Robust Timing Estimation for High Data Rate Mobile OFDM Systems

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Abstract: The Symbol timing estimation in a high data rate mobile OFDM systems is a challenging task, this is due to the high delay spread. A conventional timing estimation based on autocorrelation experience performance degradation due to multipath channel distortion. To improve the performance of autocorrelation technique, we propose a normalized 3-rd order central moment for symmetric correlator as test statistics. When the training symbol is received, the distribution of the symmetric correlator is Rician distribution. This will be different from no training symbol is received, the distribution of the symmetric correlator is Rayleigh distribution. After we perform coarse timing estimation using a normalized 3-rd order central moment, fine timing estimation is done using the cyclic shift of a channel estimate. The simulations results have shown that our method is robust in the fading multipath channel and has better performance than the previous methods.

Keywords: High data rate, mobile, multipath channel, OFDM, timing estimation.

1. Introduction

Demand for high data rate applications in mobile environment continues to rise. Robust mobile communication with high data rate is still challenging. High data rate transmission over mobile environment typically experience higher delay spread. OFDM (Orthogonal Frequency Division Multiplexing) systems is robust in environments with a high delay spread. OFDM is a digital multicarrier systems, wherein all channels are split into several sub-channels in order to transmit data at high rate.

Compared with single carrier systems, OFDM systems offer high frequency efficiency and increase robustness against Intersymbol Interference (ISI) and fading caused by the multipath channel. Therefore, OFDM systems have been widely adopted for WLAN [1], DVB systems [2], and WMAN 802.16 [3]. The last two applications require high data rate transmission in mobile environment. OFDM is also a new technology for Cognitive radio systems [4]-[5].
However, the performance of an OFDM systems is influenced by timing synchronization. Tight timing synchronization is needed as the timing error introduces ISI and decrease the overall system performance [6]. In this paper, the timing synchronization refers to the detection of the start of an OFDM symbol.

The symbol timing estimation in a high data rate mobile OFDM systems is a challenging task, this is due to the high delay spread. Moreover, in case high speed mobility, the channel fluctuate rapidly. A conventional timing estimation based on autocorrelation experience performance degradation due to multipath channel distortion.

To improve the performance of autocorrelation technique, we propose a normalized 3-rd order central moment for symmetric correlator as test statistics. Their values are compared with a predefined threshold to obtain the first arriving path, which refers to the start of an OFDM symbol. After we perform coarse timing estimation using a normalized 3-rd order central moment, fine timing estimation is done using the cyclic shift of a channel estimate. A computer simulation has shown that our method is robust in the fading multipath channel and achieving better performance than previous methods.

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The rest of this paper is organized as follows. Section II describes the related works. Section III describes the problem formulation. Section IV describes the proposed method. Section V describes the performance evaluation and section VI gives the conclusion.

2. Related Works

Lately many of timing synchronization techniques have been proposed. There are three types of timing synchronization techniques, the first technique is based on training symbols where this technique uses the correlation between identical part in the training symbol [7]-[10]. This technique is generally better when viewed from the side of the performance and complexity, however, this technique consumes bandwidth because there is additional data that is sent in the form of training symbol. The second technique is based on cyclic prefix where this technique uses the correlation between cyclic prefix and its data replica [11]-[14]. The performance of cyclic prefix based technique decreased in the multipath fading channel. The third technique is blind timing synchronization techniques [15]-[17]. This synchronization technique greatly save bandwidth but it takes a longer processing time and the complexity is high, so it is not suitable to be applied in the environment with high delay spread.

In this research, we will be focused on synchronization technique using training symbol, in which this technique generally has the better performance compared to other techniques in multipath channel environment. For timing estimation techniques based on training symbol, Schmidl [7] used a training symbol containing two identical parts. However, this estimator has high variance, since the schmidl's timing metric has a large plateau. To decrease the plateau, Minn [8] proposed a new training symbol which is constructed from four identical parts. This technique results sharper timing metric compared to Schmidl's timing metric, however, it still has some side lobes, thus the results of the timing estimation still has a large variance.

In order to reduce the variance, Park [9] proposed sharper timing metric using symmetric correlation property. However, the timing metric of Park's method has two large side lobes. To remove the side lobes of Park's timing metric, Yi [10] proposed a new training symbol structure that has symmetric correlation property. All of the methods mentioned above only focus on the design in the time domain training symbol and timing metric is constructed based on the correlation of identical parts in the training symbol. Therefore, the timing estimate of those techniques experienced a sharp degradation in the multipath channel with a high delay spread.
To overcome this problem, Sheng [18] proposed noise sub-spaced of channel estimate, however it requires a high computation and the performance is decreasing with increasing the frequency offset. The latest improvement of this method is proposed by Cho [19] based on statistical change of symmetric correlator, uses a Generalized Likelihood Ratio Test (GLRT). Although the GLRT method has impressive performance results compared to conventional technique, they still have performance degradation in mobile environment with higher delay spread.

