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Improved Timing Estimation Using Iterative Normalization Technique for OFDM Systems

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ABSTRACT

Conventional timing estimation schemes based on autocorrelation experience performance degradation in the multipath channel environment with high delay spread. To overcome this problem, we proposed an improvement of the timing estimation for the OFDM system based on statistical change of symmetrical correlator. The new method uses iterative normalization technique to the correlator output before the detection based on statistical change of symmetric correlator is applied. Thus, it increases the detection probability and achieves better performance than previously published methods in the multipath environment. Computer simulation shows that our method is very robust in the fading multipath channel.

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1. INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) systems offer high bandwidth efficiency and robust against multipath delay. Hence, OFDM systems have been widely adopted for a high data rate, wireless communication systems, such as WLAN [1], DVB-T2 [2], and WMAN 802.16m [3]. Both of DVB-T2 and WMAN 802.16m are supporting applications that run in a high speed mobility environment. Recently OFDM technique is also used for cognitive radio systems, which the use of frequency spectrum in the OFDM systems can be done as efficiently as possible [4]-[5]. However, OFDM systems need strict timing synchronization between transmitter and receiver, as an error in timing estimation give rise to InterSymbol Interference (ISI) and can decrease the overall performance of OFDM systems [6]-[7].

For symbol timing estimation, Schmidl [8] used a preamble consists of two identical parts for symbol timing estimation. But, the timing metric of Schmidl's method has a plateau, which causes a large variance in the timing offset estimation. To decrease the plateau, Minn [9] proposed a new training symbol with four identical parts. It results a sharper timing metric than Schmidl's method, however, it still has ambiguity due to some side-lobes at a side of the peak correlation region, thus estimation variance is still large. In order to reduce the variance, Park [10] proposed a sharper timing metric using symmetric correlation property of the preamble. Yet, the timing metric of Park's method has two large side-lobes. To eliminate the side-lobes of Park's timing metric, Yi [11] proposed a new preamble structure that has symmetric correlation property. The performance of all the above-mentioned approaches decrease in multipath channel environments.

To overcome this problem, Cho [12] proposed a method that exploits statistical change of symmetric correlator. It reduces the multipath channel effect, hence the variance of the timing offset estimation is small. However, Cho's method generates error detection if the correlation magnitude on the first arriving path is much smaller than the strongest path. To overcome this problem, we proposed an iterative normalization technique to the correlator output before the detection based on statistical change of symmetric correlator is applied. Considering the very small correlation magnitude on the first arriving path, we attempt to increase the correlation magnitude on the first arriving path to

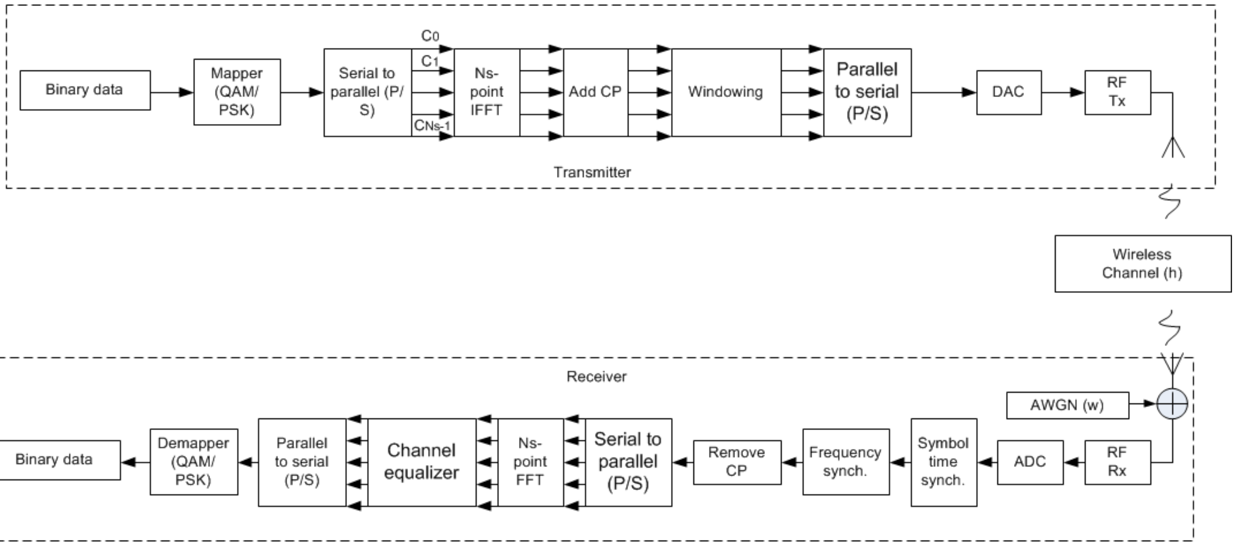


Figure 1. The Block diagram of OFDM transmission systems (synch.: synchronization).

produce an estimation method with better performance. Our experimental results show that the new timing estimator achieves better performance than previously published methods.

