Progress In Electromagnetics Research, PIER 82, 65–75, 2008

PILOT-FREE FREQUENCY TRACKING METHOD FOR ULTRA-WIDEBAND RECEIVERS

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Abstract—This paper suggests a pilot-free frequency tracking scheme for ultra-wideband orthogonal frequency-division multiplexing (UWB-OFDM) receivers. The proposed scheme uses a frequency-domain spreaded data symbols which is provided in the current UWB-OFDM system. Based on this property, we develop an improved frequency synchronization receiver without the use of pilot symbols. The simulation results indicate that the proposed scheme achieves much better performance than the conventional pilot-based schemes.

1. INTRODUCTION

Nowadays, ultra-wideband (UWB) technology which operates in an overlayed bandwidth, 3.1 GHz$\sim$10.6 GHz, has been considered as a promising technology for fulfilling the requirements for low cost and high-speed radio networks. UWB technology is providing data rate of 110 Mbps at a distance of 10 m and 480 Mbps at a distance of 2 m, but even higher data rates are coming. A traditional UWB technology is based on single-band systems employing carrier-free communications [1–4]. Recently, orthogonal frequency-division multiplexing based UWB (UWB-OFDM) schemes were proposed in [5–7], in which the UWB frequency band is divided into several subbands. In several previous publications [8–14], many researches have been performed to implement UWB components and transceivers.

In the UWB-OFDM system, the high frequency bands as well as the application of OFDM technology demand highly accurate frequency error estimation since frequency error causes a loss of orthogonality among the subcarriers which introduces inter-carrier interference (ICI) and significantly degrades the system performance [7–9]. Even though the UWB-OFDM system compensates the carrier frequency offset (CFO) by using packet/frame synchronization (PS) sequences [17], there still remains a small CFO because of the estimation error. The residual CFO can also cause ICI and signal constellation rotation due to its time-variant behavior. So it must be accurately tracked and compensated, otherwise it would lead to decision errors. There are various algorithms of CFO tracking for OFDM systems [10–13], however it is insufficient for the UWB-OFDM system since OFDM symbols are transmitted in different bands.

This paper suggests an improved frequency tracking scheme which exploits non-zero data symbols equipped with frequency-domain spreading (FDS) in the UWB-OFDM system. It is found by simulation that the UWB-OFDM system is shown to contain sufficient information to synchronize a system without the use of pilot symbols. Moreover, the throughput of the system is increased since we save the pilots for synchronization.

This paper is organized as follows: Section 2 describes the signal model for the UWB-OFDM system. Section 3 briefly addresses the conventional pilot-aided frequency tracking methods. In Sections 4, an improved frequency synchronization algorithm without the use of pilot signals is suggested for UWB-OFDM. In Section 5, we then present simulation results verifying the performance of the frequency tracking schemes. Finally, the concluding remarks are given in Section 6.

2. SYSTEM MODEL

In the UWB-OFDM system, N complex symbols are modulated onto N sub-carriers by using the inverse fast Fourier transform (IFFT) on the transmitter side and N_{zp} samples are zero-padded to form a guard interval. The transmitted baseband signal for the n-th sample of the l-th OFDM symbol can be simply expressed as

$$x_l(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_l(k) e^{j2\pi nk/N} \tag{1}$$

where $X_l(k)$ is the non-zero symbol transmitted on the k-th subcarrier. Then, the useful part of the received signal is given by

$$y_l(n) = \sum_{i \geq 0} h(i) x_l(n - i - \epsilon) e^{j2\pi n \Delta_f / N} + w_l(n) \tag{2}$$

with

$$h(t) = G \sum_{m \geq 0} \sum_{n \geq 0} \beta_{m,n} \delta(t - T_m - \tau_{m,n}) \tag{3}$$

where G is the lognormal shadowing term, the real-valued channel gain is defined by $\beta_{m,n}$ for cluster m and ray n, ϵ is the integer-valued unknown arrival time of symbol, Δ_f is the CFO normalized by carrier spacing, and $w_l(n)$ is the samples of zero-mean complex additive white Gaussian noise (AWGN). In Eqn. (3), the m-th cluster arrives at T_m and its n-th ray arrives at $\tau_{m,n}$ relative to the first path in cluster m.

