Progress In Electromagnetics Research B, Vol. 7, 1–12, 2008

PARAMETER ESTIMATION AND ERROR REDUCTION IN MULTICARRIER SYSTEMS BY TIME-DOMAIN SPREADING

E.-S. Shim and Y.-H. You

School of Computer Engineering
uT Communication Research Center
Sejong University
98 Kunja-Dong, Kwangjin-Ku, Seoul 143-747, Korea

Abstract—This paper suggests parameter estimation and error reduction scheme in a multicarrier transmission system. A multicarrier orthogonal frequency division multiplexing (OFDM) signal by using a time-domain spreading (TDS) coupled with a cyclic time shift enables a pilot-less synchronization. Exploiting the modified OFDM signal endowed with the TDS, the proposed synchronization receiver can accurately estimate the carrier-frequency offset as well as the timing offset of OFDM signals without the use of training symbol.

1. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) has been chosen for several broadband wireless local area network (LAN) standards like IEEE802.11a and European HIPERLAN/2, and personal area network standards like ultra-wideband (UWB) WiMedia [1, 2]. Many studies have been performed to improve the efficiency of components and transceivers in OFDM-based wireless systems. However, it is commonly known that OFDM systems are very sensitive to synchronization errors, which cause inter-channel interference (ICI) and inter-symbol interference (ISI) when the fast Fourier transform (FFT) window timing is not provided within the ISI-free part of the guard interval [3]. Also, frequency offset that is caused by doppler shift or misalignment between frequency oscillators exists causing ICI which leading the system performance deteriorating drastically [4].

Most frequency and timing estimation methods use periodic nature of the time-domain signal by using a cyclic prefix (CP) [5–7], or by designing the training symbol having repeated parts [8–11].

Schemes proposed in [5–7] can estimate the frequency offset by using CP without using training sequences and hence requires no additional bandwidth, but the performance of the estimator depends on the length of CP and its estimation range does not exceed half the subcarrier spacing [6]. The Schmidl's synchronization method uses a preamble containing the two same halves. This method gives simple and robust estimates for symbol timing and carrier frequency offset [10]. However, the timing metric of Schmidl's method has a plateau, which causes large variance of the timing estimate. To reduce the uncertainty due to the timing metric, Minn proposed a method as modification to Schmidl's [11]. The result of Minn's preamble gives more sharp timing metric and smaller variance than Schmidl's.

This paper deals with a pilot-less timing and frequency synchronization methods for OFDM systems in a multipath fading channel. To do this, we provide a modified OFDM system using a time-domain spreading (TDS) coupled with a cyclic time shift. In particular, we devise or select algorithms for the sequential estimation of symbol timing, and carrier frequency offset, which can provide benefit to the overall system performance. The proposed synchronization receiver is based on correlation methods that exploit repeated information-bearing OFDM symbols, thus removing the need of training symbols.

This paper is organized as follows. Next section suggests the OFDM system based on TDS. Section 3 deals with the pilot-less timing and frequency offset synchronization scheme. In Section 4, we then present simulation results illustrating the synchronization performance, and we conclude this paper with Section 5, which summarizes the main results.

2. OFDM SYSTEM WITH TIME-DOMAIN SPREADING

In order to remove the use of training sequences, some modifications on the conventional OFDM system are highlighted at the transmitting and receiving sides. In this section, OFDM system employing N subcarrier and a cyclic prefix (CP) of length N_g is considered.

2.1. Transmitter

For the notational convenience, we express information-bearing OFDM symbol vector during $(2l+m)$-th period to be composed of (N/N_g+1) N_g-dimensional vectors denoted by $\mathbf{x}_{2l+m}(i)$ for $i = 0, 1, \ldots, N/N_g$

and is thus given by

$$\hat{\mathbf{x}}_{2l+m} = [\underbrace{\mathbf{x}_{2l+m}(0)}_{\text{CP}} \; \underbrace{\mathbf{x}_{2l+m}(1)\ \mathbf{x}_{2l+m}(2) \cdots \mathbf{x}_{2l+m}(N/N_g)}_{\mathbf{x}_{2l+m}}] \tag{1}$$

where $\mathbf{x}_{2l+m}(0)$ denotes a vector of CP for $m = 0, 1$ and becomes $\mathbf{x}_{2l+m}(0) = \mathbf{x}_{2l+m}(N/N_g)$.