2. OFDM SIGNAL MODEL

Fig. 1 shows an OFDM transmission system that consists of a sequence of OFDM symbols, where each of the OFDM symbol which has a duration of T_s seconds is generated by a number of N_s points Inverse Fast Fourier Transform (IFFT) from a block of sub-symbols $\{C_k\}$. Cyclic Prefix (CP) with a length of N_g is added at the start of the OFDM symbol that is longer than the duration of the Channel Impulse Response (CIR). Thus, the OFDM signal transmitted through the frequency selective fading channel with a delay spread length of L_{ch} is expressed as follows:

$$y(d) = \sum_{m=0}^{L_{ch}-1} h(m)x(d-m) + w(d), \tag{1}$$

where d is time index, $h(m)$ is the channel impulse response, $w(d)$ is white Gaussian noise with zero mean, and $x(d)$ is the output signal from IFFT describes as follows:

$$x(d) = \sum_{k=0}^{N-1} C_k e^{j2\pi kd/N_s}. \tag{2}$$

The delay of the receiving signal $r(d)$ at the receiver can be modelled as follows:

$$r(d) = y(d-d_\epsilon)e^{j2\pi \frac{d}{N_s}\xi_f}, \tag{3}$$

where d_ϵ is an unknown integer-valued of arrival time of an OFDM symbol and ξ_f is the Carrier Frequency Offset (CFO) normalized to the subcarrier spacing.

3. PROPOSED METHOD

3.1. Symmetric Correlator

In time domain, the form of Park's preamble is defined as follows [10]:

$$P_{Park} = [A_{N_s/4} \quad B_{N_s/4} \quad A^*_{N_s/4} \quad B^*_{N_s/4}], \tag{4}$$

where $A_{N_s/4}$ represents samples with length $N_s/4$ generated by IFFT of a Pseudo Noise (PN) sequence, and $A^*_{N_s/4}$ represents the conjugate of $A_{N_s/4}$. $B_{N_s/4}$ is symmetric of $A_{N_s/4}$ and is generated by the method in [10]. Thus, the symmetric correlator $T(d)$ is defined as:

$$T(d) = \sum_{k=1}^{N_s/2-1} r(d+k)r(d+N_s-k). \tag{5}$$

3.2. Statistical Property of Symmetric Correlator

As in [12], the Probability Distribution Function (PDF) of $T(d)$ is defined as follows:

$$\rho(d) = \sum_{k=1}^{N_s/2-1} r(d+N_s/2-k)r(d+N_s/2+k), \tag{6}$$

for $|d-d_0| < L_r$, $\rho(d)$ follow a complex normal distribution as:

$$\rho(d) \sim \begin{cases} CN(0, K\sigma_r^4), & d \notin L \\ CN(Kh^2(d-d_0)\sigma_x^2 e^{2\pi\xi_f}, K\sigma_r^4), & d \in L, \end{cases} \tag{7}$$

where L_r is the number of identical part of the preamble $(L_r = N_s/2)$, $K = (N_s/2-1)$, $\sigma_r^2 = \kappa\sigma_x^2 + \sigma_w^2, \kappa = \sum_m |h(m)|^2$, $\sigma_x^2 = \frac{1}{N_s}\sum_{k=0}^{N_s-1}|x_p(k)|^2$, σ_w^2 is noise variance, and $x_p(k)$ denote the preamble signal in time domain. d_0 indicates the start of preamble $(d_0 = 0)$, which corresponds to the first arriving path and $L(= (d_0, d_0+1, ..., d_0+L_{ch}))$ is multipath channel index. Accordingly, for correlator length $(L_r > |d-d_0|)$, $T(d)$ is a Rician random variable with PDF:

$$\begin{aligned} f(T(d);\sigma^2, v(d)) = \frac{T(d)}{\sigma^2} exp(-\frac{T^2(d)+v^2(d)}{2\sigma^2}) \\ I_0(\frac{T(d)v(d)}{\sigma^2}), \end{aligned} \tag{8}$$

where $I_0(x)$ is modified the first kind of Bassel function with order zero,

$$v(d) = \begin{cases} K|h^2(d-d_0)|\sigma_x^2, & d \in L \\ 0, & d \notin L, \end{cases} \tag{9}$$

and $\sigma^2 = K\sigma_r^4/2$.