In this paper, we assume that the symbol timing error ϵ is perfectly compensated and the estimate of CFO $\hat{\Delta}_f$ is obtained by using PS sequence [5]. Then, the received symbol after FFT demodulation in the presence of small residual CFO Δ_r can be approximated by [21, 22]

$$Y_l(k) \approx GH(k)X_l(k)e^{j2\pi\Delta_r lN_sT} + W_l(k) \tag{4}$$

where T is the sampling clock period, $N_s = N + N_{zp}$, $H(k)$ is the channel's frequency response with zero-mean and variance σ_H^2 incorporating the time-invariant phase term during the l-th symbol period, $W_l(k)$ is a zero-mean complex Gaussian noise term with variance σ_W^2, and $\Delta_r = \hat{\Delta}_f - \Delta_f$. In Eqn. (4), $GH(k)$ is independent of symbol index l because the channel remains same during the whole packet transmission time in the UWB channel model and log-normal shadowing is modeled with $G = 10^{g/20}$ where g has a normal distribution with zero mean and standard deviation $\sigma_g = 3$ [23].

3. CONVENTIONAL PILOT-AIDED FREQUENCY TRACKING ALGORITHM

The aim of frequency tracking method is to estimate Δ_r and small CFO remains in tracking mode. In this paper, we introduce two conventional frequency tracking algorithms. The first method is a conventional estimator developed in [18]. The second method can be viewed as an extension of the method discussed in [19].

3.1. Method 1

This method tracks the CFO by comparing the phase rotation of the current symbol with the next D symbol that delays D-symbol interval. If we observe L consecutive pilot symbols, the estimation of the CFO can be written as [18]

$$\hat{\Delta}_r = \frac{1}{2\pi N_sTN_pDL}\sum_{l=D+1}^{L+D}\sum_{i=1}^{N_p}[\arg\{\varphi_l(k_i)\} - \arg\{\varphi_{l-D}(k_i)\}] \tag{5}$$

with

$$\begin{aligned}\varphi_l(k_i) &= Y_l(k_i)\hat{C}^*(k_i)X_l^*(k_i)\\ &= |C(k_i)|^2 E_s e^{j2\pi\Delta_r l N_s T} + C(k_i)E_s\alpha(k_i)e^{j2\pi\Delta_r l N_s T}\\ &+ C^*(k_i)X_l^*(k_i)W_l(k_i) + \alpha(k_i)X_l^*(k_i)W_l(k_i)\end{aligned} \tag{6}$$

where N_p is the number of pilot subcarriers, $X_l(k_i)$ is the pilot symbol assigned to the k_i-th subcarrier, $E_s = |X_l(k_i)|^2$, $\hat{C}(k)$ is the estimate of $C(k) = GH(k)$ which can be estimated by using the channel estimation (CE) sequence provided in the UWB-OFDM, L is the number of averaging symbol, and $\alpha(k) = \hat{C}(k) - C(k)$ is the estimation error. As we can see in Eqn. (6), the UWB-OFDM system needs to estimate $C(k)$ because OFDM symbols may be transmitted in different sub-bands according to time-frequency codes (TFCs) [5]. In the UWB-OFDM system, $N_p = 12$ pilot symbols are put in subcarriers $\{k_1, \cdots, k_6, k_7, \cdots, k_{12}\} = \{-55, -45, \cdots, -5, 5, \cdots, 45, 55\}$ [5].

3.2. Method 2

To reduce complexity and symbol delay introduced in Method 1, we modify the method done in [19] to get robust estimation. This method estimates the CFO per each symbol by using pilot symbols, and averages out rotated phase for L symbols. By using Eqn. (6), the rotated phase of the l-th OFDM symbol is estimated by

$$\Omega_l = \frac{1}{2\pi N_s T l}\arg\left\{\sum_{i=1}^{N_p}\varphi_l(k_i)\right\}. \tag{7}$$

An estimate of Δ_r is now obtained by looking for the average of Ω_l over L consecutive pilot symbols, i.e.

$$\hat{\Delta}_r = \frac{1}{L}\sum_{l=1}^{L}\Omega_l. \tag{8}$$

4. PILOT-FREE FREQUENCY TRACKING ALGORITHM

4.1. Algorithm Description

To improve the estimation accuracy and save pilot symbols reserved for synchronization, a pilot-free frequency tracking method is suggested, which exploits a non-zero data symbol with a conjugate-symmetric property around DC in the UWB-OFDM system. The current UWB-OFDM system provide time domain diversity by time-domain spreading (TDS) and frequency domain diversity by FDS. Both FDS and TDS techniques shall be used when the data unit is encoded at a data rate of 53.3 or 80 Mbps.

