Performance Analysis of Synchronization for an OFDMA System

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***Abstract*—We present the time and frequency synchronization algorithm as well as the cell search scheme for cellular systems. Coarse time and fractional frequency offset estimates are performed in the time domain by using the primary preamble, while the cell search and the integer frequency offset estimate are performed in the frequency domain and afterwards the fine time and frequency offset estimates are performed by using the secondary preamble. All algorithms are evaluated under rapidly time-varying multipath fading channels and an initial carrier frequency mismatch. The simulation results show that the proposed algorithm can provide a robust synchronization and cell-search capability, even in bad cellular environments.**

Keywords-synchronizatoin; preamble; OFDMA.

I. Introduction

Orthogonal frequency division multiplexing access (OFDMA) is an efficient multicarrier technique which has been proposed for current and next generation wireless communication systems, for example IEEE 802.16e (mobile WiMAX) and IEEE 802. 16m [1] [2]. However, time offsets (TOs) and frequency offsets (FOs) between the base-station (BS) and the mobile users (MUs) arising due to local oscillator mismatch and/or the mobility of the users destroy the orthogonality among the user's sub-carriers. Inter symbol interference (ISI) and Inter carrier interference (ICI) caused by these TOs and FOs severely degrade the performance of the whole system. Therefore, the estimation and the compensation of TO and FO are imperative at the BS and the MUs.

In many situations that time delays and Doppler spreads exist, TO and FO synchronization only at the downlink of OFDMA systems is not sufficient and calls for TO and FO synchronization at the uplink as well. However, TO and FO synchronization is much more challenging at the uplink due to the presence of multiple TOs and FOs and the fact that the received signal at the BS is the sum of the transmitted signals from all the users. In addition, ensuring the identifiability of cell is also an important requirement. By utilizing cell-specific reference signal, target TO and FO can be restored from a signal disturbed by other users' TOs and FOs mismatch.

Various solutions of synchronization for OFDMA systems have been proposed in the literature [3]$\sim$ [6], but only a few of them also discuss the identifiability [7] [8]. In this paper,

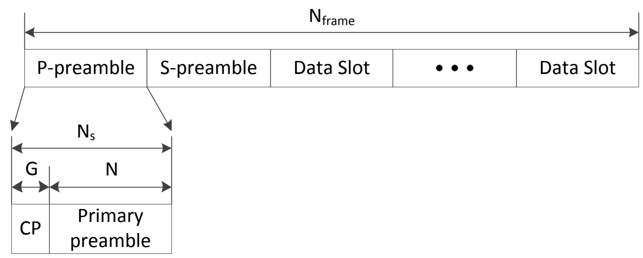

Figure 1. Abstract frame structure

we invest an overall synchronization process including the identification. Moreover, we consider the mobility. The mobility of the receiver relative to transmitter is the main factor that affects the rate of fading. As the receiver moves with some velocity relative to the transmitter, the phase shifts of the received signal changes. This phenomenon is known as the Doppler effect. In practical OFDMA systems, a frequency offset due to the Doppler effect usually exists between the transmitter and the receiver.

This paper is organized as follows: Section II introduces a basic OFDMA system. Section III presents the proposed synchronization algorithm in detail. Section IV shows the performance of overall proposed scheme and comparison with the performance of without-fine synchronization scheme. Finally, Section V gives some conclusions.

II. System Model

As shown in Figure 1, we consider a packet-based OFDMA communication system, where a preamble is placed at the beginning of the packet. The preamble consists of two different components, which are denoted as the primary preamble and the secondary preamble as similar to IEEE802.16m [2]. The length of each preamble is an OFDM symbol, which is the same length of a data symbol. We consider an OFDM symbol with two identical halves in the time domain as the primary preamble. The primary preamble is common for all BSs and is used for the TO and FO synchronization. The secondary preamble is used for the cell-ID identification and it can also be used to estimate more accurate TO and FO in bad cellular environments. In this paper, we propose a robust synchronization technique

 ISBN: 978-1-61208-203-5

using the primary preamble for coarse synchronization and using the secondary preamble for the fine synchronization as well as the cell-ID identification.