3.3. Timing Estimation Based on Statistical Change of Symmetric Correlator

From the PDF derived in (8), [12] observes the statistical change of $T(d)$ upon the reception of the preamble. Then, by the Generalized Likelihood Ratio (GLR) approach, the timing metric is defined as:

$$M_T(d) = exp\left(-\frac{1}{2}\Phi(d)+1\right) I_0\left(\sqrt{\Phi(d)^2 - 2\Phi(d)}\right), \tag{10}$$

where $\Phi(d) = \frac{T^2(d)}{\sigma_0^2(d)}$, $\sigma_0^2(d) = \frac{1}{2J}\sum_{k=0}^{J-1} T^2(d-k)$, and J is the observation length for detection. Thus, the timing estimation is defined as:

$$\hat{d}_\epsilon = \underbrace{argmax}_{d}(M'_T(d)), \tag{11}$$

where

$$M'_T(d) = \begin{cases} M_T(d)|, & T(d) > R \\ 0, & otherwise, \end{cases} \tag{12}$$

and R is the threshold, which set to avoid False Alarm in Eq. (12). The Probability of False Alarm (P_{FA}) is derived from Eq. (8) at $v(d) = 0$ as:

$$P_{FA} = exp(-R^2/2\sigma^2), \tag{13}$$

if σ^2 replaced by σ_0^2, the threshold can be obtained for the given False Alarm rate as:

$$R = \sqrt{-2\sigma_0^2 log P_{FA}}. \tag{14}$$

3.4. The Proposed Timing Estimation

Cho's technique exploits the statistics of $T(d)$ change upon the reception of the preamble. It detects the change of parameter $v(d)$ from 0 for $d < d_0$ to $v(d) = K|h^2(0)|\sigma_x^2$ at $d = d_0$. This technique generates error in detecting the first arriving path when the gain on the first channel path $(|h^2(0)|)$ is much smaller than the strongest path $(|h^2(m)|)$, where m is $1, 2, ..., L_{ch} - 1$. Thus, it makes the correlation magnitude on the first arriving path much smaller than the stronger path and causes $\Phi(d_0) < \Phi(d_s)$, where d_s is time index on the stronger path. Therefore, Cho's detection technique fails to detect the first arriving path.

To overcome this problem, we proposed an iterative normalization technique to be applied to the correlator $T(d)$ before the detection based on statistical change of symmetric correlator is applied. It increases the correlation magnitude on the first arriving path and suppress the correlation magnitude on other paths, which are associated with the time side-lobes that are sometimes can appear as the stronger path. In other words, we give higher weighting factor to other paths than to the first arriving path. Hence, making the value of $\Phi(d_0) \geq \Phi(d_s)$. Thus, Cho's detection technique can successfully detect the first arriving path.

Cho method is actually second-order normalization technique, but this technique can not be applied directly to the iterative normalization technique because it does not has a stable performance when the number of iterations is increased. This is due to Park's timing metric which is compliant with WMAN 802.16m [3] systems has two large lobes so that the short of observation length (Cho's observation length less than or equal to the channel length) from Cho's method can not be used for iterative technique. We set the observation length for iterative normalization equal to the number of identical parts (L_r), since the magnitude of side-lobes depend on the number of identical parts of the preamble. This is done to achieve stable performance until q iterations.

The iterative normalization technique $Z_i(d)$ is expressed as:

$$Z_i(d) = \sqrt{\frac{Z_{i-1}^2(d)}{\sigma_{Z(i-1)}^2(d)}}, \tag{15}$$

where i is the index of iteration and $\sigma_{Zi}^2(d)$ is the variance of correlator at i iteration and is defined as:

$$\sigma_{Zi}^2(d) = \frac{1}{N_{norm}} \sum_{k=0}^{N_{norm}-1} Z_i^2(d-k), \tag{16}$$

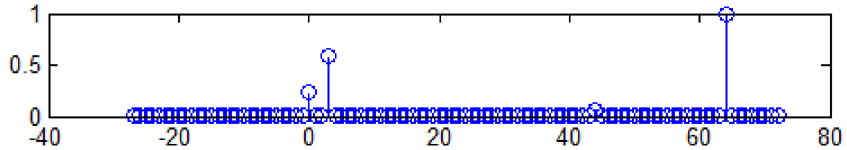
where N_{norm} is the observation length for iterative normalization.