In our approach, $\mathbf{x}_{2l+1}$ is designed to be the $(N+N_g)$-th (or $-N_g$-th) cyclic-shifted version of $\mathbf{x}_{2l}$. Then, each component of the $(2l+1)$-th OFDM data symbol $\mathbf{x}_{2l+1}$ can be easily formulated from the $2l$-th frequency-domain OFDM symbol $X_{2l}(k)$ including information data and pilot symbol and reads

$$x_{2l+1}(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_{2l}(k) e^{j2\pi k(n+N_g)/N} \tag{2}$$

where we can find

$$X_{2l+1}(k) = X_{2l}(k) e^{j2\pi k N_g/N}. \tag{3}$$

From Eqns. (2) and (3), $\hat{\mathbf{x}}_{2l+1}$ can be expressed as

$$\hat{\mathbf{x}}_{2l+1} = [\underbrace{\mathbf{x}_{2l}(1)}_{\text{CP}} \; \underbrace{\mathbf{x}_{2l}(2)\ \mathbf{x}_{2l}(3) \cdots \mathbf{x}_{2l}(N/N_g)\ \mathbf{x}_{2l}(1)}_{\mathbf{x}_{2l+1}}]. \tag{4}$$

Using this formulation, the CP of $\hat{\mathbf{x}}_{2l+1}$ can be viewed as a cyclic suffix (CS) of $\hat{\mathbf{x}}_{2l}$.

2.2. Receiver

At the receiver, the useful part of the received signal including CP is given by

$$y_{2l+m}(n) = \sum_{i=0}^{L} h(i) x_{2l+m}(n-i-\tau) e^{j2\pi(n+m\cdot N_e)\Delta/N} + w_{2l+m}(n) \tag{5}$$

where $N_e = N + N_g$, $h(i)$ denotes the channel impulse response with maximum delay spread L, τ is the integer-valued unknown arrival time of symbol, Δ is the frequency offset normalized by carrier spacing, and $w_{2l+m}(n)$ is the samples of zero-mean complex AWGN during $(2l+m)$-th period. Frequency offset Δ is divided into two parts, i.e., $\Delta = \Delta_i + \Delta_f$ with $\Delta_i = \text{int}(\Delta)$ and $\Delta_f \in [-1/2, 1/2)$.

Let the sample indexes of a perfectly synchronized OFDM symbol be $\{-N_g, -N_g+1, \ldots, -1, 0, 1, \ldots, N-1\}$, the timing offset be τ, and the maximum channel delay spread be ϵ_{max}, where N_g is the length of the CP. Then, if $\tau \in \{-N_g+\epsilon_{max}, -N_g+\epsilon_{max}+1, -N_g+\epsilon_{max}+2 \ldots 0\}$, the orthogonality among the subcarriers will not be destroyed and the timing offset will only introduce a phase rotation in every subcarrier symbol. When the timing estimate falls outside the ISI-free part of the GI in ordinary OFDM systems, interference will be introduced [3]. This is still true for the proposed system when $-N_g \leq \tau \leq -N_g+\epsilon_{\max}$. When $\tau > 0$, on the other hand, since $x_{2l+1}(n)$ is designed to be the N_e-th cyclic-shifted version of $x_{2l}(n)$ at the proposed OFDM transmitter, the received FFT output can be given by

$$\begin{aligned} Y_{2l}(k) &= \frac{1}{\sqrt{N}} \sum_{p=0}^{N-1-\tau} y_{2l}(p+\tau) e^{-j2\pi pk/N} \\ &\quad + \frac{1}{\sqrt{N}} \sum_{p=N-\tau}^{N-1} y_{2l+1}(p+\tau-N_e) e^{-j2\pi pk/N} \\ &= \frac{1}{\sqrt{N}} \sum_{p=0}^{N-1} y_{2l}(p+\tau) e^{-j2\pi pk/N} \end{aligned} \tag{6}$$

which means that the orthogonality among the subcarriers will not be destroyed in the proposed OFDM system.

