Symbol Timing Synchronization for Ultra-Wideband (UWB) Multi-band OFDM (MB-OFDM) Systems

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Abstract— A low-complexity correlation based symbol timing synchronization (CBTS) algorithm for UWB MB-OFDM systems is presented. The correlation based scheme attempts to locate the start of the FFT window during frame synchronization sequence (FS) of the received preamble by firstly correlating the received samples with known training samples and then identifying the first significant multi-path component by comparing the correlated samples of two consecutive OFDM symbols against a predefined threshold. Performance of the proposed algorithm is measured through mean-squared error (MSE) of timing estimation and probability of synchronization. Each of the 100 channel realizations for UWB channel model1 (CM1) (0-4m LOS) and CM2 (0-4m NLOS) are simulated for 1000 noisy channel realizations for 17dB SNR. Synchronization probability and MSE for CM1 and CM2 are reported for 320Mbps data rate.

Keywords- MB-OFDM; OFDM; timing synchronization; UWB

I. *INTRODUCTION*

Ultra-wideband (UWB) communication has attracted keen interest of researchers since Federal Communications Commission (FCC) has allocated 7.5GHz large unlicensed bandwidth for UWB communication devices in 2002. Now a days, UWB is a physical layer solution for short range (>10m) high data rate (55Mbps-480Mbps) wireless personal area networks (WPAN) as well as low data rate (100Kbps) wireless sensor networks. Among the several proposals for efficient use of the huge bandwidth, multi-band orthogonal frequency division multiplexing (MB-OFDM) has been accepted as commercially more viable than 'impulse-radio-based' and 'code-division multiple-access (CDMA) based' UWB transmission. MB-OFDM is a combination of OFDM modulation with data transmission by frequency hopping (FH) over different frequency bands.

In any OFDM based system, synchronization at the receiver is a critical and vulnerable criterion. Synchronization in MB-OFDM UWB system requires estimation of the symbol timing and carrier frequency offsets. Synchronization errors cause inter symbol interferences (ISI) and inter carrier interferences (ICI) resulting severe degradation in system performances. In this paper, symbol timing synchronization which is finding an estimate of the start point of FFT window is addressed.

The conventional timing synchronization schemes [1], [2] proposed for narrow band OFDM systems are based on finding the correlation peak utilizing correlation either in cyclic prefix [1] or in duplicate training symbols [2]. All these schemes can give satisfactory estimation of timing when first received multi-path is stronger than the successive ones. Experimental results on UWB channel show that, in some environments, stronger multi-paths may appear later [3]. Hence, correlation peak based timing estimation may result false lock to delayed stronger multi-path.

The proposed correlation based timing synchronization (CBTS) scheme tries to find out first significant multi-path by comparing the difference between two successive correlated OFDM symbols against a threshold. A correct instant of the start of the FFT window is estimated when the threshold is crossed. It is shown that, with CBTS, synchronization probability increases and MSE reduces considerably in both channel models (CM) CM1 and CM2 compared to results reported by Yak *et al.* [4].

The organization of this paper is as follows: MB-OFDM system specifications, characterization of UWB channel and signal model are provided in section II. Proposed timing synchronization algorithm, CBTS is described in section III. Section IV presents simulation parameters, results, performance measure and discussion. Section V concludes the paper.

II. MB-OFDM SYSTEM

A. MB-OFDM Specifications

In MB-OFDM proposal [5], the 7.5GHz bandwidth is divided into fourteen (14) bands. For mode 1 devices, data packets hop over the first three bands following a time frequency interleaved (TFI) pattern. Synchronization in MB-OFDM system is data-aided [5]. In standard preamble, first 21 packet synchronization sequences (PS) are dedicated for packet detection, AGC stabilization, coarse timing and frequency synchronization; next 3 frame synchronization sequences (FS) are meant for fine timing and frequency synchronization followed by 6 channel estimation sequences (CE) as shown in Fig.1. Depending on a fixed TFI pattern, a particular preamble pattern is selected. The PS and FS sequences have same magnitude but opposite polarity.