In the time domain, the n-th sample of a base-band equivalent OFDM symbol is given by

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X(k) e^{j2\pi kn/N}, \tag{1}$$

where $j = \sqrt{-1}$, $-G \leq n \leq N-1$, N is the total number of subcarriers for an OFDM symbol, $X(k)$ is the k-th modulated signal in the frequency domain, and G is the length of cyclic prefix (CP), which is assumed to be longer than the length of channel impulse response. The signal is transmitted through a frequency selective channel. Let $h(n)$ denote the base-band equivalent discrete-time channel impulse response of length ν. A carrier frequency offset of ϵ (normalized with subcarrier spacing) causes a phase rotation of $2\pi\epsilon n/N$. Assuming a perfect sampling clock, the received samples of the OFDM symbol are given by

$$y(n) = e^{j[(2\pi\epsilon n/N)+\epsilon_0]} \sum_{l=0}^{\nu-1} h(l)x(n-l) + z(n), \tag{2}$$

where ϵ_0 is an initial arbitrary carrier phase and $z(n)$ is a zero mean symmetric complex white Gaussian noise with variance σ_z^2. $x(n-l)$ is the $(n-l)$-th transmitted sample in the time domain.

III. Robust Synchronization and Cell Search Scheme

We construct a procedure including coarse time and frequency synchronization, cell search, and fine time and frequency synchronization as illustrated in Figure 2. If the decoder fails several times by a wrong cell-ID or large synchronization errors, the synchronization will be refreshed. Similarly when the estimated cell is not confirmed after several iterations, which means that the cell were estimated falsely, the complete process is performed from the beginning. We now introduce the procedure of overall synchronization scheme step by step.

A. Coarse Time and Frequency Offset Estimation

For coarse synchronization, the primary preamble is used. The primary preamble excluding CP consists of two identical halves. Using the character of the primary preamble, we can obtain a coarse TO and FO jointly. Based on [9], the timing metric by using auto-correlation in the time domain is given by

$$M(k) = \frac{|P(k)|^2}{R^2(k)}, \tag{3}$$

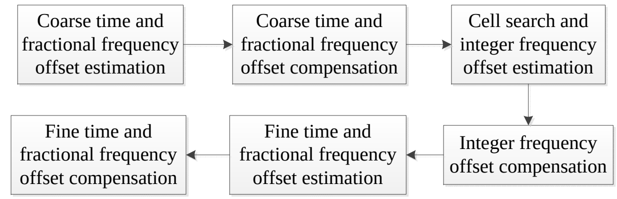

Figure 2. Proposed synchronization process

where $P(k)$ and $R(k)$ are

$$P(k) = \sum_{i=0}^{G+N/2-1} y(k+i)y^*(k+i+N/2), \tag{4}$$

$$R(k) = \frac{1}{2} \sum_{i=0}^{G+N-1} |y(k+i)|^2,$$

where $(\cdot)^*$ denotes the complex conjugate, $y(k)$ is the k-th sample of the base-band equivalent received signal, and $R(k)$ gives an estimate of the energy in $G+N$ samples of the received signal for the normalization. $N/2$ is chosen such that the angle of $P(k)$ lies in the range [-π,π] [10].

Then, we can obtain the estimated TO, τ_{coar}, and the estimated FO, ε_{coar}, from the metric $M(k)$ and $P(k)$, separately.

$$\tau_{coar} = arg \max_k M(k), \tag{5}$$

$$\varepsilon_{coar} = -\frac{1}{\pi} \angle(P(k)).$$

B. Cell search and integer FO estimation

The cell-ID can be jointly estimated with the integer FO. For the cell search, a simple method is to use a cross correlation between the received signal and the secondary preamble in the frequency domain. However, the algorithm based on the cross correlation between the reference signal and the received signal of the secondary preamble has performance degradation due to TO and FO mismatch between them. Therefore, we adopt a differential cross-correlation method that is robust to TO and FO over frequency selective channels and has the clear peak value at the estimated frame timing from the coarse synchronization.

For the integer FO estimation, we exploit the cyclic shifts of the secondary preamble sequence according to the cell-ID. The quantity of integer FO can be estimated by the subcarrier cyclic shift value maximizing the metric. This is described as follows:

$$C(k,i) = \frac{W(k,i)}{V(k,i)}, \tag{6}$$

where

$$W(k,i) = \sum_{k=0}^{N_l-D-1} \alpha_{k+D}\alpha_k^*\beta_{k+D,i}^*\beta_{k,i}, \quad (7)$$

$$V(k,i) = \frac{1}{4\eta}\sum_{k=0}^{N_l-D-1} |\alpha_{k+D}|^2 + |\alpha_k|^2 + \eta|\beta_{k+D,i}|^2 + \eta|\beta_{k,i}|^2, \quad (8)$$

$\alpha_k = Y(L_c(k))$, α_{k+D}=$Y(L_c\ (k+D))$, $\beta_{k,i}$=$S((L_c(k)+i)modN)$, and $\beta_{k+D,i}$=$S((L_c(k+D)+i)modN)$. η is $\frac{1}{N_l}\sum_{k=0}^{N_l-D-1} Y(L_c(k))$ which is the normalization factor. $Y(\cdot)$ is the received signal and $S(\cdot)$ is the reference signal, and $L_c(\cdot)$ is a pilot subcarrier index allocated in the frequency domain. D is the coefficient for the differential cross-correlation and set to 1 in this paper.