3. Problem Formulation

The OFDM transmission system shown in Figure. 1, where a sequence of OFDM symbol transmitted from the transmitter to the receiver. Each of the OFDM symbol generated from a block subsymbol $\{C_k\}$ by using Inverse Fast Fourier Transform (IFFT) which has duration τ seconds. At the beginning of the OFDM symbol, Cyclic Prefix (CP) with 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). This is done to avoid the ISI caused by multipath channel, so that the signal transmitted over the multipath channel with a delay spread length of L_c is defined as:

$$y(d) = \sum_{m=0}^{L_c-1} h(m)x(d-m) + n(d), \quad (1)$$

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

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

On the receiver side, the received signal $r(d)$ is delayed as a result of their transmission time, so it can be modeled as follows:

$$r(d) = y(d - d_\epsilon)e^{j2\pi\frac{d}{N}v}, \quad (3)$$

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

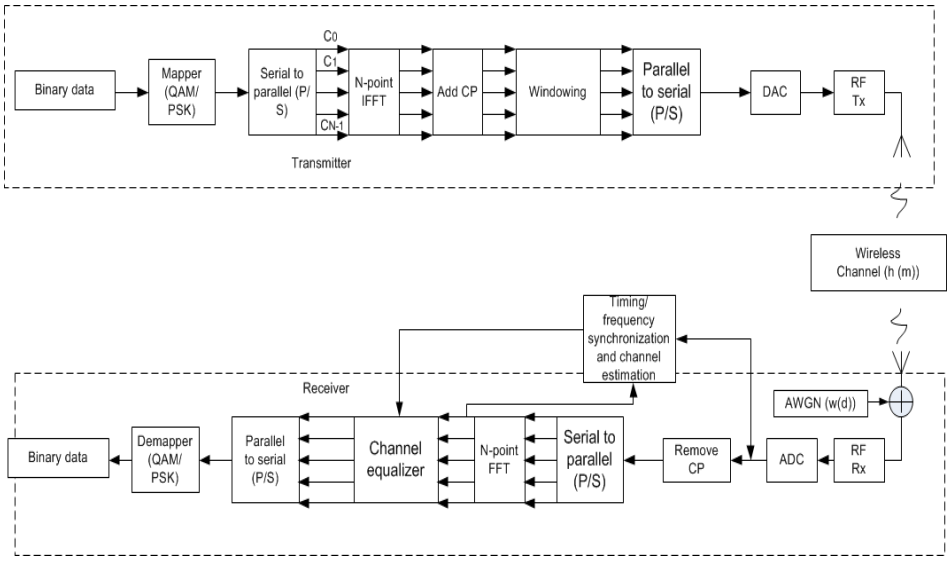

Figure 1. OFDM Systems Transmission

The purpose of timing synchronization in OFDM systems is to calculate the value of d_ε. The autocorrelation technique (AutoCorr) [9] is usually used to calculate the value of d_ε. This technique is designed using a training symbol with two identical parts that are mutually symmetric as shown in Figure. 2. N is the number of samples in one OFDM symbol and Ng is the number of samples in CP. Eq. (4) shown the representation of a training symbol in the time domain.

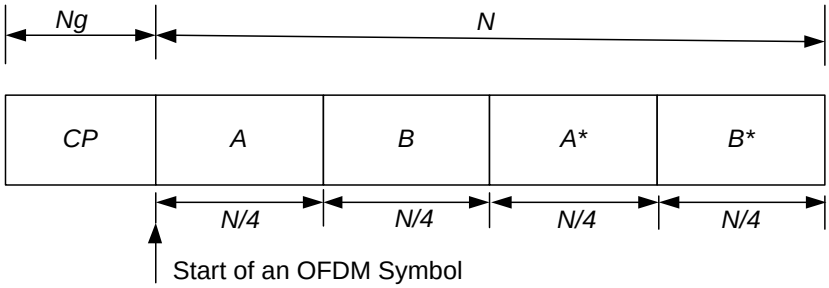

Figure 2. OFDM Training symbol

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

Where $A_{N/4}$ represents the samples length of $N/4$, $B_{N/4}$ is symmetric of $A_{N/4}$, and $A^*_{N/4}$ is conjugate of $A_{N/4}$. This training symbol can be generated using IFFT by allocating a binary Pseudo Noise (PN) sequence at every $Q - th$ subcarrier in the frequency domain as follows :

$$X_p(k) = \begin{cases} \pm 1, & mod(k, Q) = 0, \\ 0, & otherwise, \end{cases} \quad (5)$$

where $X_p(k)$ is the training signal at the $k-th$ subcarrier in the frequency domain and $mod(,)$ is the modular function. Q is the number of identical parts and is equal to 8 and 2 for WLAN [1] and WMAN 802.16m [3] systems, respectively. Hence, The symmetric correlation property of training symbol is defined as:

$$x_p(N/2-k) = x_p^*(N/2+k), 1 \le k \le N/2-1, \quad (6)$$

where x_p is a training signal in the time domain.

