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Fine Frequency Synchronization Method for MB-OFDM UWB Systems

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ABSTRACT

In this paper, a fine residual frequency offset estimation scheme is proposed for multiband orthogonal frequency division multiplexing ultra-wideband (MB-OFDM UWB) systems. The basic idea of our approach is based on the fact that two adjacent OFDM symbols carry the identical information in the MB-OFDM UWB system, thus removing the need of pilot symbols. The mean square error of the synchronization scheme is evaluated and simulation results are used to verify the effectiveness of the proposed estimator. When compared to the pilot-aided conventional estimator, the proposed estimator has a lower estimation error.

Key Words : UWB, MB-OFDM, Carrier frequency offset, Pilot symbol

Ⅰ. Introduction

Recently, multi-band orthogonal frequency division multiplexing (MB-OFDM) systems have attracted much research attention and have been standardized for the high-rate ultra-wideband (UWB) physical layer[1]. In the MB-OFDM UWB specification, frequency hopping and OFDM are implemented for high data-rate transmission over wireless channels. Although these techniques are very promising, the disadvantages associated with OFDM are also inherent by MB-OFDM UWB and one major limitation of OFDM is its sensitivity to frequency synchronization errors[2,3]. A residual frequency offset (RFO) and sampling frequency offset (SFO) are both introduced by small differences in oscillator frequencies between the transmitter and receiver, which causes time and subcarrier varying phase rotations and fast Fourier transform (FFT) window shift[4,5]. Therefore, RFO and SFO tracking is critical part of OFDM-based wireless receivers.

This paper deals with the problem of RFO estimation without the use of pilot signals in the MB-OFDM UWB system. Since the proposed estimator uses the inherent information of MB-OFDM UWB signals, no additional pilot symbols is needed. It is found by simulation that the proposed RFO estimator yields an improved estimation performance at the expense of the reduced estimation range, when compared to the conventional estimator.

This paper is organized as follows: Section II describes the signal model for the MB-OFDM UWB system. In Section III, a pilot-less RFO estimation scheme is suggested for MB-OFDM UWB. In Section IV, we then present simulation results verifying the performance of the frequency estimator, and we conclude this paper with Section V.

Ⅱ. System Model

In the MB-OFDM UWB system, N complex symbols are modulated onto N sub-carriers by using the inverse FFT on the transmitter side and N_g samples are zero-padded to form a guard interval. After compensating the carrier frequency offset with initial packet/frame synchronization sequence[2,3], there might still be a RFO and possible SFO.

After FFT demodulation during the l-th symbol

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period, the received signal in the presence of small SFO Δ_s and RFO Δ_r reads[6,7]

$$R_l(k) = SC_{b(l)}(k)X_l(k)e^{j2\pi(K_{b(l)}\Delta_r + k\Delta_s)lN_u/N} + W_l(k) \quad (1)$$

where S is the log-normal shadowing term, $X_l(k)$ is the OFDM symbol transmitted on the k-th subcarrier in the l-th symbol period, $b(l)\in\{1,2,3\}$ is the id of the frequency band occupied by the l-th symbol, $C_{b(l)}(k)$ is the channel's frequency response incorporating the time-invariant phase with zero mean at the frequency band $b(l)$, $N_e = N+N_g$, and $W_l(k)$ is a zero-mean complex Gaussian noise term, and $K_{b(l)}$ is a real constant depending on implementations of carrier frequencies generation. In this paper, assuming the carrier frequency synthesizer for mode 1 of the MB-OFDM UWB, $[K_1,K_2,K_3] = [13/16, 15/16, 17/16]$ is considered[3].

Ⅲ. RFO Estimation Scheme for MB-OFDM UWB

In the MB-OFDM UWB system, both frequency domain spreading (FDS) and time domain spreading (TDS) techniques shall be used when the data unit is encoded at a data rate of 53.3 or 80Mb/s. When the data unit is encoded at data rate of 106.7, 160 or 200Mb/s, only TDS technique is adopted. In all cases, a pair of two consecutive OFDM symbols denoted by $\{X_{2l}(k), X_{2l+1}(k)\}$ conveys the same information in the MB-OFDM UWB system. In order to estimate the frequency error without the help of pilot symbols, a simple way of implementing a fine frequency estimator is suggested in this section.