At the receiver, an initial CFO estimation is done by using PS synchronization symbols, followed by the channel estimation. Then, the equalized signal in the l-th symbol is given by

$$\hat{Y}_l(k) = Y_l(k)\hat{C}^*(k). \tag{9}$$

Using the FDS property which is provided in the UWB-OFDM system, the proposed frequency tracking algorithm is based on post-FFT temporal correlation by using non-zero data symbols. Since $X_l(k) = X_l^*(N-k)$, it follows that

$$X_l(k)X_l(N-k) = |X_l(k)|^2 = |X_l(N-k)|^2, \quad 1 \le k \le N-1. \tag{10}$$

When we consider the non-zero signal samples excluding the guard subcarriers in the UWB-OFDM system, the temporal correlation is designed to has the form:

$$\phi_l(k) = \hat{Y}_l(k)\hat{Y}_l(N-k), \quad N_g/2+1 \le k \le (N-N_n)/2 \tag{11}$$

which is further derived by

$$\phi_l(k) = |G|^4|H(k)H(N-k)|^2 E_s e^{j4\pi\Delta_r lN_sT} + \mathcal{C}_l(k) + \mathcal{W}_l(k) \tag{12}$$

where N_n is the number of null subcarriers, N_g is the number of guard subcarriers, $\mathcal{W}_l(k)$ is the combined zero-mean AWGN term, and $\mathcal{C}_l(k)$ is the interference term introduced by channel estimation error $\alpha(k)$ given by

$$\begin{aligned}\mathcal{W}_l(k) = 2&\left\{|C(k)|^2C^*(N-k)W_l(N-k) + |C(N-k)|^2C^*(k)W_l(k)\right\}\\ &\cdot \mathrm{Re}\{X_l(k)\}e^{j2\pi\Delta_r lN_sT} + C^*(k)C^*(N-k)W_l(k)W_l(N-k)\end{aligned} \tag{13}$$

and

$$\begin{aligned}&\mathcal{C}_l(k)\\ &= Y_l(k)Y_l(N-k)\left[\alpha(k)C(N-k) + \alpha(N-k)C(k) + \alpha(k)\alpha(N-k)\right].\end{aligned} \tag{14}$$

Since $\mathrm{E}[\mathcal{W}_l(k)] = \mathrm{E}\left[\mathcal{C}_l(k)\right] = 0$, one can find that

$$\arg\left\{\mathrm{E}\left[\phi_l(k)\right]\right\} = 4\pi\Delta_r lN_sT \tag{15}$$

where $\mathrm{E}\{x\}$ is the mean of x. Consequently, the pilot-free estimator is expressed in a form identical to Eqn. (8) with Ω_l replaced by

$$\Omega_l = \frac{1}{4\pi N_s T l} \arg\left\{ \sum_{k=N_g/2+1}^{(N-N_n)/2} \phi_l(k) \right\}. \tag{16}$$

As we can see from Eqn. (16), since the pilot-free synchronizer uses $N_d = (N - N_n - N_g)/2$ non-zero data samples, we save the pilots for synchronization and the throughput of the system is increased.