By utilizing the property of $B_{N/4}$ that is symmetric with $A_{N/4}$, then the symmetric correlator $P(d)$ is defined as :

$$P(d) = \left| \sum_{k=1}^{\frac{N}{2}-1} r(d+k) r(d+N-k) \right|. \quad (7)$$

The timing estimation of OFDM symbol is done by taking the maximum value of the timing metric is defined as follows:

$$M_{Park}(d) = \frac{|P(d)|^2}{|R(d)|^2}, \quad (8)$$

where

$$R(d) = \sum_{k=0}^{N/2-1} |r(d+k+\frac{N}{2})|^2. \quad (9)$$

4. Proposed Method

The proposed timing synchronization method consists of coarse timing synchronization and fine timing synchronization. Coarse timing is an initial estimate of the arrival of OFDM symbol (training symbol) while fine timing is required to correct errors that occur in the coarse timing. Fine timing performed after calculating the frequency offset and channel impulse response, and the results are used to remove the CP. The receiver consists of Block of Radio Frequency (RF), Analog to Digital Converter (ADC), Timing and Frequency Synchronization, Remove CP, Fast Fourier Transform (FFT), Channel Equalizer, Quadrature Amplitude Modulation (QAM)/Phase Shift Keying (PSK), and Binary data as shown in Figure. 3.

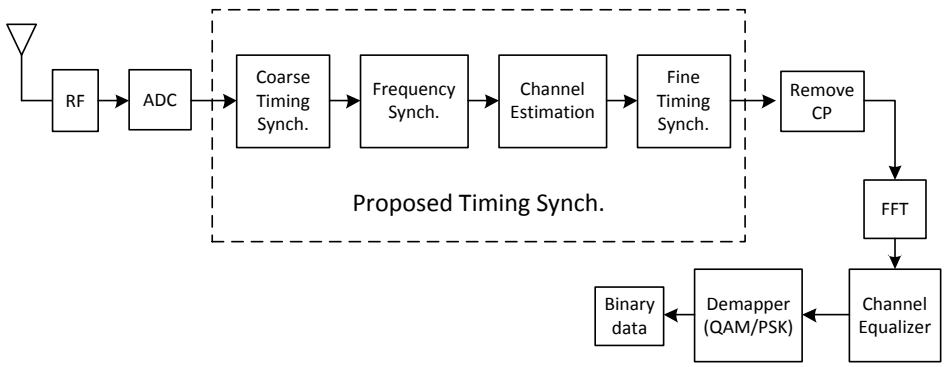

Figure. 3. The Receiver Block of OFDM systems (Sync.:Synchronization).

For coarse timing synchronization, we propose an estimation method based on differences in distribution of the symmetric correlator. To acquire the distribution of symmetric correlator, let define $\rho(d) = \sum_{k=1}^{\frac{N}{2}-1} r(d+k) r(d+N-k)$. When $\rho(d)$ is passed through multipath channel, $\rho(d)$ has two distribution conditions that are complex normal distribution with zero mean when

no training symbol is received and complex normal with non-zero mean when training symbol is received. So we can write it as follows:

$$\rho(d) = \begin{cases} CN(0, B\sigma_r^4) & d \notin L, \\ CN(Bh^2(d-d_0)\sigma_x^2 e^{2\pi v}, B\sigma_r^4) & d \in L, \end{cases} \quad (10)$$

where $B = (N/2 - 1)$, $\sigma_r^2 = \kappa\sigma_x^2 + \sigma_n^2$, $\kappa = \sum_m |h(m)|^2$, $\sigma_x^2 = \frac{1}{N}\sum_{k=0}^{N-1} |x_p(k)|^2$, σ_n^2 is noise variance with zero mean, and $L(= d_0,\ d_{0+1}, \dots, d + L_c)$ is multipath channel index. Where the first arriving path is denoted by $(d_0 = 0)$, which indicate the start of the training symbol.
Since $P(d) = |\rho(d)|$, then the PDF of $P(d)$ when no training symbol is received is Rayleigh distribution as follows:

$$f(P(d); \sigma^2, 0) = \frac{P(d)}{\sigma^2} exp\left(-\frac{P^2(d)}{2\sigma^2}\right), \quad (11)$$

and the PDF of $P(d)$ when training symbol is received is Rician distribution as follows:

$$f\big(P(d); \sigma^2, a(d)\big) = \frac{P(d)}{\sigma^2} exp\left(-\frac{P^2(d)+a^2(d)}{2\sigma^2}\right) I_0\left(\frac{P(d)a(d)}{\sigma^2}\right), \quad (12)$$

where I_0 is the first kind of modified Bessel function with zero order,

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

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

By making observations along J of $P(d)$, then the change of the parameters $a(d)$ can be formulated as follows:

- H0 : $a(d) = 0$, with Rayleigh distribution at $d \neq d_0$,
- H1 : $a(d) = B|h^2(d-d_0)|\sigma_x^2$, with Rician distribution at $d = d_0$,

where H0 indicating no change in the parameter $a(d)$, while H1 indicates a change in the parameter $a(d)$ when $d = d_0$. To detect the change in the parameter $a(d) = B|h^2(d-d_0)|\sigma_x^2$, we proposed a normalized 3-rd order central moment to perform statistics test. The idea behind the proposed method is based on the mean difference between the distribution of H0 and H1.