Our proposed method is performed as follows. First, we set $Z_0(d) = T(d)$, and then the iteration process is applied to (15) for $i = 1$ to q, where q is the number of iteration. After obtaining $Z_q(d)$, we set back $T(d) = Z_q(d)$. Then, the timing estimation can be calculated using (10) and (11).

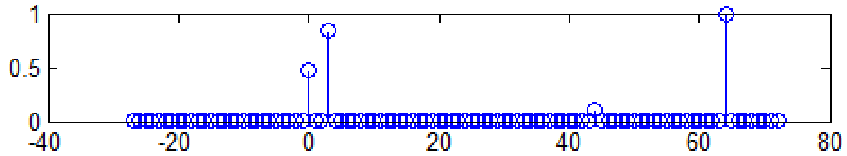
Fig. 2 Shows the simulation result using Cho's method (Fig. 2(c)) compared to that using our proposed method with $q = 3$ (Fig. 2(d)). Those figures represent normalized value against their maximum value. The correct timing point d_0 (the first arriving path) is indexed as 0. Under such situations, we can observe that Cho's method fails to detect the first arriving path because the correlation magnitude on the first arriving path much smaller than the stronger path (Fig. 2(a)), hence $\Phi(d_0) < \Phi(d_s)$. Meanwhile, our proposed method can detect the first arriving path; this improvement can be inferred from the rise of the correlation magnitude $v(d_0)$ and the decrease of the correlation magnitude on other paths (Fig. 2(b)), hence $\Phi(d_0) \geq \Phi(d_s)$ and Cho's detection technique can successfully detect the first arriving path.

4. RESULTS AND DISCUSSION

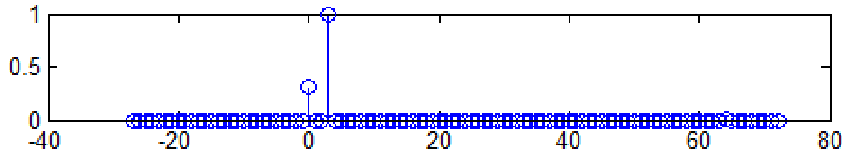
In this part, we tested the performance of the proposed method using computer simulation in the term of timing metric and measure the Mean Squared Error (MSE) of symbol timing. The MSE of symbol timing is defined as $E[(t_{estimation} - t_{offset})^2]$, which indicates the average squared difference between the estimation time at receiver and



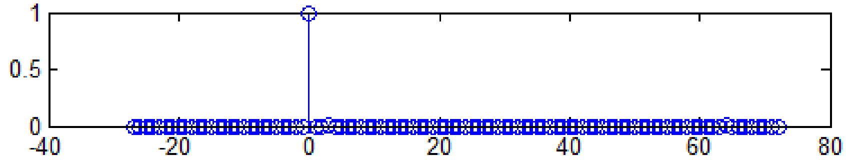
(a) Symmetric correlator output (T(d))



(b) Iterative normalization with q=3



(c) Cho and Park method



(d) Proposed method

Figure 2. Comparison detection under the Vehicular B channel [13] with SNR = 20 dB, $N_s = 2048$, and $N_g = 256$ on symmetric correlator output ($T(d)$).

Table 1. Complexity Comparison

Method	Number of Complex Multiplication	Number of Complex Addition
Park et al.	$N_s/2$	$N_s/2-1$
Cho and Park	$N_s/2$	$N_s/2+J-3$
Proposed with q=2	$N_s/2$	$N_s/2+J+2N_{norm}-5$
Proposed with q=3	$N_s/2$	$N_s/2+J+3N_{norm}-6$

the time offset caused by transmission. We run our simulation at sampling rate 0.1 μs, CP is set to $1/8$ of the OFDM symbol, and 16-QAM is used as data modulation. The simulation is conducted on the Vehicular B multipath channel model with vehicle speed set to 120 km/hour [13]. Note that we use $N_s = 2048$ under the Vehicular B channel, so that the duration of CP is longer than the duration of CIR. The CFO is modelled as uniform random variable distributed in range ± 3 and P_{FA} is set to 10^{-6}. The observation length for detection is set to $J = N_g/2$ and the observation length for iterative normalization is set to $N_{norm} = N_s/2$.