B. UWB Channel model

IEEE802.15.3 channel modeling sub-committee has specified four different kinds of channel model (CM1-CM4) depending on transmission distances based on modified Saleh-Valenzuela (S-V) model for UWB. UWB channel model is cluster based where individual ray shows independent fading. The channel coefficients are log-normally distributed (with normal distribution mean μ=0 and standard deviation σ=3) and incorporate log-normal shadowing. A typical impulse response for separated clusters is shown in Fig.2. Due to wide bandwidth involved impulse response of an UWB channel shows frequency dependency (not included in IEEE802.15.3 channel models). Unlike narrowband systems, UWB power profile may have stronger components at later clusters. Power decay profile of UWB shows exponential power decay for both the clusters and rays within a cluster. It is found experimentally that cluster decay rate is a function of the delay of the corresponding cluster. The multi-path channel can be expressed as,

$$h(t) = X\sum_{j=0}^{J}\sum_{i=0}^{I}\alpha_{i,j}\delta(t-T_j-\tau_{i,j}) \quad (1)$$

where, $\alpha_{i,j}$ = channel coefficient for *ith* ray of *jth* cluster

T_j = delay of *jth* cluster
$\tau_{i,j}$ = delay of *ith* ray related to *jth* cluster arrival time
$\tau_{0,j}$= 0, by definition
X= log-normal shadowing

C. MB-OFDM Signal

MB-OFDM symbols are constructed by suffixing 32 (N_{ZP}) null samples called zero padded (ZP) samples and 5 (N_g) null guard samples to 128 (N) length IFFT output sequence according to frame format [5].

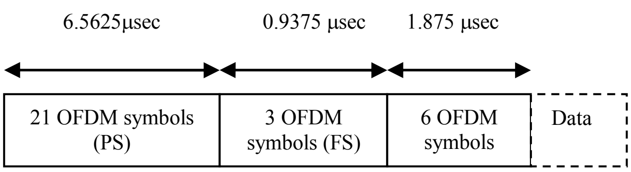

Figure 1. MB-OFDM Frame Format

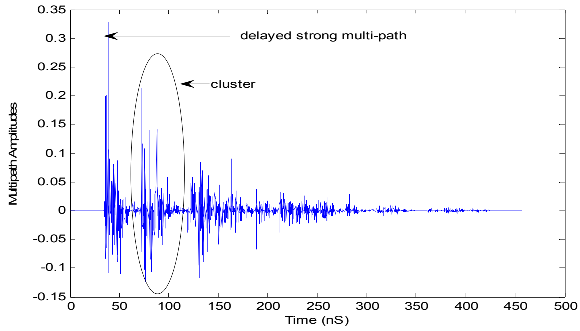

Figure 2. Impulse Response for UWB channel with non-overlapping clusters

A total length of N+N_{ZP}+N_g samples of one MB-OFDM symbol is mentioned as 'sample max'(sa_{max}) in this paper.

Let, $\{S\}$ is the QPSK modulated time domain sequence transmitted over time-dispersive UWB fading channel given as,

$$S = \{\ldots\ldots s_n, s_{n+1}, \ldots\ldots\ldots\}, \quad (2)$$

$\{h_b\}$ = complex base band equivalent UWB channel coefficients,

$$h_b = \{h_{b,1}, h_{b,2}, \ldots\ldots\ldots, h_{b,P}\}, \quad (3)$$

P = length of channel impulse response. Let, $\{R\}$ is the received sample sequence at the UWB receiver front end given as,

$$R = \{\ldots\ldots, r_n, r_{n+1}, \ldots\ldots\}. \quad (4)$$

Let, there are 'L' nos. of MB-OFDM symbol each having 'sample max' no. of samples in transmitted preamble. Then, *nth* received sample of *lth* OFDM symbol $r_{n,l}$ is given as,

$$r_{n,l} = \sum_{p=1}^{P} s_{n-p-\tau,l}h_{b,p} + n_{n,l} \quad (5)$$

where, $n_{n,l}$ =complex additive white Gaussian noise associated with the *nth* sample of the *lth* MB-OFDM symbol and τ= timing offset. The received samples are cross-correlated with known training sequences i.e. the preamble pattern $\{t\} = \{t_1, t_2, \ldots\ldots\ldots, t_N\}$ and the cross-correlated output of the *nth* sample of the *lth* MB-OFDM symbol $C_{n,l}$ is given as,

$$C_{n,l} = \sum_{i=1}^{N} r_{n+i,l}t_i^* \quad \text{for}, 1 \le l \le L; 1 \le n \le sa_{\max} \quad (6)$$

where, * denotes complex conjugate operation.

III. TIMING SYNCHRONIZATION ALGORITHM

As stated in the section II-A, MB-OFDM preamble bears a clear demarcation between PS and FS sequences as the later is 180^0 out of phase from the previous one. Assuming that packet detection is over, our timing synchronization algorithm CBTS attempts to estimate the start of the first FS sequence and hence computes the start of the FFT window for it. The scheme for CBTS is shown in Fig.3. The timing offset 'τ' is,

$$\tau = \hat{n} - n_{exact} \tag{7}$$

where, n_{exact} is the starting sample of FFT window and $\hat{n}$ is the estimated timing instant of n_{exact}.