To sharpen the mean difference of the two distributions, we use a higher order statistics. Here, we use a normalized 3-rd order central moment for comparing the mean of two different distribution. This technique compares the value of the 3-rd order central moment with its average value. This is done to improve the detection of the first arriving path by utilizing the differences of signal distribution.
Hence, our method can be defined as follows :

$$M(d) = \frac{E[(P(d)-\mu_P(d))^3]}{N_P(d)}, \quad (13)$$

where $\mu_P(d)$ is mean of correlator $P(d)$ and $N_P(d)$ is normalization value. The normalization factor is defined as mean of 3-rd order central moment $(E[E[(P(d) - \mu_P(d))^3]])$.
hence, the timing estimation can be defined as :

$$\hat{e} = \underbrace{argmax}_{d} (M'(d)), \quad (14)$$

where

$$M'(d) = \begin{cases} M(d), & P(d) > T, \\ 0, & otherwise, \end{cases} \quad (15)$$

and T is the threshold for timing estimation. To avoid error detection (False Alarm) in Eq. (15), we only take the timing point that is exceed the threshold.
The probability of False Alarm is derived from (11) as follows :

$$P(P(d) > T) = \exp\left(-\frac{T^2}{2\sigma^2}\right), \quad (16)$$

and the threshold can be determined for the given False Alarm rate :

$$T = \sqrt{-2\sigma^2 log\ P_{FA}}, \quad (17)$$

where P_{FA} is the target of probability of False Alarm and σ^2 is replaced by σ_0^2, which is derived from maximum likelihood (ML) estimate under H0 is given by

$$\sigma_0^2(d) = \underset{\sigma^2}{sup} \prod_{k=0}^{J-1} f(P(d-k); \sigma^2, 0) = \frac{1}{2J} \sum_{k=0}^{J-1} P^2(d-k). \quad (18)$$

The example of $P(d)$ and $M(d)$ from our timing metric simulation shown in Figure. 4, where each of those timing metric normalized to their maximum value and 0 index is set as the correct timing point (the first arriving path). It can be seen that the maximum value of $M(d)$ is located on the first arriving path, while the maximum value $P(d)$ is not on the first arriving path, resulting in delayed time estimate. Therefore, we use the maximum value of $M(d)$ to calculate the coarse timing estimate.

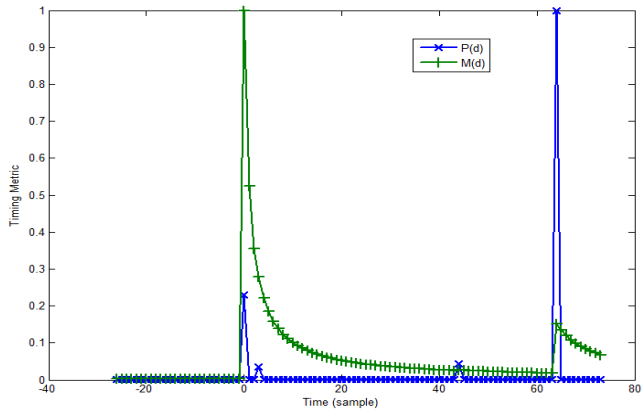

Figure 4. Plots for $P(d)$ and $M(d)$ under Vehicular B channel with SNR = 20 dB, CFO=1.4, N=2048, $N_G = 256$ and $Q = 2$.

To improve the performance of the coarse timing estimation to determine the first arriving path, we add a method for fine timing estimation. Similiar method has been proposed as in [20], where fine timing estimation is used for coarse timing error correction that happen before the first arriving path (in CP region). Meanwhile, our technique is used for coarse timing error correction that happen after the first arriving path (in training symbol region). This happens because the correlation results of the symmetrical correlation form is always in the symbol training region.

After obtaining coarse timing estimate ($\hat{e}$), then we calculate the frequency offset ($\hat{v}$). There are two step to estimate the frequency offset. First, we calculate the fractional frequency offset ($\hat{e_f}$) using method in [11] as follows:

$$\hat{e_f} = \frac{angle\left(\sum_{n=\hat{e}-N_g}^{\hat{e}-1} y(d) * y(d+N)\right)}{2\pi} \quad (19)$$

and the second step is to calculate the integer frequency offset ($\hat{e_I}$) using method in [21]. Where, the estimate of $\hat{e_I}$ is $\hat{q} = q$ which maximize the metrix :

$$F(q) = \frac{\left|\sum_{k\in K} Y_{2k+2q} C_k^* Y_{2k+2q+2}^*\right|^2}{\left(\sum_{k\in K} |Y_{2k+2q}|^2\right)^2} \quad (20)$$

where $K = \{0,1,\ldots,N/2-2\}$ and $C_k = \frac{X_{2k}}{X_{2k+2}}$, for $k = 0,1,\ldots,\frac{N}{2}-2$. So, $\hat{v} = \hat{e_f} + \hat{e_I}$.