When the MB-OFDM UWB system is equipped with only TDS, two consecutive OFDM symbols are related to each other by[1]

$$X_{2l+1}(-k) = X_{2l}^{Q}(k) + jX_{2l}^{I}(k),\ -N_u/2 \le k \le N_u/2 \quad (2)$$

where N_u is the number of used subcarriers and $X_{2l}^{I/Q}(k)$ are the real and imaginary parts of $X_{2l}(k)$, respectively. By using the relation between two consecutive symbols $X_{2l}(k)$ and $X_{2l+1}(k)$, i.e., $X_{2l}(k)X_{2l+1}(-k) = j|X_{2l}(k)|^2$, one can find that

$$\begin{aligned} T_{2l}(k) &= (-j)\,Y_{2l}(k)\,Y_{2l+1}(-k) \\ &= E_s e^{j2\pi(\phi_{2l} - k\Delta_s)\rho} + \widehat{W}_{2l}(k) \end{aligned} \quad (3)$$

with

$$Y_{2l}(k) = R_{2l}(k)/\widehat{H_{b(2l)}}(k),\ -N_u/2 \le k \le N_u/2 \quad (4)$$

and

$$\phi_{2l} = K_{b(2l)}\Delta_r(2l) + K_{b(2l+1)}\Delta_r(2l+1) \quad (5)$$

where $Y_{2l}(k)$ is the channel-compensated version of $R_{2l}(k)$, $E_s = |X_{2l}(k)|^2$, $\rho = N_e/N$, $\widehat{H_{b(2l)}}(k)$ is the estimate of $H_{b(2l)}(k) = SC_{b(2l)}(k)$, and $\widehat{W}_{2l}(k)$is the noise contribution caused by the additive noise and channel estimation error.

In order to derive the pilot-less RFO estimator for MB-OFDM UWB, we device a temporal correlation to take expression

$$T_{2l}^{*}(k)\,T_{2l+D_1}(k) = E_s^2 e^{j2\pi[\phi_{2l+D_1} - \phi_{2l}]\rho} + \widetilde{W}_{2l}(k) \quad (6)$$

where D_1 is the period (measured in OFDM symbols) of the sequence of the band-id pairs $[b(2l), b(2l+1)]$ occupied by two consecutive OFDM symbols for a given band-hopping pattern or time-frequency code (TFC), and the noise contribution $\widetilde{W}_{2l}(k)$ is given by

$$\begin{aligned} \widetilde{W}_{2l}(k) = {} & E_s e^{-j2\pi[\phi_{2l} - k\Delta_s]\rho}\,\widehat{W}_{2l+D_1}(k) \\ & + E_s e^{j2\pi[\phi_{2l+D_1} - k\Delta_s]\rho}\,\widehat{W}_{2l}^{*}(k) \\ & + \widehat{W}_{2l}^{*}(k)\,\widehat{W}_{2l+D_1}(k) \end{aligned} \quad (7)$$

The MB-OFDM UWB specification provides ten different TFC's from TFC1 to TFC10 and these codes provide frequency hopping from a sub-band to another at the end of each OFDM symbol. In (6), the parameter D_1 depends on the TFCs, i.e. $D_1 = 6$ for TFCs 1~4 and $D_1 = 2$ for TFCs 5~10. Based on the above definition, it follows that

$$K_{b(2l+m)} = K_{b(2l+D_1+m)},\ m = 0,1 \quad (8)$$

and

$$\phi_{2l+D_1} - \phi_{2l} = \Delta_r [K_{b(2l)} + K_{b(2l+1)}] D_1 \tag{9}$$

which yields

$$T^*_{2l}(k)\, T_{2l+D_1}(k) = E_s^2 e^{j2\pi\Delta_r[K_{b(2l)}+K_{b(2l+1)}]D_1\rho} + \widetilde{W}_{2l}(k) \tag{10}$$

An estimation of Δ_r is now obtained by

$$\widehat{\Delta}_r = \frac{\sum_{k=-N_u/2}^{N_u/2} \measuredangle\left\{T^*_{2l}(k)\, T_{2l+D_1}(k)\right\}}{2\pi N_u [K_{b(2l)} + K_{b(2l+D_1)}] D_1 \rho} \tag{11}$$

with $\measuredangle$ denoting the angle of complex number. Finally, our estimation of the residual CFO is obtained by averaging $\widehat{\Delta}_r$ over all possible pairs of band-id's for a given TFC. There are three different band-id pairs for TFCs 1~4, while there is only one band-id pair for TFCs 5~10.