For demodulating the $(2l+1)$-th OFDM symbol to combine two repeated symbols, additionally, we can use a pre-advancement of FFT windowing with a length of $N_a = N_g$ thanks to two-symbol repetition coupled with a cyclic time shifting. With this provision, the right-most term of $\hat{\mathbf{x}}_{2l+1}$ denoted by $\mathbf{x}_{2l}(1)$ is regarded as CS of $\hat{\mathbf{x}}_{2l+1}$. Even if the start position of the FFT window is out of GI interval, the orthogonality among the subcarriers will not be destroyed and the only effect suffered by the subchannel symbols is a change in phase provided that a positive timing error is less than the length of CP. So, the interference-free region of the FFT window over two consecutive OFDM symbols is given by

$$\Xi = \{-N_g + \epsilon_{max}, -N_g + \epsilon_{max} + 1, \ldots 0, 1, \ldots, N_g\}. \tag{7}$$

With this provision, we can expect that the proposed OFDM system does not suffer from timing-error-induced interference even when $0 < \tau \leq N_g$.

3. PILOT-LESS PARAMETER SYNCHRONIZATION

In this section, we introduce suitable synchronization techniques for the proposed OFDM system. Synchronization proceeds generally in the following manner: initial timing, fractional frequency offset (FFO) estimation, integer frequency offset (IFO) estimation, and fine symbol timing.

3.1. Estimation of Timing Offset

The proposed estimation method is based on Minn's sliding window method [11] and uses the correlation between the two consecutive received information-bearing OFDM signals $y_{2l}(n)$ and $y_{2l+1}(n)$. To avoid timing metric plateau, two correlation windows of length N_g samples are separated by $2N$ samples. So, $2N$ is the distance between the periodic portion of length N_g introduced by two-symbol repetition coupled with the cyclic time shift.

In our work, the correlation function denoted by $P_A(d)$ and the received energy denoted by $R_A(d)$ are respectively computed as

$$P_A(d) = \sum_{i=0}^{N_g-1} y_{2l}(d+i) \cdot y^*_{2l+1}(d+i+N-N_g) \tag{8}$$

and

$$R_A(d) = \frac{1}{2} \sum_{m=0}^{1} \sum_{i=0}^{N_g-1} |y_{2l+m}(d+i+m(N-N_g))|^2. \tag{9}$$

The timing metric function is defined as

$$M_A(d) = \frac{1}{N_g+1} \sum_{k=-N_g}^{0} \frac{|P_A(d+k)|^2}{(R_A(d+k))^2}. \tag{10}$$

The complexity of the proposed method in Eqns. (8)–(10) is between those of Minn's sliding window method and Minn's training symbol method [11], which will be validated in the following section, if a sliding window of length $N_g = N/4$ is used. Here, we propose another low-complexity method, which is quite similar to Schmidl's method [10]. In this case, two windows of length $2N_g$ samples are separated by $2N$ samples. With this provision, we define $P_B(d)$ and $R_B(d)$ as follows

$$P_B(d) = \sum_{i=-N_g}^{N_g-1} y_{2l}(d+i) \cdot y^*_{2l+1}(d+i+N-N_g) \tag{11}$$

and

$$R_B(d) = \sum_{i=-N_g}^{N_g-1} |y_{2l}(d+i)|^2. \qquad (12)$$

Plugging Eqns. (11)–(12) into $|P_B(d)|^2/(R_B(d))^2$ yields a timing metric for this approach.