The results of the frequency offset estimation is compensated to the received signal to calculate the channel impulse response using the least square method [22] to obtain $\left\{\hat{H}(k),\ k = 0, Q, \ldots, \frac{N}{Q} - Q\right\}$. This method can be described as follows:

$$\hat{H}(k) = \frac{\hat{Y}(k)}{\hat{X}(k)} \quad (21)$$

Thus, the CIR estimation is done by performing N/Q-points IFFT on $\left\{\hat{H}(k)\right\}$, we obtained CIR estimate as follows:

$$\hat{\mathbf{h}} = \left[\hat{h}(0), \hat{h}(1), \ldots, \hat{h}(N/Q-1)\right]. \quad (22)$$

Figure 5 shows the CIR estimate normalized to the respective maximum value when coarse timing estimate was right at the first arriving path. The CIR has at most N_G path, while all other samples correspond to noise. Figure. 6 shows the CIR estimate normalized to the respective maximum when coarse timing estimate was not right at the first arriving path. Under these conditions CIR experience cyclic shift with delay δ.

Hence, we can search the first arriving path from $N/Q - N_G$ to N/Q. Due to the area is noise subspace then we can detect the first arriving path by comparing the value of normalized CIR to certain tershold, This value is taken to be greater than the noise and not too large so that it can detect a weak channel path. For searching the the first arriving path we apply the following step :

Step 1: Set $\tau = 0$;
Step 2: Set $N\_|h(k)|$ =Normalized $|h(k)|$ to their maximum value;
Step 3 : Search τ from $i = N/Q - N_G \; to \; N/Q$:
If $N\_|h(k)| \geq f\_th$
set $\tau = i$;
else
set $\tau = N/Q$;
Step 4 : Set $\delta = N/Q - \tau$.

After we obtain δ, the fine timing estimation become:

$$\hat{e}_f = \hat{e} - \delta, \quad (23)$$

where $\hat{e}$ is the coarse timing estimate and δ is the delay of fine timing estimate.
The Proposed time synchronization algorithm is perform as follow:

- Step 1 : Coarse timing estimation is perform using Eq. (14).
- Step 2 : Frequency offset estimation is perform using a method in [11] and [21].
- Step 3 : Frequency offset compensation is applied to the received signal ($r(d)$).
- Step 4 : Channel estimation is perform using least square method as in [22].
- Step 5 : Fine timing estimation is perform using Eq. (23).

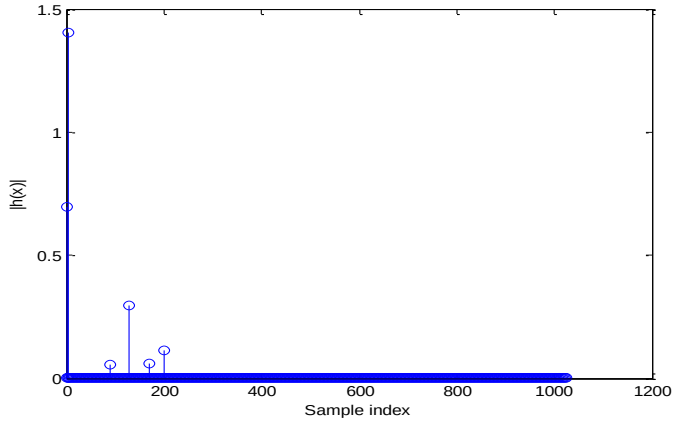

Figure 5. Normalized CIR with number of sample N/Q=1024, with N=2048 and Q=2.

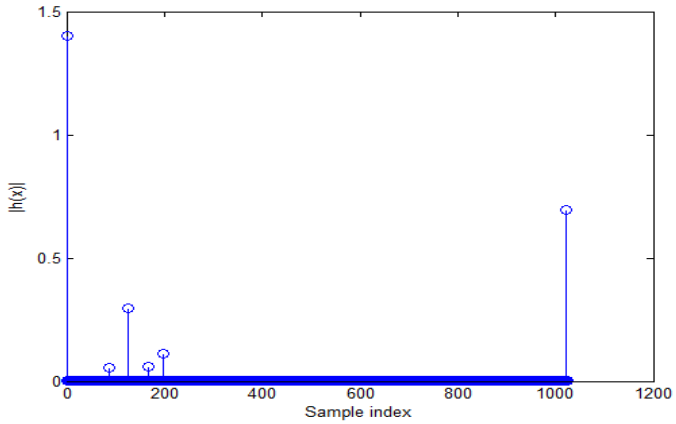

Figure. 6. Normalized CIR with number of sample N/Q=1024, with N=2048 and Q=2.