Each received correlated sample of *lth* MB-OFDM symbol is subtracted from the corresponding correlated sample of *(l-1) th* MB-OFDM symbol. The difference value for *nth* sample of two consecutive MB-OFDM symbols is given as,

$$D_n = C_{n,l} - C_{n,(l-1)} \quad \text{for, } 2 \le l \le L. \tag{8}$$

If both the samples belong to MB-OFDM symbols of the same polarity, the difference value D_n will give only the associated noise magnitude. But when they belong to MB-OFDM symbols of different polarity, difference output D_n increases. When the received sequence is about aligned with the first sample of FFT window of FS sequence, D_n reaches to a considerable magnitude. The difference outputs are constantly compared with a predefined threshold 'λ'. If the absolute value of D_n exceeds 'λ', initial timing estimation point $\hat{n}$ is deduced to be at 'n'. The actual start of the FFT window is then computed by,

$$n_{sync} = \hat{n} + \text{'}sample\ max\text{'}. \tag{9}$$

IV. SIMULATION RESULTS AND DISCUSSIONS

A. Simulation environment

Simulation is carried out using the preamble pattern1 for 320Mbps uncoded MB-OFDM system. Timing offset is estimated based on the received samples in band 1. For a typical SNR of 17dB (as specified for high data rate applications), CBTS algorithm is tested for the UWB channel models: CM1 and CM2. For each threshold, 100,000 noisy realizations are carried out in each CM environment.

B. Performance Measure of CBTS algorithm

Performance of the CBTS algorithm is measured through the mean-squared error (MSE) of the estimation and probability of synchronization (P_{exact}). Both of the above criterions are evaluated by the probability distribution of synchronization algorithm in corresponding CM environment. Fig.4 shows a typical probability distribution for CM1 under noiseless condition with CBTS algorithm.

1) Mean- Squared Error (MSE): MSE is defined as

$$MSE = \sum_{\forall \hat{n}} (\hat{n} - n_{exact})^2 P(\hat{n}) \tag{10}$$

where, $P(\hat{n})$ is the probability of estimating n_{exact} to be at $\hat{n}$. MSE values for different 'λ' values for both the 17dB SNR and noiseless condition are tabulated for CM1 and CM2 in Table I. It is observed from Table I that, for threshold value '180', CM1 gives a minimum MSE of '0.43' samples under noiseless condition and '0.513' samples with the same threshold value for 17dB SNR. For CM2, threshold value of '180' gives minimum MSE of '1.65' samples and 'λ=200' gives minimum MSE of '1.7142' samples for noiseless and 17dB respectively.

2) Exact Synchronization Probability (P_{exact}): The total synchronization probability is defined here as,

$$P_{total} = P_{exact} + P_{ZP} \tag{11}$$

where, P_{ZP} is the probability of estimating timing instant within the zero-padded region and the exact probability P_{exact} is probability of estimating $\hat{n} = n_{exact}$. If $\hat{n}$ falls inside the ZP region, the sub carriers will experience only the phase rotations which can be corrected later. However, we are interested here with exact synchronization probability, a higher value of which determines more accurate channel estimation in the receiver.

Table II summarizes the P_{exact} for CM1 and CM2 for different thresholds under noiseless and 17dB SNR. It is noticeable that an optimum threshold of '180'gives outstanding synchronization probability of '94.5%' in case of CM1 and '74%' for CM2 under noiseless condition. With SNR=17dB, CM2 gives maximum 'P_{exact} =68%' for 'λ=200' where CM1 gives maximum 'P_{exact} =92.6%' for 'λ=220'. The P_{ZP} can be evaluated for each CM environment by estimating their corresponding delay spreads.

Table III gives comparative study of CBTS algorithm with FTA algorithm proposed by Yak *et al*. [4] for MSE and synchronization probability. It is observed that maximum synchronization probability is several times higher for both the channel models with proposed CBTS algorithm. For CM1, FTA gives lesser MSE than CBTS under both noiseless and 17dB SNR. For CM2, CBTS gives less MSE than reported values of FTA under both the condition of considerations.

