

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