3.2. Estimation of Fractional Frequency Offset

The estimation of the fractional part has been investigated in [7–10]; many of the techniques do not require the knowledge of the integer part of the carrier frequency offset. Considering the structure of the proposed OFDM signal, estimation of FFO is achieved by calculating the phase difference between two consecutive OFDM signals. Using the proposed timing metric, symbol timing offset $\hat{d}$ is estimated. Then, the FFO estimator is obtained from the argument of a correlation result as follows

$$\hat{\Delta}_f = \frac{1}{2\pi} \arg\left\{P_{\Delta_f}(\hat{d})\right\} \qquad (13)$$

where

$$P_{\Delta_f}\left(\hat{d}\right) = \sum_{i=0}^{N-1} y_{2l}\left(\hat{d}+i\right) y_{2l+1}^{*}\left(\hat{d}+i-N_g\right). \qquad (14)$$

The proposed FFO estimation method is quite similar to Schmidl's estimation method, which uses a training symbol containing two identical halves and results in a frequency acquisition range of ± 1 subcarrier spacing [10]. On the other hand, since the distance of the repeated signal parts is N as shown in Eqn. (14), which in turn allows a reduced-variance frequency offset estimation, a maximum frequency acquisition range of the proposed estimator is only $\pm 1/2$ subcarrier spacing as like Moose's methods [5]. Therefore, the estimate suffers from the subcarrier ambiguity when $|\Delta_f| > 0.5$.

3.3. Estimation of Integer Frequency Offset

The problem of subcarrier ambiguity for $|\Delta_f| > 0.5$ can be solved by using a pre-advancement of FFT windowing with a length of $N_a < N_g$ at the $(2l+1)$-th OFDM symbol. It is assumed that the symbol timing is known, and that the FFO is estimated and corrected. The retrieved blocks of two consecutive OFDM symbols at the receiver are in the forms of

$$Y_{2l}(k) = H_{2l}(k-\Delta_i)X_{2l}(k-\Delta_i) + Z_{2l}(k) \tag{15}$$

and

$$\begin{aligned} Y_{2l+1}(k) &= e^{j2\pi\Delta_i N_g/N} e^{-j2\pi(k-\Delta_i)(N_a-N_g)/N} H_{2l+1}(k-\Delta_i) \\ &\quad \cdot X_{2l+1}(k-\Delta_i) + Z_{2l+1}(k) \end{aligned} \tag{16}$$

where $H_{2l+m}(k)$ is the channel's frequency response and $Z_{2l+m}(k)$ is a zero-mean complex Gaussian noise term.

In an analogy to Morelli and Mengali estimator (MME) developed in [12], the likelihood function has the form of

$$\Lambda(p) = \sum_{k\in\mathcal{S}_c} Y_{2l}^*(k+p)Y_{2l+1}(k+p)e(p,k) \tag{17}$$

with

$$e(p,k) = e^{-j2\pi p N_g/N} e^{-j2\pi(k-p)N_g/N} \tag{18}$$

where a notation of p denotes a trial value of Δ_i and $\mathcal{S}_c$ is the set of subcarrier indices used for correlation. In this paper, let the number of elements in $\mathcal{S}_c$ be N_c and the correlation is done over N_c subcarriers spaced at a distance $\lfloor N/N_c \rfloor$ form each other, when $\lfloor x \rfloor =$ first integer $< x$.

For a simple description, we assume that $H_{2l}(k) = H_{2l+1}(k)$ and SNR $\rightarrow \infty$. Recalling from Eqn. (3) that $X_{2l+1}(k) = X_{2l}(k)e^{j2\pi k N_g/N}$, $\Lambda(p)$ takes form

$$\Lambda(p) = e^{-j2\pi(p-\Delta_i)(N_g-N_a)/N} \sum_{k\in\mathcal{S}_c} |\mathcal{X}_{2l}(k+p-\Delta_i)|^2 \tag{19}$$

where $\mathcal{X}_{2l}(k+p-\Delta_i) = X_{2l}(k+p-\Delta_i)H_{2l}(k+p-\Delta_i)$. The argument of Eqn. (19) is given by

$$\arg\{\Lambda(p)\} = \frac{2\pi}{K}(p-\Delta_i) \tag{20}$$

where $K = N/(N_g - N_a)$ and the argument becomes zero when $p = \Delta_i$ because this term has only real term.