5. Performance Evaluation

The performance of our timing estimator is evaluated by computer simulation along with previous methods using Mean Absolute Error (MAE) and Mean Squared Error (MSE). The MAE defined as $E[|t_{estimation} - t_{offset}|]$, which measures the average of the estimated timing errors between the estimated time at the receiver with the time delay caused by transmission. The MSE defined as $E[(t_{estimation} - t_{offset})^2]$ which measures the average of the squared estimated timing errors between the estimated time at the receiver with the time delay caused by transmission. In this simulation we assume that the signal has ergodicity and wide sense stationary properties.

We setup the simulation by transmitting a frame consisting of a training symbol [9] that was preceded by one random OFDM symbol and followed by two random OFDM data symbols. The estimation process of the arrival OFDM of symbol can be depicted in Figure. 7. The parameters of our simulation shown in Tabel 1.

Table 1. OFDM Simulation Parameters

No.	Parameter	Value
1.	Data modulation technique	16-QAM
2.	FFT size	2048
3.	CP length	1/8 of OFDM symbol
4.	Sampling rate	0.1 μs
5.	Channel model	Vehicular B channel [23]
6.	CFO	Uniform random variable distributed in range $\pm$ 2
6.	P_{FA}	10^{-6}
7.	Vehicle speed	120 km/h
8.	J	$N_g/2$
9.	Q	2
10.	f_th	0.2

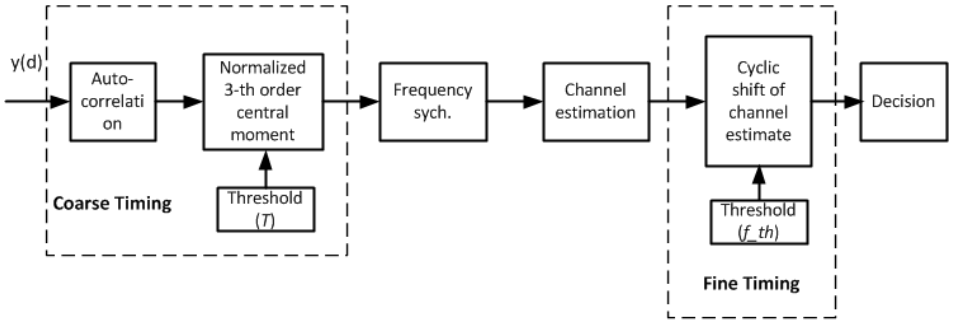

Figure 7. Timing estimation of the arrival of OFDM Symbol.

Figure 8 and Figure 9 show the MAE and MSE of our simulation under Vehicular B channel. In our simulations, the performance of each method are tested using various SNR values. We run a computer simulation as much as 10.000 iterations for each trial.

Figure. 8 and Figure. 9 show the performance of three methods under Vehicular B channel. Autocorrelation method gave the lowest performance due to multipath channel distortion. The multipath channel distortion caused autocorrelation method experienced a delayed timing estimate. Unlike the autocorrelation method, our method is less likely to experienced a delayed timing estimate.

Our proposed method also gave a higher performance compared to GLRT method. There are two different things that make our method perform better : the test statistics (coarse time synchronization) and fine time synchronization (finely search the correct timing for the detected training symbol). The first improvment from our method can be inferred from using central moment and higher order than GLRT method. GLRT method actually second order normalization technique. This makes the method suboptimal compared to our method. For the second reason is our method uses cyclic shift of channel estimation for fine time synchronization. Thus, we get more accurate results, where the delay estimation is a shift of channel estimate, whereas in the GLRT method, fine time synchronization is only done by comparing with a certain threshold.