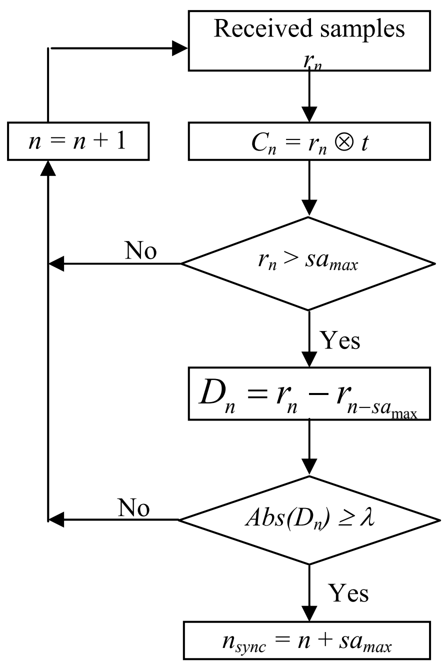

Figure 3. The CBTS algorithm

TABLE I. MSE FOR CM1 & CM2 UNDER NOISELESS CONDITION AND 17DB SNR

λ	CM1		CM2	
	noiseless	***17dB***	***noiseless***	***17dB***
180	**0.43**	**0.513**	**1.65**	9.2609
200	0.5	0.629	2.1	**1.7142**
220	0.61	0.7703	2.54	2.4133
240	0.69	0.9302	2.84	3.0823

TABLE II. SYNCHRONIZATION PROBABILITY FOR CM1 & CM2 UNDER NOISELESS CONDITION AND 17DB SNR

λ	CM1		CM2	
	noiseless	***17dB***	***noiseless***	***17dB***
180	**94.5%**	77.724%	**74%**	57.63%
200	94%	90.64%	72%	**68%**
220	93%	**92.6%**	67%	67.48%
240	92.5%	92.4%	65%	64.7%

TABLE III. COMPARATIVE STUDY OF MSE AND PROBABILITY OF SYNCHRONIZATION WITH CBTS AND FTA ALGORITHM[4]

Performance criterions	**CM1**		**CM2**	
	CBTS	***FTA***	***CBTS***	***FTA***
MSE, (Min) (samples)	0.43 (noiseless)	0.32 (noiseless)	**1.65** (noiseless)	4.02 (noiseless)
	0.513 (17dB)	0.365 (17dB)	**1.7142** (17dB)	9.129 (17dB)
Synch. prob. (Max)	**94.5%** (P_{exact}) (noiseless)	85% (P_{total}) (noiseless)	**74%** (P_{exact}) (noiseless)	55% (P_{total}) (noiseless)
	92.6% (P_{exact}) (17dB)	81.48% (P_{total}) (17dB)	**68%** (P_{exact}) (17dB)	49% (P_{total}) (17dB)

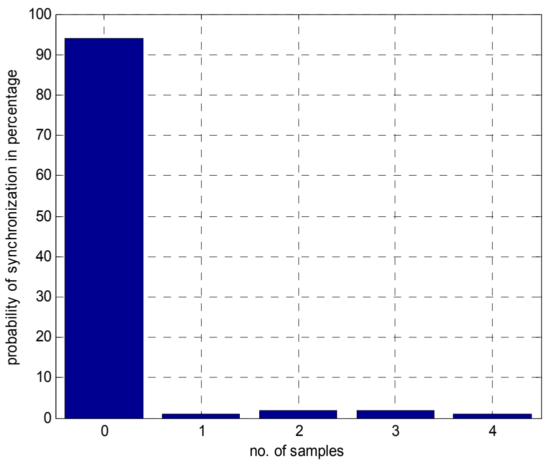

Figure 4. Synchronization probability distribution for CM1 under noiseless condition and λ=180 with CBTS

C. *Discussion*

A thorough investigation with different threshold levels for different channel models, CM1 and CM2 shows that, a proper selection of threshold in different UWB channel model environment is essential to get minimum MSE and maximum synchronization probability. Further, it can be said intuitively that optimum threshold values need to be updated for different SNR values under same UWB channel model environment. It is obvious that, a higher value of P_{exact} and minimum value of MSE is always desired for better channel estimation. However, a higher value of P_{total} never guarantees better channel estimation since $\hat{n}$ can take many different values depending on the variable length of channel delay spread (in terms of no. of samples) estimated.

Performance of the presented algorithm can be further improved if 90% channel realizations are retained and worst 10% channels are discarded.

V. CONCLUSION

CBTS locks the timing instant by comparing the difference of correlation samples for two consecutive MB-OFDM symbols with a predefined threshold in contrast with the conventional correlation based techniques which find strongest multi-path component by finding correlation peak. A threshold of ‘180’ gives minimum MSE of ‘0.513’ samples and a threshold of ‘220’ gives maximum synchronization probability of ‘92.6%’under SNR=17dB.

For CM2, the maximum synchronization probability of ‘68%’ with a threshold of ‘200’ and minimum MSE of ‘1.742’ samples at the same threshold is obtained for 17dB SNR. The reported results with CBTS algorithm give significant improvement in synchronization probability for both the channel models and lesser MSE for CM2 over the reported results in [4].

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