With this provision, the proposed IFO estimator becomes

$$\hat{\Delta}_i = \min_{|p|\leq M} \{|\arg\{\Lambda(p)\}|\} \tag{21}$$

where M denotes the largest expected value of $|p|$ depending on the frequency stability of the transmitter and receiver oscillators. In pilot-aided IFO estimators discussed in [10, 12], its estimation range for frequency ambiguity is not limited, while estimation range of our approach depends on the parameters N_a and N_g because a complex plane is divided into K regions as shown in Eq. (20). So, our frequency estimation range is limited by $M = K/2 - 1$, which is due to the fact that the pattern of phase rotation is repeated every $K/2$ subcarrier.

4. SIMULATION RESULTS AND DISCUSSIONS

In this section, to verify the effectiveness of the proposed estimators, OFDM system with $N = 128$ and $N_g = N/4$ is considered. Here, we assume that the channel has an exponentially decaying power-delay intensity profile with $L = 32$ paths.

Figure 1 presents the bit error rate (BER) performance of both ordinary system and proposed systems when the values of SNR are 15 and 25 dB, respectively. In this example, we assume perfect channel equalization. When $\tau < 0$, the proposed OFDM system with 16-QAM and the ordinary OFDM system with QPSK show a same BER performance without decreasing transmission efficiency. On the other hand, the proposed system shows a better performance rather than the ordinary OFDM system when $0 < \tau \leq N_g$ with the aid of cyclic shifting.

Figure 2 shows the means and variances for the timing synchronization receivers. Here, we assume that frequency offset $\Delta = 0.2$. The performance of the timing estimators has been investigated by computer simulation for four cases: 1) Schmidl's method with 90% maximum points averaging [10], 2) Minn's sliding window method (Minn A) [11], 3) Minn's training symbol method (Minn B) [11], 4) proposed method A with Eqn. (8), and 5) proposed method B with Eqn. (11). We can see that the mean value of Schmidl's method is shifted to CP range, while the mean of other methods is at roughly the correct timing point. The mean square error (MSE) of the proposed method B is lower than that of Schmidl's and Minn B methods with approximately same complexity because $N_g = N/4$ is used. When compared to Minn's algorithms, the proposed method A gives a better or equivalent MSE performance without the need of training symbols.

Figure 3 depicts the MSE of FFO estimator. In this example, we assume perfect timing synchronization and $|\Delta_f| < 0.5$. We can see that the proposed FFO estimator gives very accurate estimation of frequency offset compared to Schmidl's estimator [10] without any training sequence.

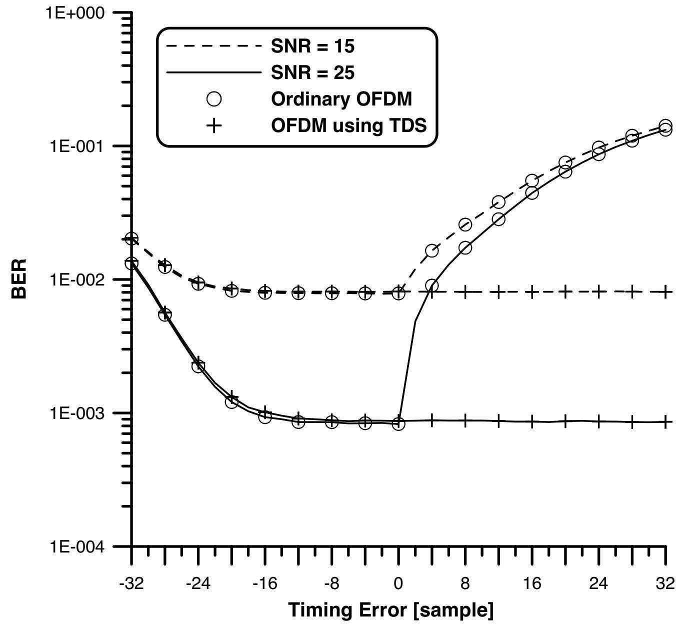

Figure 1. BER performance of both ordinary and proposed OFDM systems versus timing error.