Then, we can obtain the estimated cell-ID, κ, and the estimated integer FO, ξ, from the metric $C(k,i)$.

$$\kappa = arg\max_k C(k,i), \quad (9)$$
$$\xi = arg\max_i C(k,i).$$

The magnitude $|C(k,i)|$ is expected to show a centrally located high peak over threshold when the cell-ID was correctly estimated. In the opposite case, if a correlation will be performed between two unequal reference sequences or between a reference sequence and received signal, then $|C(k,i)|$ will not show a significant peak and the estimated cell-ID shall be considered as false.

C. Fine Time and Frequency Offset Estimation

After performing the coarse time synchronization scheme, the estimated time is moved earlier by a few samples. This means that the FFT starting point is located within CP, and then makes to avoid ISI. The conventional method applied to fine time synchronization calculates a cross correlation value generated by producing the received signal and local samples with known long training symbols. However, the multipath channel introduces inter-path interference (IPI) into the received signal which can not be removed by the correlation based method in the conventional time offset estimation. Thus, we propose a new fine time and frequency synchronization scheme by using the secondary preamble.

Assuming a candidate of FO as ϵ in the fixed point, we can calculate $j(n)$ from the received signal $y(n)$ as follows:

$$j(n) = e^{-2\pi\epsilon n}y(n). \quad (10)$$

For a sake of simplicity, **j** is a vector of $j(\cdot)$ in the time domain and **S** is a vector of the reference signal $S(\cdot)$ in the frequency domain.

$$\mathbf{J} = FFT(\mathbf{j}). \quad (11)$$

Then,

$$\begin{aligned}\mathbf{h} &= IFFT(\mathbf{J}\cdot\mathbf{S}^*), \quad (12)\\ &= \frac{1}{N}\sum_{k=0}^{N-1} Y(k)S^*(k)e^{j2\pi kn/N}\\ &= \frac{1}{N}\sum_{k=0}^{N-1} X(k)H(k)e^{j2\pi k\delta/N}S^*(k)e^{j2\pi kn/N}\\ &= \frac{1}{N}\sum_{k=0}^{N-1} H(k)e^{j2\pi k(n+\delta)/N}\\ &= h(n+\delta)\end{aligned}$$

where $X(k)S^*(k)$=1 in the case of the corrected cell-ID estimation and the **h** is the channel impulse response vector. Then, we can jointly obtain the estimated TO, τ_{fine}, and the estimated FO, ε_{fine}, from the final metric, $h^{'}(\cdot)$.

$$\tau_{fine} = \max_k h^{'}(k,\epsilon), \quad (13)$$
$$\varepsilon_{fine} = arg\max_\epsilon h^{'}(k,\epsilon),$$

where

$$h^{'}(k,\epsilon) = \sum_{k=0}^{H-1} h(k,\epsilon). \quad (14)$$

Here, $h^{'}(\cdot)$ is calculated by a summation of the first metric $h(\cdot)$ with length H in order to improve the performance of the peak value in the multi-path fading channel.

IV. Simulation Results

Several simulations are carried out to evaluate the performance of the proposed synchronization method. The main parameters for an OFDMA system are chosen as follows: The number of subcarriers is 2048 and the nominal channel bandwidth is 20MHz, and the carrier frequency is 2.4GHz. The used channel is Veh-A of ITU-R of which the relative delay and the average power are [0;310;710;1090;1730;2510](ns) and [0;-1;-9;-10;-15;-20](dB), respectively [11].

The performance achieved by the proposed estimator is evaluated in terms of the mean squared error(MSE) according to signal-to-noise ratio(SNR), $E[|H(k)S(k)|^2/|Z(k)|^2]$. It is computed as

$$MSE(\hat{\theta}) = E[|\hat{\theta}-\theta|^2], \quad (15)$$

where $E[\cdot]$ denotes the expectation and $\hat{\theta}$ is an estimated value with respect to θ.

Figures 3 and 4 depict the MSE curve when the time offset by propagation delay is 500μs and the normalized frequency offset is 1.01. We can see that the proposed algorithm works robustly for a high delay spread fading channel in the presence of both Doppler spread and an initial frequency offset.