4.2. Performance Analysis

In order to evaluate the estimation performance, we define a normalized interference-to-phase ratio (IPR) as $\mathrm{IPR} = P_I/D_r$, where D_r is the degree of phase rotation introduced by Δ_r and P_I is the normalized interference power by signal power defined by

$$P_I = \mathrm{Var}\left\{ \sum_k \phi_l(k) \right\} \Bigg/ \left| \mathrm{E}\left\{ \sum_k \phi_l(k) \right\} \right|^2 \tag{17}$$

where $\mathrm{Var}\{x\}$ denotes variance of x. From Eqns. (6) and (12), we can find that $D_r = 2\pi N_s T$ for Method 2 and $D_r = 4\pi N_s T$ for the pilot-free method. After some straight forward calculations, IPR for the conventional scheme becomes

$$\mathrm{IPR} = \frac{\mathcal{G}_1 + \mathcal{G}_1 \mathrm{E}\{|\alpha(k)|^2\} \cdot \mathrm{SNR} + \mathrm{E}\{|\alpha(k)|^2\}}{2\pi N_s T N_p \mathcal{G}_1^2 \cdot \mathrm{SNR}} \tag{18}$$

where $\mathcal{G}_1 = \mathrm{E}\{|G|^2\} = 10^{\sigma_g^2 \ln(10)/200}$, $\mathrm{SNR} = E_s/\sigma_W^2$, and $\mathrm{E}\{|\alpha(k)|^2\}$ denotes the mean square error of the channel estimate. Since $\alpha(k)\alpha(N-k)$ can be omitted in Eqn. (14) for relatively high SNR, the proposed estimator has

$$\mathrm{IPR} = \frac{\mathcal{G}_2 \cdot \mathrm{SNR}^{-1} + 4\mathcal{G}_3 + 4\mathcal{G}_3 \mathrm{E}\{|\alpha(k)|^2\} \cdot \mathrm{SNR} + 6\mathcal{G}_2 \mathrm{E}\{|\alpha(k)|^2\}}{4\pi N_s T N_d \mathcal{G}_2^2 \cdot \mathrm{SNR}} \tag{19}$$

where $\mathcal{G}_2 = \mathrm{E}\{|G|^4\}$ and $\mathcal{G}_3 = \mathrm{E}\{|G|^6\}$.

5. SIMULATION RESULTS AND DISCUSSIONS

In our simulations, 80 Mbps UWB-OFDM system with $N = 128$, $N_n = 6$, $N_p = 12$, $N_g = 10$, and $N_{zp} = 37$ is considered. Here, the

UWB channel model that has been contributed in IEEE 802.15.SG3a is used for simulation [23]. At the receiver, least square (LS) channel estimation and one-tap frequency-domain equalization are used.

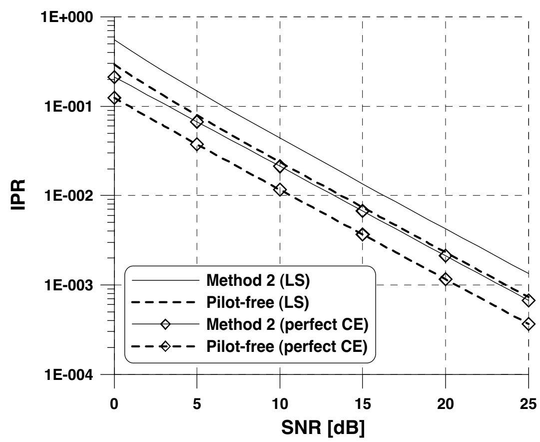

Figure 1. IPR of frequency tracking methods versus SNR in CM1.

Figure 1 plots the IPR of Method 2 and proposed schemes according to Eqns. (18) and (19) when $L = 1$ is used. When the LS channel estimation is used, $E\{|\alpha(k)|^2\} = 1/\mathrm{SNR}$. As expected, it is found that the pilot-free method is insensitive to interference in comparison with Method 2.

In Fig. 2 and Fig. 3, the comparison of the throughput performance of the UWB-OFDM receivers for channel model 1 (CM1) and CM3 are shown, respectively, when TFC 1 is used. Here, the results were based on a packet size of $L_p = 512$bytes and $\Delta_r = 5\,\mathrm{ppm}$. To have the approximately same computational burden, $D = 4$ and $L = 14$ in Method 1 and Method 2, and $L = 2$ and $N_d = 56$ in the pilot-free method are chosen. At the receiver, the CFO estimation is done once by using L subsequent symbols and the same estimate is used for whole packet. From both figures, we can find that Method 1 fails to get successful estimation in spite of $L + D$ symbol delay and high complexity. On the other hand, Method 2 and pilot-free method show very similar performance to the ideal case at high SNR. When compared to Method 2, the UWB-OFDM receiver with pilot-free tracking provides approximately 12% throughput enhancement because we can save the pilots for synchronization.