MSE of symbol timing under the Vehicular B channel are shown in Fig. 3. For that channel model, the proposed method outperforms other methods shown in a much smaller MSE, which indicate that the stable timing position can be accomplished with less number of preamble detection. Park's method has the lowest performance, this is due to autocorrelation technique yields a delayed timing estimate. The proposed method has better performance than Cho's method, this is because at every iteration in iterative normalization technique increasing the gain of correlation magnitude on the first arriving path and pressing the others path gain, while in the Cho's method, the detection is made without iterative normalization technique so that the very small gain of correlation magnitude on the first arriving path causes a failure in detecting the first arriving path (the correct timing point). Note that the proposed method with $q = 3$ is better than the proposed method with $q = 2$ in the expense of increasing complexity. When we increase $q > 3$, we find that the performance does not significantly improved.

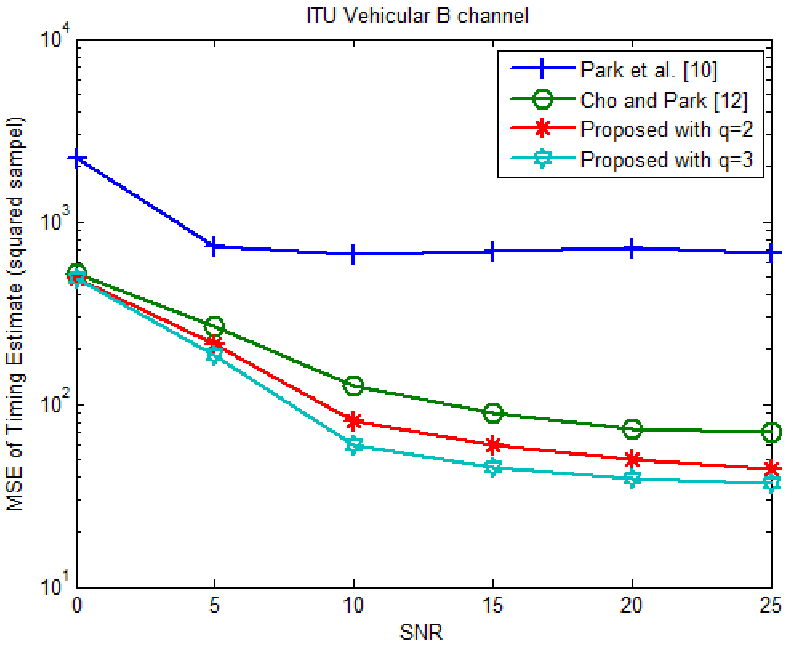


Figure 3. Performance of three methods under Vehicular B channel.

The complexity of the proposed method in comparison with the previous methods shown in the Table 1. In the proposed method with $q = 2$, we need $N_s/2$ complex multiplication and $N_s/2 - 2$ complex addition to calculate $T(d)^2$. Then, it needs 2 division and $2N_{norm} - 2$ complex addition to calculate iterative normalization. After that, it needs 1 division and $J - 1$ complex addition to obtain $\Phi(d)$. In the proposed method with $q = 3$, we need $N_s/2$ complex multiplication and $N_s/2 - 2$ complex addition to calculate $T(d)^2$. Then, it needs 3 division and $3N_{norm} - 3$ complex addition to calculate iterative normalization. After that, it needs 1 division and $J - 1$ complex addition to obtain $\Phi(d)$. We can write (15) as $Z_i^2(d) = \frac{Z_{i-1}^2(d)}{\sigma_{Z(i-1)}^2(d)}$ so, the root equation can be avoided and is not considered in complexity analysis. From Table 1, we can observe that our proposed method can be realized with comparable complexity to the previous methods. Thus, our proposed estimator can provide an improved performance with a slight additional complexity than previous methods.

5. CONCLUSION

We already proposed an improvement of the timing estimation based on statistical change of symmetric correlator. It uses iterative normalization technique to the correlator output before the detection based on statistical change of symmetric correlator is applied. This technique increases the detection probability and achieves superior estimation performance in multipath environments. The proposed estimator achieves better performance than previous published methods as shown in smaller MSE. Hence, the proposed estimator appropriate to be implemented for timing synchronization in mobile OFDM systems with high delay spread environment.

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