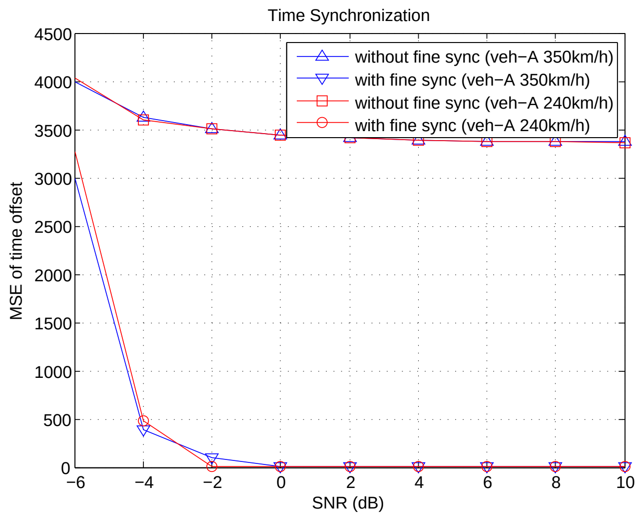

Figure 3. Mean Squared Error of time synchronization

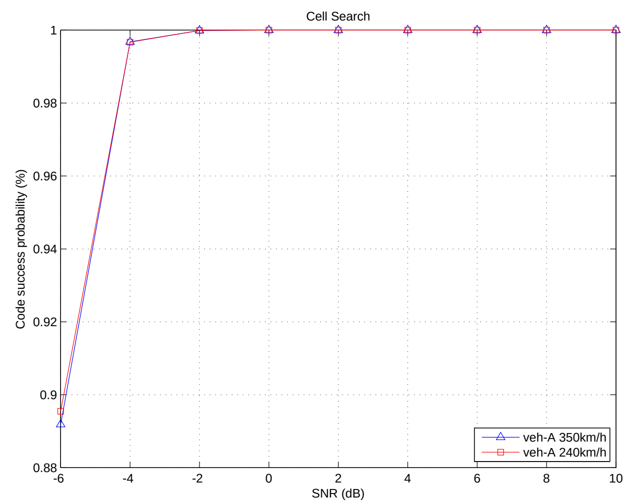

Figure 5. Success probability of cell search

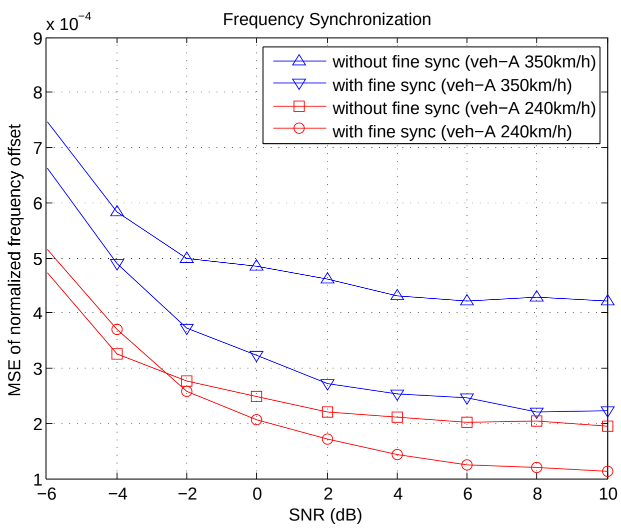

Figure 4. Mean Squared Error of frequency synchronization

Figure 5 shows the code detection probability for cell search. It provides the reliable cell search ability without additional reference signal by the result of time synchronization. Furthermore, the simulation results show that the performance of the proposed estimator is tolerant to the variation in the mobility of a user.

V. Conclusion

In this paper, a novel preamble-based synchronization and cell-search technique for OFDMA cellular systems was proposed. The preamble is composed of the primary and the secondary preamble. With the primary preamble, the initial coarse time and frequency offset estimation are performed. With the secondary preamble, the cell-search algorithm is proceeded in a hierarchical manner, the integer frequency offset estimation and the cell-ID sequence estimation. The fine time and frequency offset estimation is also performed with the secondary preamble. The overall performance of the synchronization and cell search was analyzed in terms of MSE in time and frequency-selective fading channels. Therefore, we conclude that the proposed algorithm provides the robust synchronization and cell-search capability, even in bad cellular environments.

Acknowledgment

This research was supported by the KCC (Korea Communications Commission), Korea, under the R&D program supervised by the KCA (Korea Communications Agency) (KCA 10-911-04-003)

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