Ⅳ. Simulation Results

In our simulations, 200Mb/s MB-OFDM UWB system with $N = 128$, $N_u = 112$, $N_g = 37$, and $\Delta_s = \pm 20$ ppm is chosen according to the MB-OFDM UWB specification, while Δ_r is assumed to be 20% for $\pm$20ppm frequency tolerance[1]. The UWB channel models (CMs) are used for simulations[8] and a simple least square (LS) estimator is adopted to estimate the channel in (4). As a reference, we consider a pilot-aided conventional RFO estimation scheme[4], which is in the form

$$\widehat{\Delta}_r = \frac{\sum_{i=1}^{N_p} \measuredangle\left\{R^*_{2l}(k_i) R_{2l+D_2}(k_i)\right\}}{2\pi N_p K_{b(2l)} D_2 \rho} \tag{12}$$

where $N_p = 12$ is the number of pilots[1] and D_2 is the temporal distance between non-zero identical parts of the pilot symbol transmitted in the same frequency band. Similarly, an average estimation over different bands $\{b(2l)\}$ is applied, depending on the type of TFCs. To fairly evaluate the conventional and proposed approaches, $D_1 = D_2$ is used in the following examples.

The MSE performances of the RFO estimators in CM1 and CM3 are depicted in Fig. 1 and Fig. 2, respectively. Although the signal is transmitted at one frequency band in the case of TFCs 5~7, the conventional scheme is designed to have the average estimate over two temporal correlations with each having D_2 distance since the proposed scheme uses four OFDM symbols for synchronization. The curves show the different MSE performances as they differ in the amount of correlation distance and the number of frequency bands according to the TFCs used. When compared to the conventional method[4], the proposed method gives an improved MSE per-

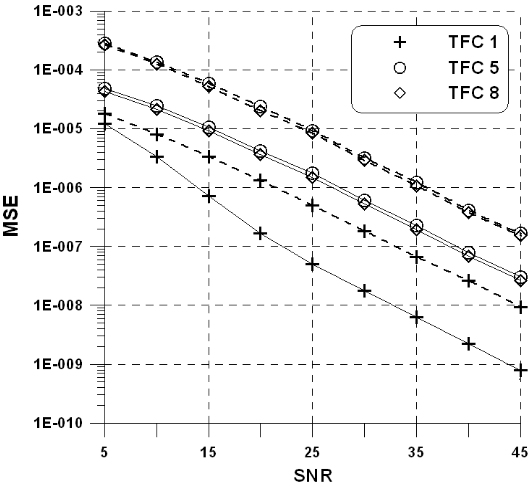

Fig. 1. MSE performance of the frequency estimators versus TFC in CM1: (1) solid lines - proposed (2) dashed lines - conventional

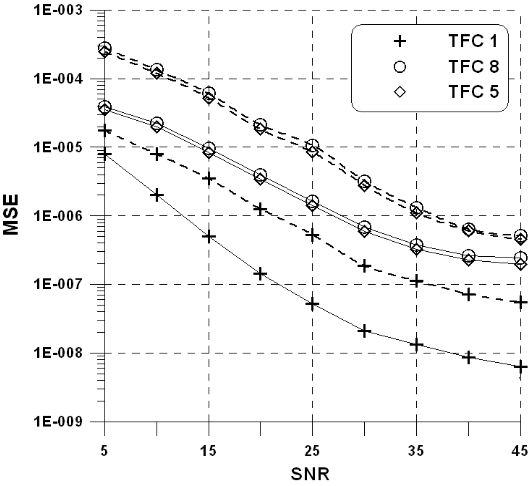

Fig. 2. MSE performance of the frequency estimators versus TFC in CM3: (1) solid lines - proposed (2) dashed lines - conventional

formance, expecting the lower BER. However, the complexity of the proposed scheme in terms of complex multiplications and additions is increased because $N_u > N_p$ is used, and the estimation range is shortened by a factor of $\max[K_{b(2l)} + K_{b(2l+1)}]/\max[K_{b(2l)}]$. However, it is seen that the performance of the proposed scheme gets worse at low SNRs when TFC1 is used. This is due to the fact that the estimation range in the case of TFC1 is much smaller than that in the case of other TFCs, thus its performance becomes sensitive to the additive noise and channel estimation error. Besides, an error floor in CM3, which is more dispersive than CM1, is observed.

Ⅴ. Conclusion

In this paper, we considered the issue of pilot-less residual frequency offset estimation for the MB-OFDM UWB system. The performance of the proposed estimator was compared with that of the conventional estimator, and simulation results show that the proposed scheme has a better RFO estimation performance in terms of MSE. Besides, the current MB-OFDM UWB system has been shown to contain rich structural information, which is sufficient to synchronize the system without explicit pilot symbols.

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