Figure 4 shows the bit error rate (BER) performance of UWB-OFDM receiver versus the number of averaging symbol L when SNR $= 5\,[\mathrm{dB}]$ and TFC 1 is used. As we can see from Fig. 4, Method 2

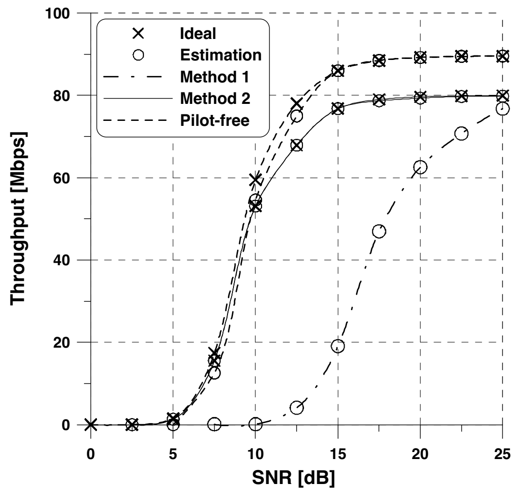

Figure 2. Throughput performance of frequency tracking receivers in CM1.

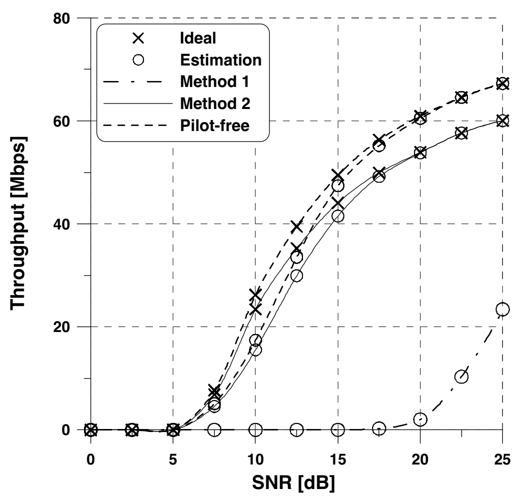

Figure 3. Throughput performance of frequency tracking receivers in CM3.

gives very accurate estimation when L is over 14, but it fails to rapidly come close to the ideal case when the packet size increases. On the other hand, the parameters $L = 5$ and $L = 14$ are enough to track the frequency error when $L_p = 512$ bytes and $L_p = 2048$bytes are used in the pilot-free method, respectively.

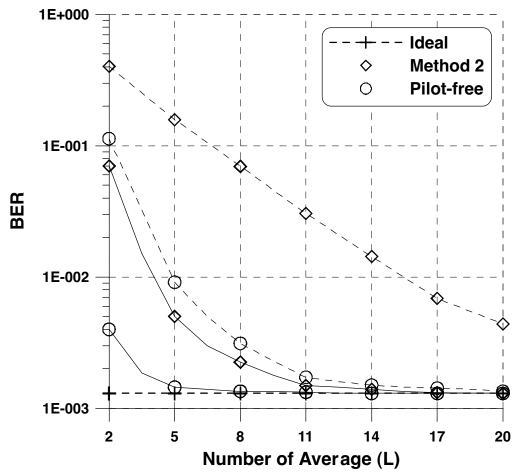

Figure 4. BER performance of frequency tracking receivers in CM1: (1) Solid lines: $L_p = 512$bytes (2) Dashed lines: $L_p = 2048$ bytes.

6. CONCLUSION

In this paper, an improved frequency tracking scheme has been presented for UWB-OFDM systems. We applied the existing frequency tracking methods to the UWB-OFDM system, and proposed a pilot-free frequency tracking scheme. The performance of the proposed tracking method is compared with that of conventional pilot-assisted methods in terms of BER and throughput, and it is shown by simulation that the proposed pilot-free scheme gives very accurate estimation and increases the throughput.

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.

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