Figure 4 illustrates the probability of failure, $\Pr\left\{\hat{\Delta}_i \neq \Delta_i\right\}$ of IFO estimators. In this example, the estimation range of the proposed IFO estimator is limited by $M = 3$ and $M = 7$ when $N_a = 16$ and $N_a = 24$, respectively, and the same range is applied to MME. As can be seen from the figure, the proposed method has smaller probability of error estimation than MME regardless of value of N_a. If the allowable frequency tolerance of the system is relatively small, the proposed estimator is designed to have more improved performance when $N_a = 16$. Since the number of possible phases introduced by both cyclic time shift and length of CP is reduced by factor-of-two against $N_a = 24$, which is analogous to reduction of the range M, further performance improvement over the MME is observed at the sacrifice of estimation range (i.e., $|p| \leq 3$). Considering trade-offs between the performance accuracy and estimation range depending on the system parameters N and N_g, the design parameter N_a should be carefully chosen.

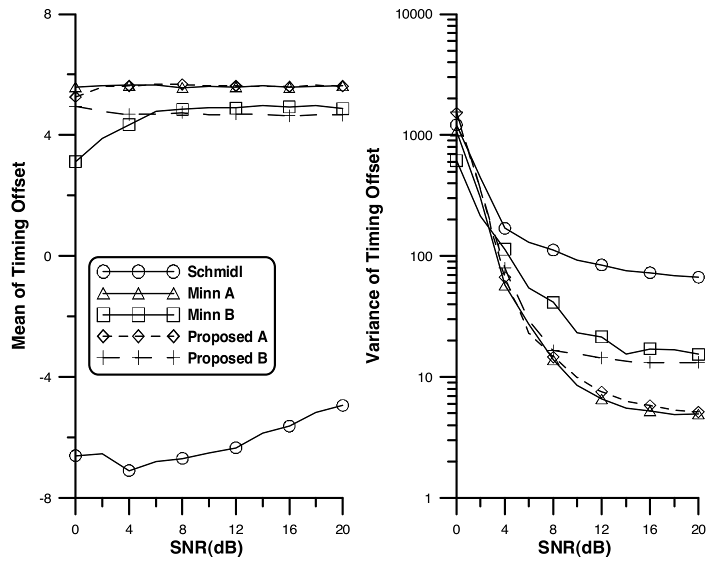

Figure 2. Mean and MSE of timing estimators.

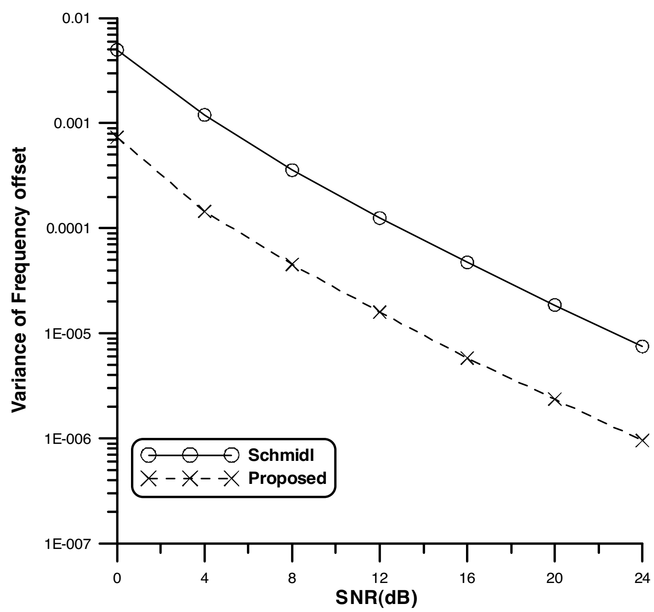

Figure 3. MSE of FFO estimators.