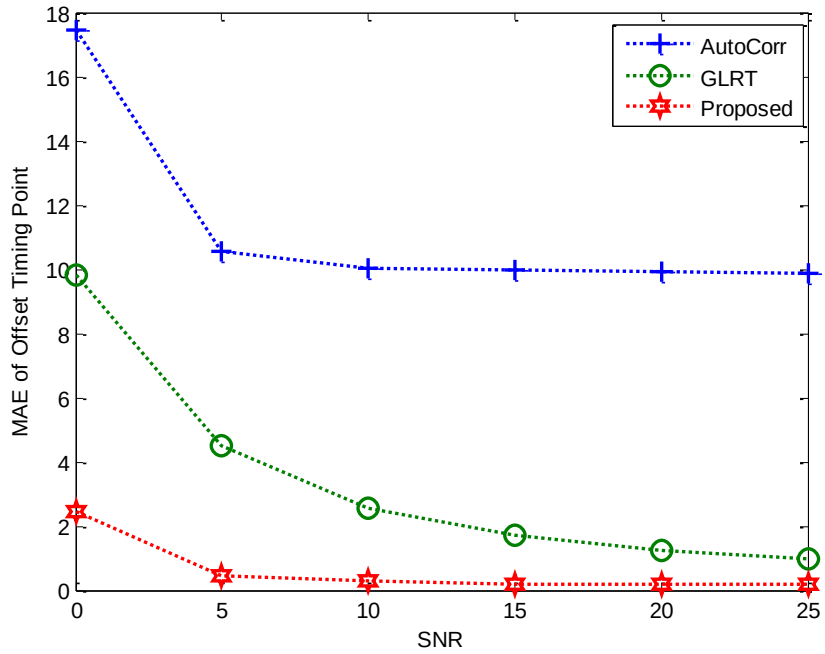

Figure. 8. MAE Performance of three methods under Vehicular B channel.

To measure the overall performance of OFDM systems, we evaluate BER performance under Vehicular B channel. Figure. 10 shows the BER performance of three methods under Vehicular B channel. Its shown that our proposed method has better performance in BER test due to using normalized 3-rd order central moment for coarse timing estimation and combine with cyclic shift of channel estimate for fine timing estimation.

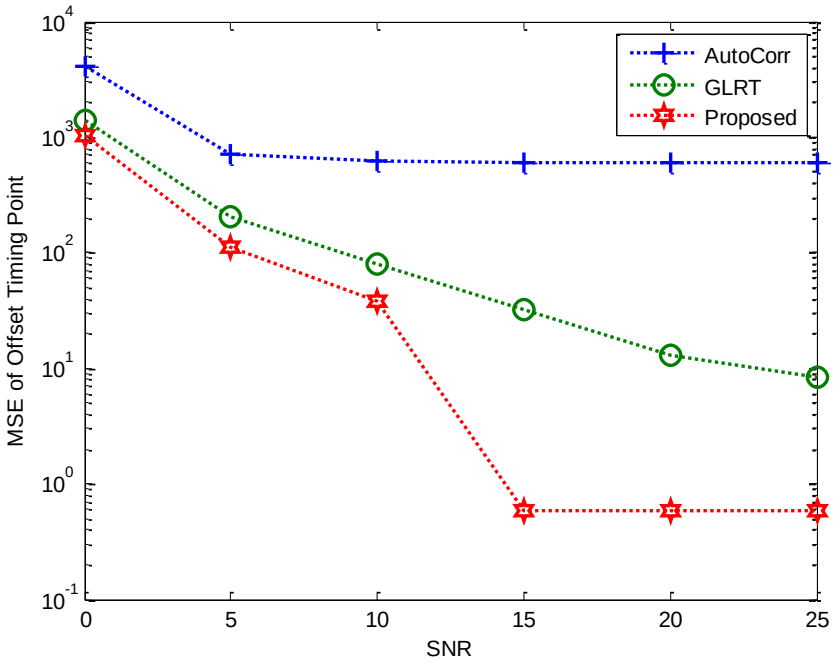

Figure. 9. MSE Performance of three methods under Vehicular B channel.

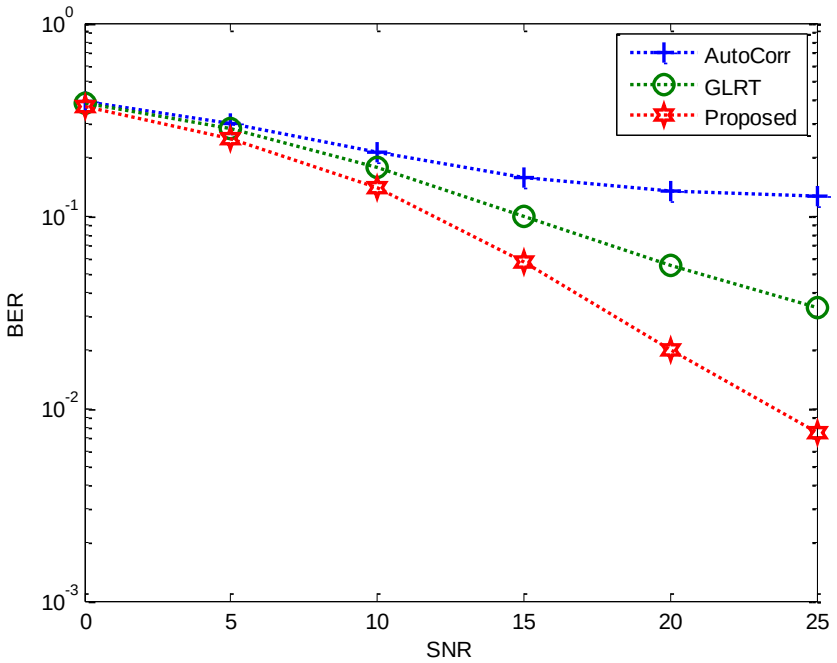

Figure. 10. BER Performance of three methods under Vehicular B channel.