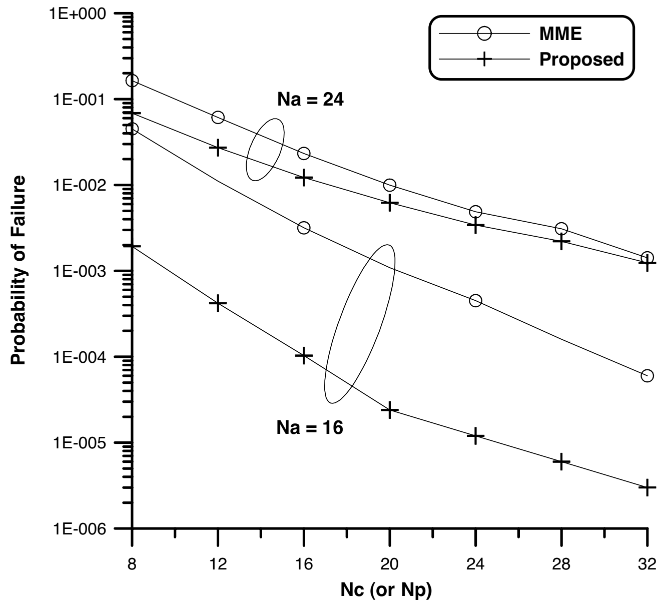

Figure 4. Probability of failure of IFO estimators (SNR = 4 dB).

5. CONCLUSION

In order to resolve the time and frequency uncertainty in multicarrier transmission systems, a synchronization receiver which do not require the transmission of training symbols has been suggested in this paper. From the simulation results, it was observed that the proposed synchronization receiver gives very accurate estimates of the time and frequency error without additional training sequence. In addition, the proposed OFDM system provides a robustness against a positive OFDM timing error provided that it is less than the length of the CP.

ACKNOWLEDGMENT

This research is supported by the Ubiquitous Computing and Network (UCN) Project, the Ministry of Information and Communication (MIC) 21st Century Frontier R&D Program in Korea, and this research is supported by Seoul R&BD Program.

REFERENCES

1. Doufexi, A., S. Armour, M. Butler, A. Nix, D. Bull, J. McGeehan, and P. Karlsson, "A comparison of the HIPERLAN/2 and IEEE802.11a wireless LAN standards," *IEEE Commun. Mag.*, Vol. 40, No. 5, 172–180, May 2002.
2. ECMA International, Standard ECMA-368, "High rate ultra wideband PHY and MAC standard," December 2005.
3. Speth, M., F. Classen, and H. Meyr, "Frame synchronization of OFDM systems in frequency selective fading channels," *Proc. of VTC'97*, 1807–1811, May 1997.
4. Pollet, T., "The BER performamce of OFDM systems using nonsynchronized sampling," *Proc. of GLOBCOM'94*, 253–257, 1994.
5. Moose, P., "A technique for orthogonal frequency division multiplexing frequency offset correcting," *IEEE Trans. Commun.*, Vol. 42, 2908–2914, October l994.
6. Van de Beek, J.-J., M. Sandell, and P. O. Borjesson, "ML estimation of time and frequency offset in OFDM systems," *IEEE Trans. Signal Processing*, Vol. 45, 1800–1805, July 1997.
7. Hsieh, M. and C. Wei, "A low-complexity frame synchronization and frequency offset compensation scheme for OFDM systems over fading channels," *IEEE Trans. vehicular Technology*, Vol. 48, No. 5, September 1999.
8. Tanda, M., "Blind symbol-timing and frequency-offset estimation in OFDM systems with real data symbols," *IEEE Trans. Commun.*, Vol. 52, 1609–1612, October 2004.
9. Zhang, Z., K. Long, and Y. Liu, "Complex efficient carrier frequency offset estimation algorithm in OFDM systems," *IEEE Trans. Broadcasting*, Vol. 52, No. 2, 1609–1612, June 2004.
10. Schmidl, T. M. and D. C. Cox, "Robust frequency and timing synchronization for OFDM," *IEEE Trans. Comm.*, Vol. 45, 1613–1621, December 1997.
11. Minn, H., M. Zeng, and V. K. Bhargava, "On timing offset estimation for OFDM systems," *IEEE Communication Letters*, Vol. 4, 242–244, July 2000.
12. Morelli, M., A. N. Andrea, and U. Mengali, "Frequency ambiguity resolution in OFDM systems," *IEEE Communication Letters*, Vol. 4, 134–136, July 2000.