For the complexity of coarse time synchronization, it requires $\frac{N}{2}+1$ complex multiplications and $\frac{N}{2}+2J-3$ complex additions. To calculate the complexity of fine time synchronization is consists of two part. The first part is frequency estimation, it required $\frac{3}{2}N+Ng+2$ complex multiplications, $N+Ng-3$ complex additions, and $N/2$ division. The second part is channel estimation and it's normalization againts the maximum value, it required N division and the search procedure is not included in the calculation of complexity since only compares the normalized channel estimation with a theshold.

Table II shown the complexity of our algorithm along with previous methods. Figure. 11. Shows the Complexity comparison on number of complex multiplications and Figure. 12. Shows the Complexity comparison on number of complex additions. It shown that our method has slightly higher complexity compared to other methods.

TABLE II
Complexity Comparison

Method	Number of complex multiplications	Number of complex additions
AutoCorr	N/2	N/2-1
GLRT	N/2	N/2+J-3
Proposed	2N+Ng+3	3/2N+2J+Ng-6

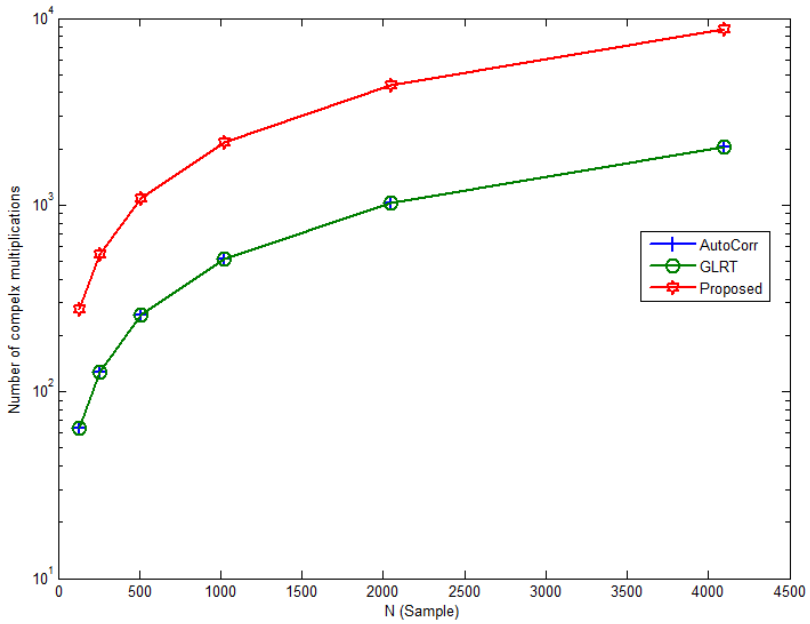

Figure. 11. Complexity comparison on number of complex multiplications.

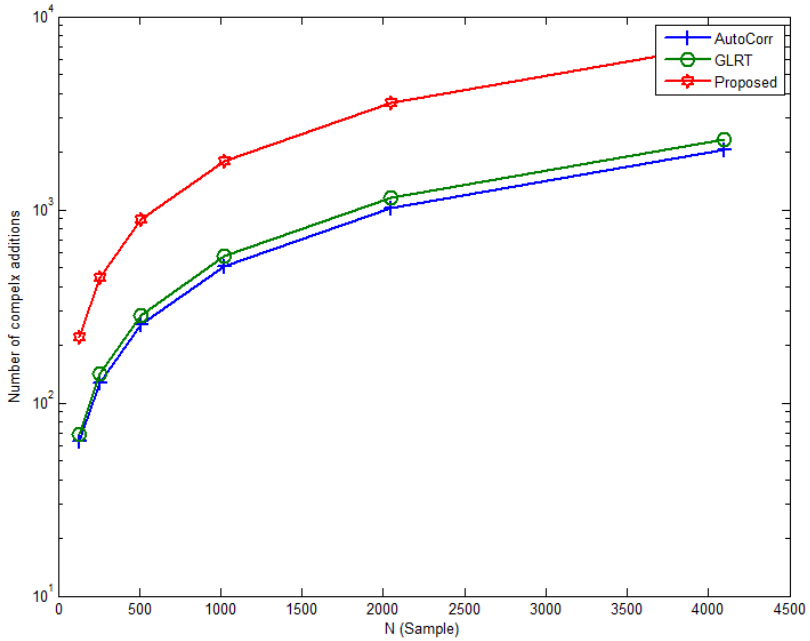

Figure. 12. Complexity comparison on number of complex additions.

Conclusion

We already discussed the performance of the autocorrelation method in environments with high delay spread. The weakness of the autocorrelation method is improved by our method. It exploits the distribution difference of the received signal combine with cyclic shift of channel estimate. The proposed time synchronization method achieved better performance in term a much smaller MAE and MSE with expense increasing complexity. BER performance shows our method has better than other method in overall system performance. The proposed timing estimator can adapted to environments with high delay spread, making it suitable for timing synchronization in high data rate mobile OFDM systems.

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